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Department of Electronics

THESIS

Presented by

Rania DJEHAICHE

To obtain the diploma of

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Domain: Science and Technology

Branch: Electronics

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Theme

Deployment and Convergence of M2M Networks and 4G/5G Mobile Networks

Discussed on 12/10/2023

In front of the jury:

ATTIA Salim	MCA	President	University of BBA
AIDEL Salih	Professor	Supervisor	University of BBA
BOUZIT Nacerdine	Professor	Examiner	University of Setif-1
AMARDJIA Nourredine	Professor	Examiner	University of Setif-1
MESSAOUDENE Idris	MCA	Examiner	University of BBA

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Faculté des Sciences et de la technologie

Département d'Electronique

THESE

Présentée par

Rania DJEHAICHE

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Thème

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ATTIA Salim	MCA	Président	Université de BBA
AIDEL Salih	Professeur	Rapporteur	Université de BBA
BOUZIT Nacerdine	Professeur	Examinateur	Université de Setif-1
AMARDJIA Nourredine	Professeur	Examinateur	Université de Setif-1
MESSAOUDENE Idris	MCA	Examinateur	Université de BBA

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  Department of Electronics, Faculty of Science and Technology, Ferhat Abbas University Setif 1.

- Pr. Amardjia Nourredine, External Independent Examiner

  Department of Electronics, Faculty of Science and Technology, Ferhat Abbas University Setif 1.

- Dr. Idris Messaoudene, Member of the jury

  Department of Electronics, Faculty of Science and Technology, University Mohamed El Bachir El Ibrahimi of Bordj Bou Arreridj.

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Deployment and Convergence of M2M Networks and 4G/5G Mobile Networks

Abstract

In today's rapidly developing world of wireless communications, Machine-to-Machine (M2M) communication, Internet of Things (IoT) technology, along with 4th Generation (4G) and 5th Generation (5G) networks are becoming critical to many applications and services. This PhD research aims to study the deployment and convergence of IoT/M2M networks and 4G/5G mobile networks. Despite their widespread use, existing IoT/M2M Smart-X systems face several limitations such as lack of integration between IoT and M2M technologies, high costs, unfriendly user interfaces, reliance on only one or two wireless communication networks, limited range of wireless communication networks, and the lack of a convergent solution. To address these limitations, our proposed solution offers four major contributions: adaptive control for IoT/M2M devices connected to heterogeneous networks (HetNets) in smart-x systems using low-cost components; dynamic use and intelligent management of IoT/M2M devices to facilitate monitoring and control of any smart-x system (office, home, building, hospital, city, etc.) through IoT platforms such as ThingSpeak, Blynk, and our versatile free IoT/M2M platform named Raniso; proposal of innovative applications including smart home automation, smart environment, smart city, smart healthcare, and smart building; and validation of the functionality of the proposed systems in terms of adaptation, control, automation, safety, comfort, energy efficiency, and performance. The objective of this dissertation to propose a hybrid (local and remote) IoT/M2M smart-x systems that are based on HetNets, consisting of Wireless Sensor Networks (WSNs) [Radio Frequency Identification (RFID), Bluetooth, Wireless Fidelity (Wi-Fi)] and Mobile Cellular Networks (MCNs) [Global System for Mobile (GSM), Long Term Evolution (LTE), and 5G].

Keywords : Internet of Things, Machine-to-Machine, Mobile Cellular Networks, Wireless Sensor Networks, Converged Networks, Heterogeneous Networks, Raniso Platform, Smart-X System, Smart Building.

نشر وتقارب شبكات M2M وشبكات المحمول 5G/4G

ملخص

في عالم الاتصالات اللاسلكية سريع التطور اليوم ، أصبحت الاتصالات من آلة إلى آلة (M2M) وتقنية إنترنت الأشياء (IoT) جنبًا إلى جنب مع شبكات الجيل الرابع (4G) والجيل الخامس(5G) حاسمة للعديد من التطبيقات والخدمات. يهدف بحث الدكتوراه هذا إلى دراسة نشر وتقارب شبكات M2M/IoT وشبكات المحمول 5G/4G. على الرغم من استخدامها على نطاق واسع ، فإن أنظمة M2M/IoT الذكية الحالية تواجه العديد من القيود مثل عدم التكامل بين تقنيات IoT و M2M ، والتكاليف المرتفعة ، وواجهات المستخدم غير الودية ، والاعتماد على شبكة اتصال لاسلكية واحدة أو اثنتين فقط ، ونطاق محدود من شبكات الاتصالات اللاسلكية ، وعدم وجود حل متقارب. لمعالجة هذه القيود ، يقدم حلنا المقترح أربع مساهمات رئيسية: التحكم التكيفي لأجهزة M2M/IoT المتصلة بشبكات غير متجانسة (HetNets) في أنظمة smart-x التي تستخدم مكونات منخفضة التكلفة ؛ استخدام ديناميكي وإدارة ذكية لأجهزة M2M/IoT لتسهيل المراقبة والتحكم في أي نظام (مكتب ، منزل ، مبنى ، مستشفى ، مدينة ، إلخ) من خلال منصات إنترنت الأشياء مثل ThingSpeak و Blynk و منصة M2M/IoT متعددة الاستخدامات والمجانية التي تحمل اسم Raniso ؛ اقتراح تطبيقات مبتكرة بما في ذلك أتمتة المنزل الذكي ، والبيئة الذكية ، والمدينة الذكية ، والرعاية الصحية الذكية ، والبناء الذكي ؛ والتحقق من صحة وظائف الأنظمة المقترحة من حيث التكيف والتحكم والأتمتة والسلامة والراحة وكفاءة الطاقة والأداء. تهدف هذه الرسالة إلى اقتراح أنظمة M2M/IoT الذكية الهجينة (المحلية والبعيدة) التي تعتمد على شبكات غير متجانسة ، وتتألف من شبكات الاستشعار اللاسلكية (WSNs) [تحديد تردد الراديو (RFID) ، والبلوتوث ، والإخلاص اللاسلكي (Wi-Fi)] والشبكات الخلوية المتنقلة (MCNs) [النظام العالمي للجوال (GSM) والتطور طويل الأمد (LTE) وشبكة الجيل الخامس].

كلمات مفتاحية: إنترنت الأشياء، من آلة إلى آلة، الشبكات الخلوية المتنقلة، شبكات الاستشعار اللاسلكية، الشبكات المتقاربة، الشبكات غير المتجانسة، منصة رانيسو، نظام X- الذكي ،المبنى الذكي.

Déploiement et Convergence des Réseaux M2M et des Réseaux Mobiles 4G/5G

Résumé

Dans le monde des communications sans fil qui se développe rapidement aujourd'hui, la communication Machine à Machine (M2M), la technologie de l'Internet des objets (IoT), ainsi que les réseaux de 4ème génération (4G) et de 5ème génération (5G) deviennent essentiels pour de nombreuses applications et services. Cette recherche doctorale vise à étudier le déploiement et la convergence des réseaux IoT/M2M et des réseaux mobiles 4G/5G. Malgré leur utilisation répandue, les systèmes IoT/M2M Smart-X existants sont confrontés à plusieurs limitations telles que le manque d'intégration entre les technologies IoT et M2M, les coûts élevés, les interfaces utilisateur peu conviviales, la dépendance à un ou deux réseaux de communication sans fil seulement, la portée limitée des réseaux de communication sans fil, et l'absence de solution convergente. Pour remédier à ces limitations, la solution que nous proposons offre quatre contributions majeures : un contrôle adaptatif pour les dispositifs IoT/M2M connectés à des réseaux hétérogènes (HetNets) dans les systèmes smart-x en utilisant des composants à faible coût ; une utilisation dynamique et une gestion intelligente des dispositifs IoT/M2M pour faciliter la surveillance et le contrôle de tout système smart-x (bureau, maison, bâtiment, hôpital, ville, etc.) à travers des plateformes IoT telles que ThingSpeak, Blynk, et notre plateforme IoT/M2M polyvalente et gratuite nommée Raniso ; la proposition d'applications innovantes incluant la domotique intelligente, l'environnement intelligent, la ville intelligente, les soins de santé intelligents, et le bâtiment intelligent ; et la validation de la fonctionnalité des systèmes proposés en termes d'adaptation, de contrôle, d'automatisation, de sécurité, de confort, d'efficacité énergétique, et de performance. L'objectif de cette thèse est de proposer des systèmes hybrides (locaux et distants) IoT/M2M smart-x qui sont basés sur des HetNets, composés de réseaux de capteurs sans fil (WSNs) [Identification par radiofréquence (RFID), Bluetooth, Fidélité sans fil (Wi-Fi)] et de réseaux cellulaires mobiles (MCNs) [Système global de téléphonie mobile (GSM), Évolution à long terme (LTE), et 5G].

Mots-clés : Internet des Objets, Machine à Machine, Réseaux Cellulaires Mobiles, Réseaux de Capteurs Sans Fil, Réseaux Convergents, Réseaux Hétérogènes, Plateforme Raniso, Système Smart-X, Bâtiment Intelligent.

Résumé étendu de la thèse en français

Introduction générale

Le déploiement et la convergence des réseaux IoT/M2M et des réseaux mobiles 4G/5G posent des défis tels que le coût, la confidentialité, la sécurité et l'évolutivité. Un autre aspect important de la convergence des réseaux IoT/M2M et des réseaux mobiles 4G/5G est l'utilisation du découpage de réseau [1]. L'objectif de notre thèse **"Déploiement et convergence des réseaux M2M et des réseaux mobiles 4G/5G"** est d'étudier le déploiement et la convergence des réseaux IoT/M2M et des réseaux mobiles 4G/5G. Plus précisément, nous visons à explorer les défis et les solutions liés au déploiement de ces réseaux, ainsi que les avantages et les défis de leur convergence. En outre, nous prévoyons d'évaluer les approches existantes de la convergence et de fournir des études de cas de déploiements réussis et de réseaux convergents dans la pratique. En fin de compte, notre thèse vise à contribuer à la compréhension de la manière dont ces réseaux peuvent être déployés et convergés efficacement pour soutenir diverses applications dans différents domaines. En comparant le travail proposé dans cette thèse avec les travaux de recherche existants, les inconvénients des systèmes actuels comprennent l'absence d'utilisation conjointe des technologies IoT et M2M, la dépendance à l'égard d'une ou deux technologies de communication sans fil au maximum, une portée de transmission sans fil limitée, une interface utilisateur généralement mal conçue, et des coûts excessifs. Par conséquent, l'approche proposée présente un système de bâtiment intelligent hybride (local et à distance) et peu coûteux basé sur l'IoT/M2M avec une interface smartphone agréable pour l'utilisateur. En outre, nous proposons dans cette thèse cinq applications innovantes, notamment la domotique intelligente, l'environnement intelligent, la ville intelligente, les soins de santé intelligents et le bâtiment intelligent. Toutes ces applications intelligentes peuvent être contrôlées et surveillées à distance par deux plateformes IoT bien connues (ThingSpeak et Blynk), ainsi que par notre plateforme IoT/M2M polyvalente et gratuite appelée Raniso, qui est utilisée comme serveur local pour contrôler le bâtiment via différents réseaux HetNets, tels que la connectivité RFID / Bluetooth / Wi-Fi et les réseaux cellulaires, tels que GSM, 4G ou 5G. En outre, grâce au mécanisme proposé, tous les appareils intelligents IoT/M2M peuvent être connectés de manière économe en énergie, sûre, pratique et rentable, et recevoir des données des systèmes smart-x proposés, les stocker dans la base de données en nuage, les afficher sur la page web ThingSpeak et les contrôler à distance via les applications Raniso et Blynk.

Chapitre 1

Le premier chapitre explique les motivations qui sous-tendent les activités de recherche axées sur le déploiement et la convergence des réseaux IoT/M2M et des réseaux mobiles 4G/5G, ainsi nos principales contributions de recherche.

Motivations et contributions à la recherche

Le déploiement et la convergence des technologies IoT/M2M et des réseaux cellulaires 4G/5G deviennent de plus en plus importants pour de nombreuses industries. Cette thèse propose un contrôle adaptatif des appareils IoT/M2M dans les systèmes smart-x (maisons, bâtiments, villes et soins de santé) à l'aide de réseaux sans fil hétérogènes comme moyen de résoudre ces problèmes et de réduire les limites existantes des systèmes actuels. En sélectionnant la connexion appropriée, qu'il s'agisse d'un WSN ou d'un MCN, au moyen d'une interface conviviale utilisant les smartphones via l'application Raniso ou l'application Blynk, indépendamment de l'heure et du lieu, les utilisateurs peuvent contrôler leurs systèmes facilement et efficacement. Les coûts sont réduits grâce à l'utilisation de composants efficaces et abordables et de l'application gratuite Raniso App pour gérer, surveiller et contrôler les équipements et les conditions du bâtiment à travers différents réseaux hétérogènes. Cette contribution à la recherche implique l'utilisation de l'application mobile que nous avons développée, Raniso, pour contrôler les appareils IoT/M2M dans les systèmes smart-x sur des réseaux sans fil hétérogènes afin d'obtenir un contrôle adaptatif. Les principales contributions de cette thèse illustrées dans la figure ci-dessous.

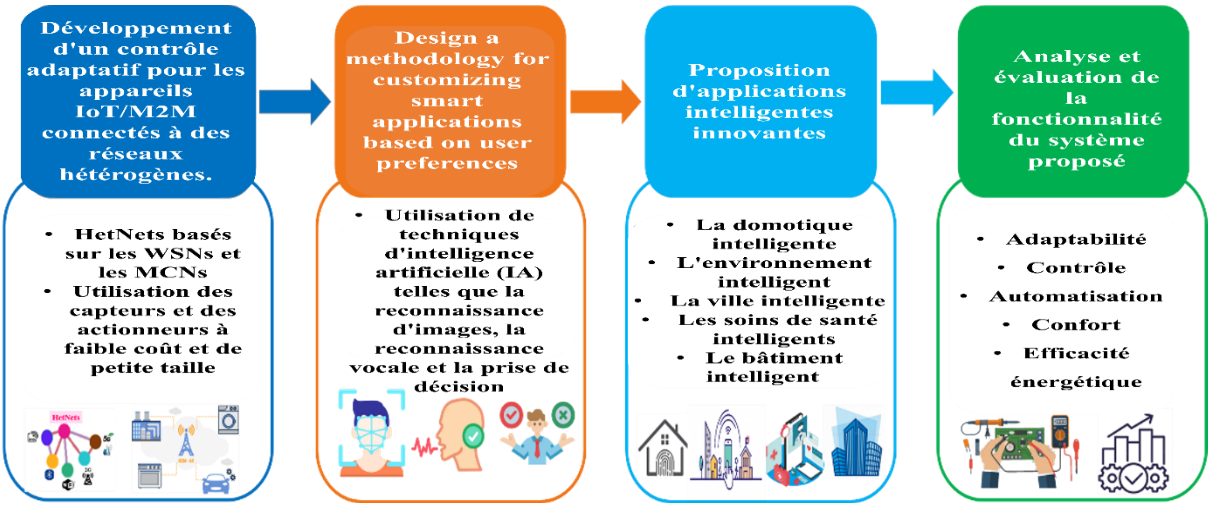

Figure 1. Contributions de la thèse.

Chapitre 2

Dans le deuxième chapitre, nous présentons un aperçu des communications IoT/M2M, y compris leur évolution, les besoins actuels et les technologies de connectivité.

Les communications IoT/M2M

Le concept de l'IoT fait référence à la capacité des appareils à communiquer sur l'internet par le biais d'appareils mobiles, de capteurs et d'actionneurs [2], ce qui permet de collecter des informations et des connaissances, offrant ainsi un moyen de prendre des décisions plus rapides et plus intelligentes [3]. L'IoT peut être exprimé par une formule simple telle que :

$$IoT = Services + Données + Réseaux + Dispositifs \qquad (1)$$

Ainsi la communication M2M fait partie intégrante de l'écosystème de l'IoT et contribue largement à son développement. Le M2M est défini comme une communication qui permet à des appareils de se connecter à travers un réseau de communication câblé ou sans fil [4].

Les technologies de communication sans fil IoT/M2M

Le Tableau 1 présente un résumé de certaines technologies sans fil IoT/M2M actuelles.

Tableau 1. Résumé de quelques technologies sans fil actuelles.

Technologie	Modulation	Bande de fréquence	Gamme	Débit de données	Bande passante du canal
Bluetooth	GFSK	2.4 GHz	50 m	2 Mbps	125,250 où 500 kHz
ZigBee	DSSS	868, 914 MHz, et 2.4 GHz	Moins de 1 km	250 Kbps	2 Mhz
RFID	ASK, FSK , PSK/OOK	(LF) —125~134 kHz (HF) —13.56 MHz (UHF) —433~956 MHz (MF)—2.45 GHz	LF/HF —10~20 cm UHF/MF—3 m	4 Mbups	LF, HF,UHF, MF
Wi-Fi	MCS	2.4 GHz, 5 GHz, 6GHz	100 m	40 Gbps (Wi-Fi 7)	20/22 MHz
LoRa	CSS	433,868 et 915 MHz	15 km	50 Kbps	125,250 où 500 kHz
Sigfox	BPSK	433,868 et 915 MHz	20 km +	100 bps	100 Hz
eMTC	QPSK, 16-QAM	Bande de fréquence LTE sous licence	Urbain:~5km Suburbain:~ 17 km	1 Mbps	1.08 MHz
NB-IoT	BPSK, QPSK	Bande de fréquences LTE sous licence	Urbain:1~ 8 km Suburbain:~ 25 km	200 Kbps	200 kHz

L'évolution des réseaux cellulaires mobiles

Au fil des ans et jusqu'à aujourd'hui, seule la 1G a complètement disparu. Les technologies GSM/GPRS/UMTS/HSPA/LTE sont toujours bien vivantes et couvrent un large éventail de secteurs d'activité pour différentes industries en termes de débit de données, de coût, de consommation d'énergie, de vitesse de transmission, de temps de latence, etc. L’évolution des réseaux cellulaires mobiles au fil des décennies est décrite dans la figure ci-dessus.

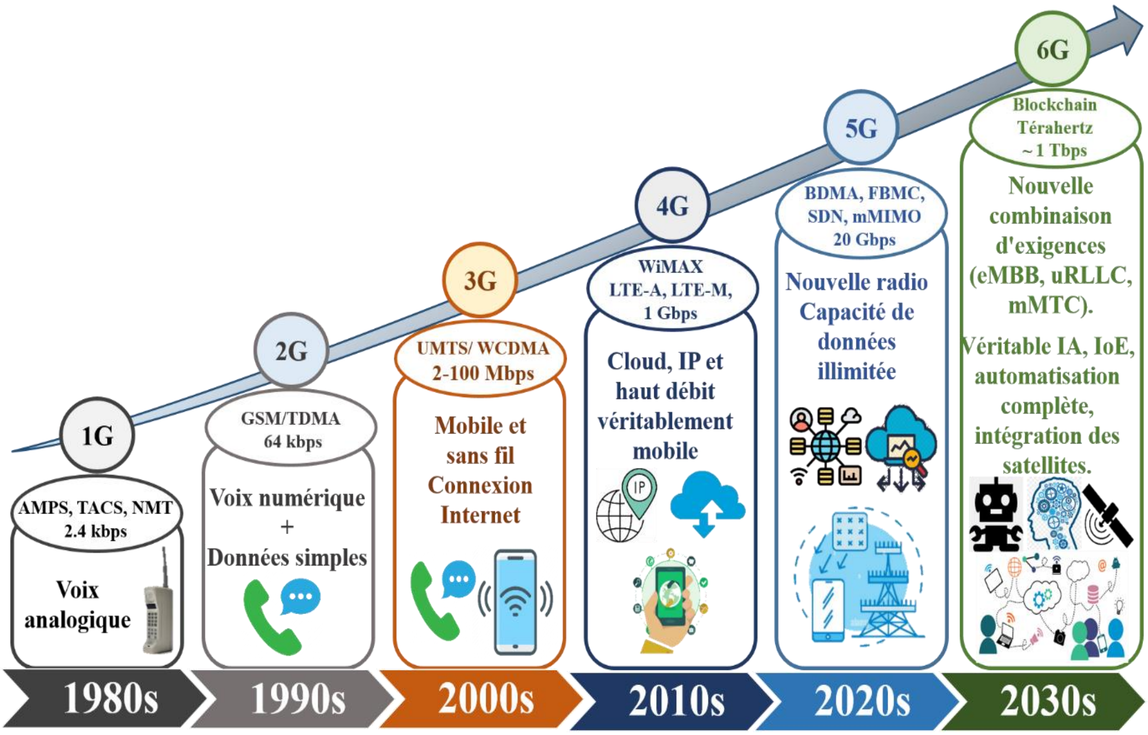

Figure 2. L’Évolution des réseaux cellulaires mobiles existants et prévus jusqu'en 2030.

La technologie de 4G pour les réseaux mobiles

Le réseau mobile 4G, normalisé par le 3GPP en tant qu'évolution à long terme (LTE), offre une vitesse plus élevée et une plus grande capacité pour les appareils cellulaires que ses prédécesseurs. Le LTE est développé pour interconnecter des systèmes de communication hétérogènes, offrant une plus grande bande passante et permettant une couverture accrue de la 4G. L'architecture de haut niveau du réseau 4G LTE se compose de trois éléments principaux : l'équipement de l'utilisateur (UE), le réseau d'accès radio terrestre UMTS évolué (E-UTRAN) et le noyau de paquets évolué (EPC) [5]. La Figure 3 donne un aperçu du réseau LTE et de ses éléments.

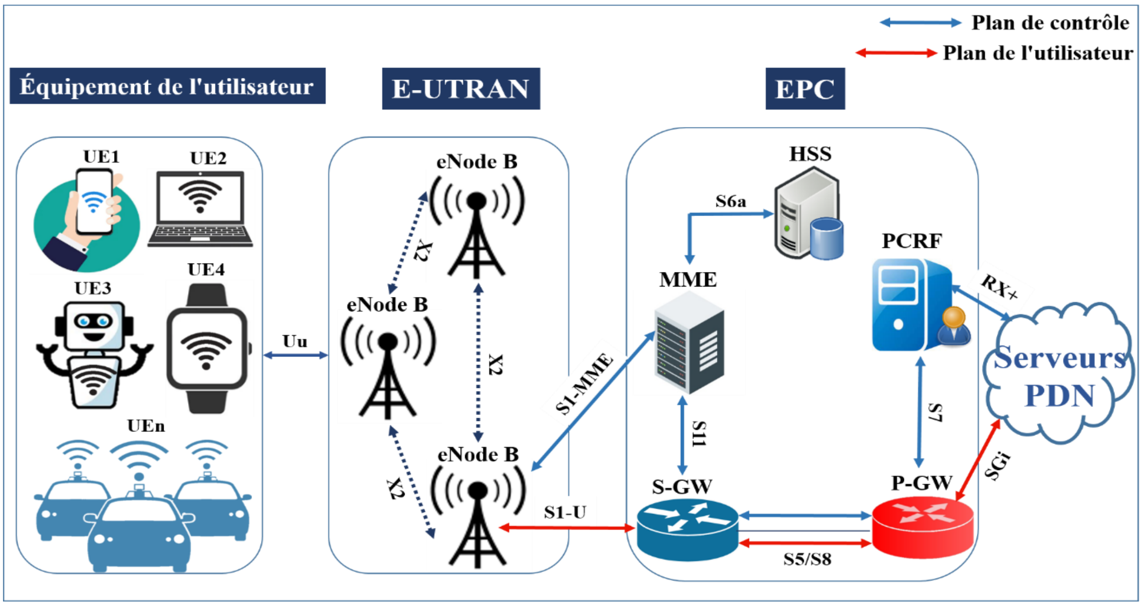

Figure 3. Architecture 4G LTE.

La Nouvelle technologie d'accès radio de 5G

La cinquième génération est censée offrir des performances de vitesse allant jusqu'à 20 Gbps [6]. L'architecture générale du réseau 5G comprend diverses technologies essentielles telles que le D2D, l'accès multiple non orthogonal, les réseaux ultra denses, l'analyse de la composition logicielle, le MIMO, le Massive MIMO et la radio cognitive (voir la Figure 4). Ces technologies viseront à répondre à toutes les exigences de la 5G.

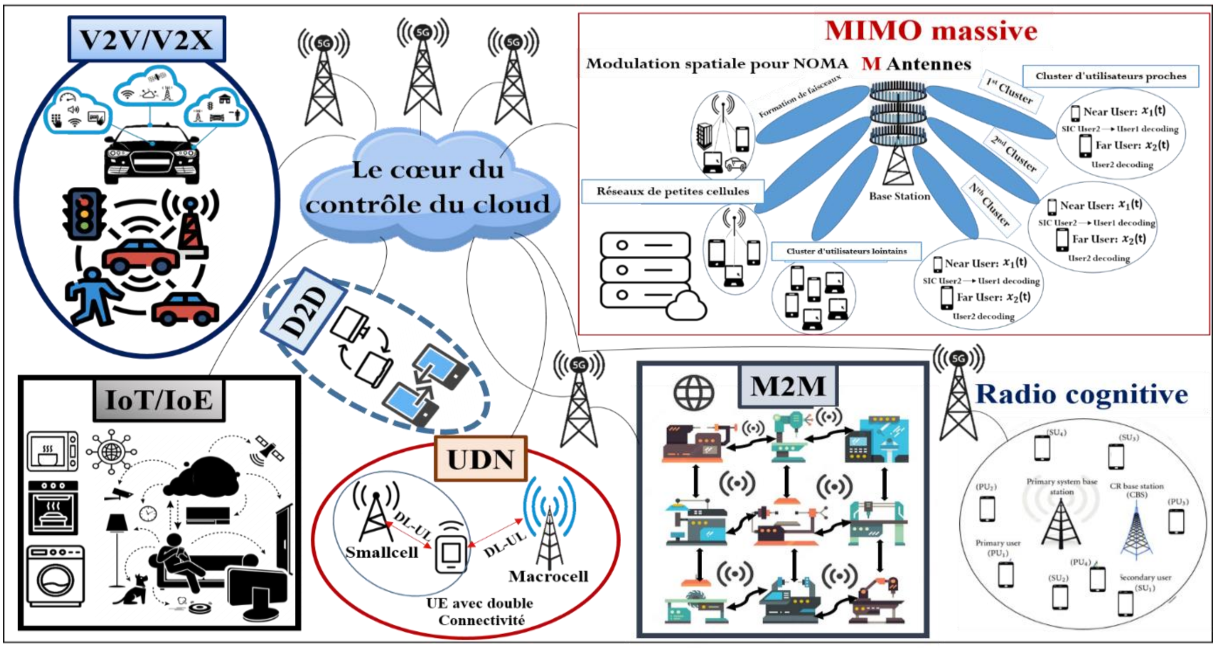

Figure 4. Une architecture générale de réseau cellulaire 5G.

Chapitre 3

Le troisième chapitre de cette thèse vise à fournir une analyse complète du déploiement et de convergence des communications IoT/M2M et des MCNs/WSNs.

Évolution des versions de la 4G LTE

La figure ci-dessous présente l'évolution des versions de la 4G LTE.

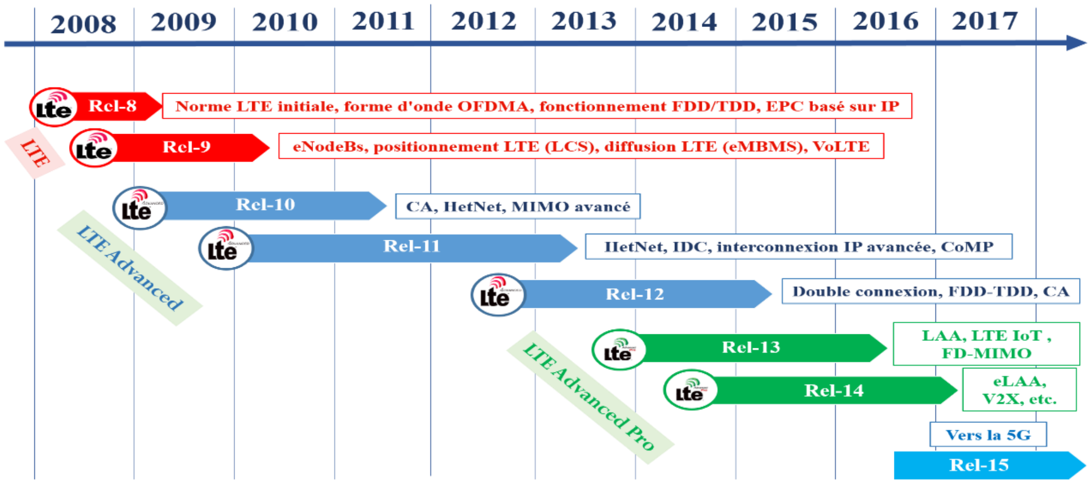

Figure 5. Évolution des versions de la 4G LTE.

Diriger l'évolution du 3GPP vers la 5G

Les versions du 3GPP pour la 5G fournissent différentes spécifications pour la mise en œuvre de la 5G NR. La Figure 6 présente l'évolution des versions de la 5G.

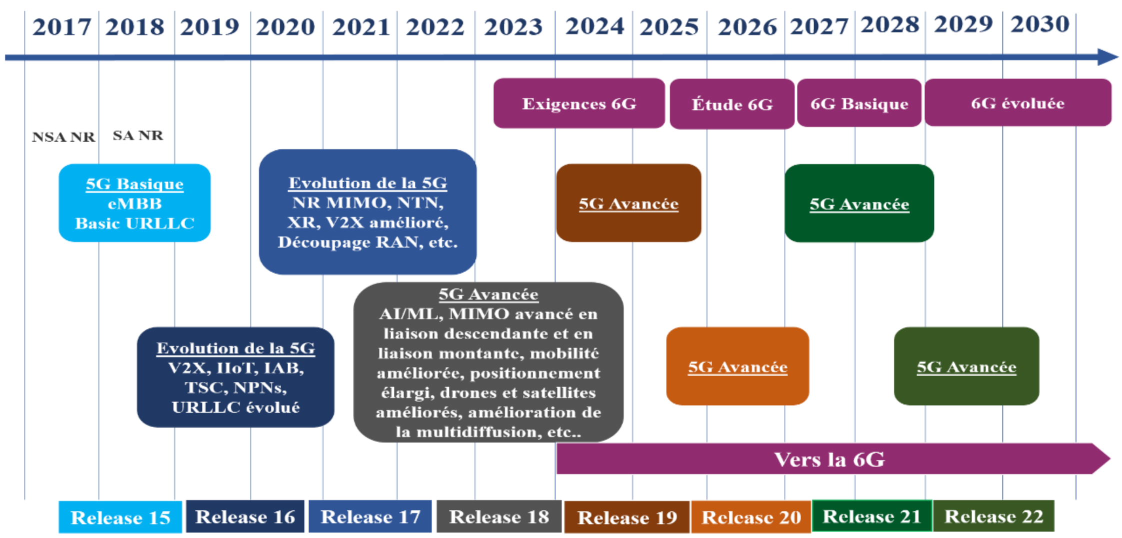

Figure 6. L'évolution des versions de la 5G.

Architecture d'interfonctionnement 4G-5G

L'architecture d'interfonctionnement 4G-5G est un ensemble de normes et de protocoles qui permettent l'interfonctionnement des réseaux cellulaires mobiles 4G et 5G. Elle permet aux deux réseaux de communiquer entre eux, ce qui permet aux utilisateurs de passer d'un réseau à l'autre en toute transparence. La Figure 7 donne une vue d'ensemble de l'interfonctionnement entre les réseaux 4G et 5G, avec les principales fonctions de réseau (NF) interfonctionnant pour fournir des services transparents aux abonnés mobiles. Toutes les NF de gauche (en bleu) font partie d'un cœur de réseau 4G et les NF de droite (en vert) font partie d'un cœur de réseau 5G.

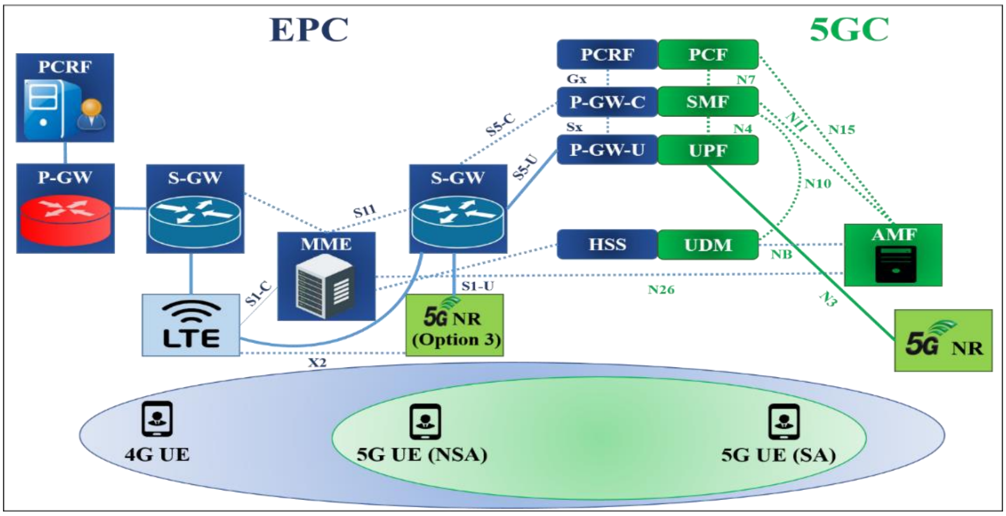

Figure 7. Architecture d'interfonctionnement 4G-5G.

Solutions convergentes pour les réseaux hétérogènes sans fil

La convergence de réseaux hétérogènes améliore les communications IoT/M2M. Les réseaux convergents sont divisés en quatre catégories : la convergence des appareils, des protocoles, des services, et la convergence totale. La convergence mobile totale est un type dans lequel les trois autres types sont intégrés [7] et peut être exprimée par l'équation suivante (2).

$$Full_{Convergence} = Device_{Convergence} + Protocol_{Convergence} + Service_{Convergence} \quad (2)$$

La convergence des MCNs et des WSNs peut être mutuellement bénéfique : Les MCNs offrent un niveau plus élevé de contrôle et d'optimisation des couches afin d'augmenter la durée de vie du réseau et les performances du WSNs, et de fournir une meilleure qualité de service lors de l'utilisation des WSNs ; les WSNs peuvent agir comme des facilitateurs cognitifs et intelligents des MCNs ; les services sans fil et les applications de plus en plus centrées sur les données sont rendus possibles par l'architecture des réseaux de convergence WSNs et MCNs ; les MCNs ont le potentiel de rendre les WSNs plus efficaces sur le plan énergétique et d'améliorer les performances du réseau ; et les terminaux mobiles MCNs agissent à la fois comme des nœuds de capteurs et comme des passerelles vers les WSNs [8]. En outre, les nœuds de capteurs des réseaux convergents WSNs et MCNs collectent des données et les envoient à un serveur de données via MCN [9], où le total des données envoyées (T_{DS}) est la somme du total des données reçues (T_{DR}) et de la perte de paquets (P_L), comme l'explique l'équation (3).

$$T_{DS} = T_{DR} + P_L \quad (3)$$

Convergence de l'architecture des réseaux

Dans l'architecture de réseau classique combinant les MCNs et les WSNs, l'architecture est hiérarchique, comme le montre la partie gauche de la Figure 8. La détection des données a lieu dans le groupe de nœuds de capteurs sans fil, tandis que le contrôle du système implique la passerelle et la station de base. Avec l'approche de convergence actualisée, la fusion des architectures MCN et WSN passe d'une architecture en couches à une architecture plate afin de réduire la signalisation hiérarchique entre les deux réseaux. Comme le montre la partie droite de la Figure 8, l'architecture convergente permet aux nœuds de capteurs de recevoir des signaux en liaison descendante de la station de base du réseau MCN. Dans l'architecture du réseau unifié, il est essentiel d'évaluer l'impact sur le MCN et la complexité accrue pour les nœuds de capteurs, afin de trouver un juste équilibre entre le coût et l'amélioration des performances [10].

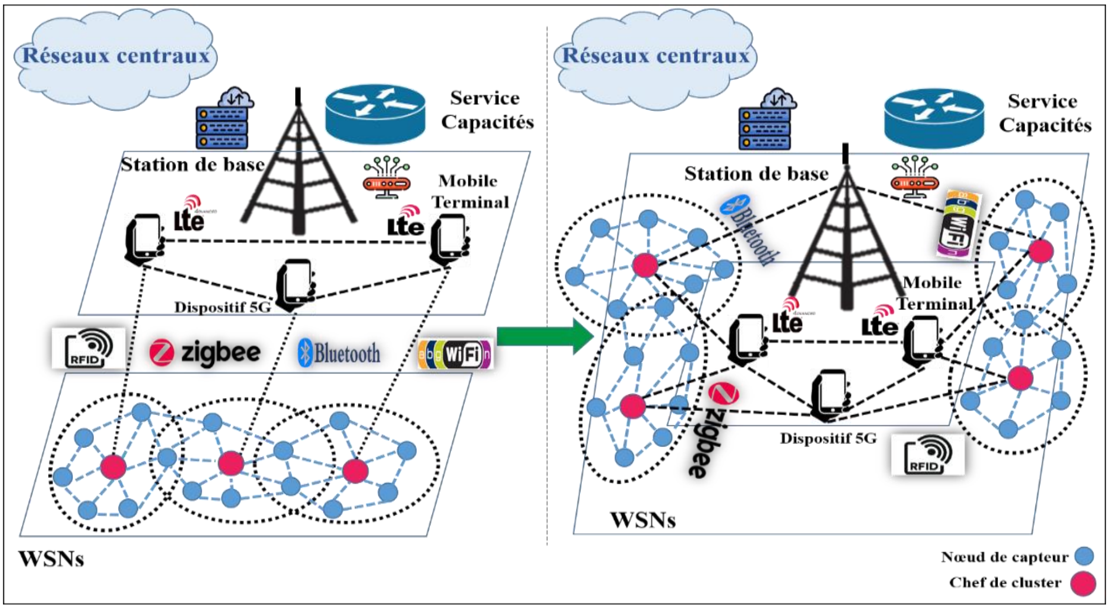

Figure 8. Architecture de réseau convergente pour les WSNs et les MCNs.

Scénario de convergence WSN et 5G MCN

Le MCN 5G transforme ce réseau de capteurs en un réseau de capteurs intelligents pour les communications M2M. Les débits de données élevés et les autres technologies 5G soutiennent les WSNs et permettent l'utilisation d'appareils intelligents dans de nouvelles applications. L'amélioration des réseaux ZigBee peut permettre la convergence des WSN et de la 5G, en améliorant les performances de transmission des données. La convergence permet la transmission de paquets collectés par le WSN via des liaisons 5G. La figure ci-dessous présente l'architecture de convergence WSN-5G.

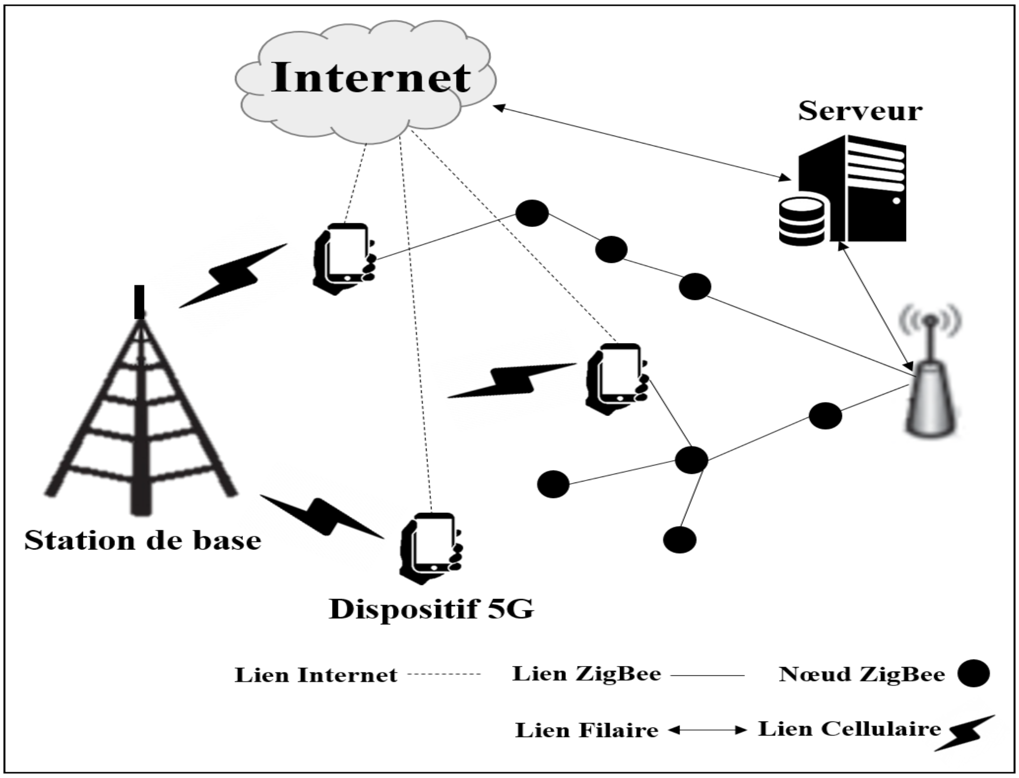

Figure 9. L'architecture de convergence WSN-5G.

Chapitre 4

Le quatrième chapitre de cette thèse traite de la conception, de la mise en œuvre et du déploiement des technologies IoT/M2M dans divers systèmes, y compris les soins de santé, les maisons, les bureaux, les bâtiments et les villes.

Les domaines d'application de l'IoT/M2M

Les applications IoT/M2M les plus connues sont présentées dans la Figure 10.

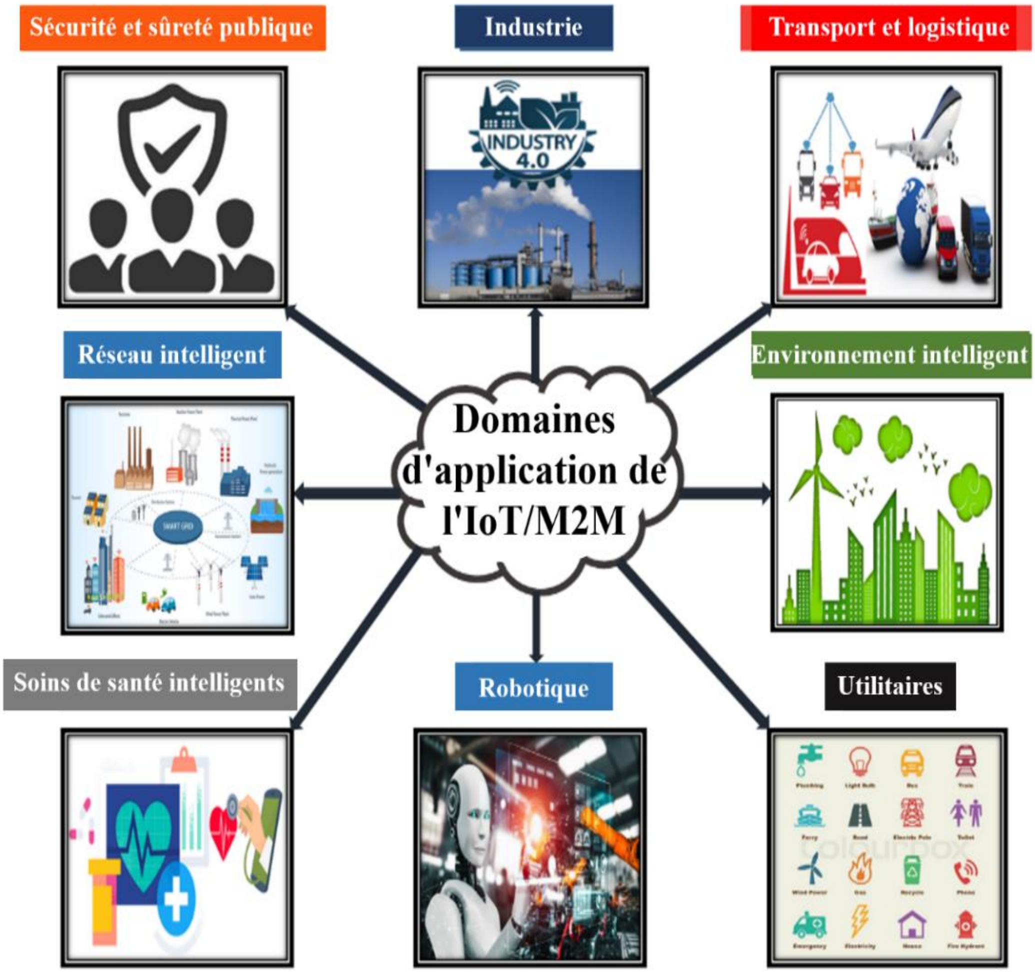

Figure 10. Les domaines d'application IoT/M2M.

Nos principaux papiers publiés dans des conférences et des chapitres de livres sont les suivants :

1. **Application de la communication M2M basée sur ZigBee pour contrôler la domotique intelligente**

Dans ce papier, nous avons présenté un domaine d'utilisation important pour M2M : la domotique basée sur la technologie sans fil ZigBee. Nous avons également décrit le système proposé, qui se compose de deux parties principales : le système de contrôle de l'unité et le système de contrôle à distance. [11].

2. **Une gestion de maison intelligente basée sur les technologies M2M/IoT**

Cet article vise à présenter la mise en œuvre de maisons intelligentes basées sur les technologies M2M/IoT à l'aide de réseaux de capteurs sans fil [12].

3. **Design and Implementation of M2M-Smart Home Based on Arduino-UNO**

Ce chapitre traite de la conception et de la mise en œuvre du M2M dans la maison intelligente afin de donner à chacun la possibilité de contrôler automatiquement sa maison à distance [13].

4. **Implémentation du système de bâtiment intelligent M2M-IoT à l'aide de l'application Blynk**

Dans ce chapitre, nous avons présenté la mise en œuvre des technologies IoT/M2M dans les "bâtiments intelligents", l'une des utilisations les plus populaires. La solution proposée a représenté un système complet pour les bâtiments intelligents basés sur M2M-IoT qui recueille des technologies de communication hétérogènes (Ethernet, Bluetooth et GSM) [14].

5. **Conception, mise en œuvre et déploiement d'applications IoT/M2M pour les villes intelligentes basées sur les réseaux MCNs**

Ce chapitre traite du déploiement et de la mise en œuvre des technologies IoT/M2M dans la ville intelligente, l'une de ses applications les plus populaires. La solution proposée présente un système complet pour les villes intelligentes IoT/M2M basé sur différents réseaux cellulaires mobiles tels que 2G, 4G, ou 5G ; pour fournir la sécurité, la commodité, l'économie d'énergie, et l'amélioration de la qualité de vie urbaine en utilisant des composants efficaces et à faible coût [15].

Chapitre 5

Le cinquième chapitre propose une meilleure approche de l'utilisation des réseaux sans fil hétérogènes composés de WSNs et de MCNs pour les systèmes de bâtiments intelligents IoT/M2M, où nous présentons en détail la conception de l'architecture et les principaux résultats du système proposé, qui fournit des lectures de serveur précises et une très faible latence, grâce auxquelles les utilisateurs peuvent facilement contrôler et surveiller tous les services proposés à distance.

Proposition d'un système de bâtiment intelligent basé sur l'IoT/M2M et utilisant des réseaux hétérogènes

L'infrastructure réseau hétérogène proposée pour le bâtiment intelligent IoT/M2M se compose de WSNs et de MCNs. Les WSNs concernent la communication entre les appareils dans le bâtiment et comprennent les réseaux locaux sans fil (WLAN) tels que le Wi-Fi, et les réseaux locaux sans fil (WPAN) tels que le Bluetooth et la RFID. En revanche, les MCNs sont le réseau de communication entre les appareils dans le bâtiment et les appareils dans le réseau extérieur et comprennent (WWAN qui utilisent des technologies de réseau cellulaire de télécommunication mobile telles que 2G, 3G, 4G et 5G/6G). L'équation suivante décrit l'infrastructure de réseau hétérogène proposée pour le système de bâtiment intelligent IoT/M2M.

$$\boldsymbol{HetNets} = \boldsymbol{WSNs}_{\boldsymbol{WLAN}_{\boldsymbol{Wi-Fi}} + \boldsymbol{WPANs}_{\boldsymbol{Bluetooth,\ RFID}}} + \boldsymbol{MCNs}_{\boldsymbol{WWANs}_{\boldsymbol{GSM,\ LTE}}} \quad (4)$$

La conception de l'architecture proposée pour les systèmes de bâtiments intelligents IoT/M2M basés sur des réseaux hétérogènes utilise divers matériels connus pour collecter et gérer les données selon les fonctions et les services d'une entreprise. La Figure ci-dessous illustre la conception architecturale proposée.

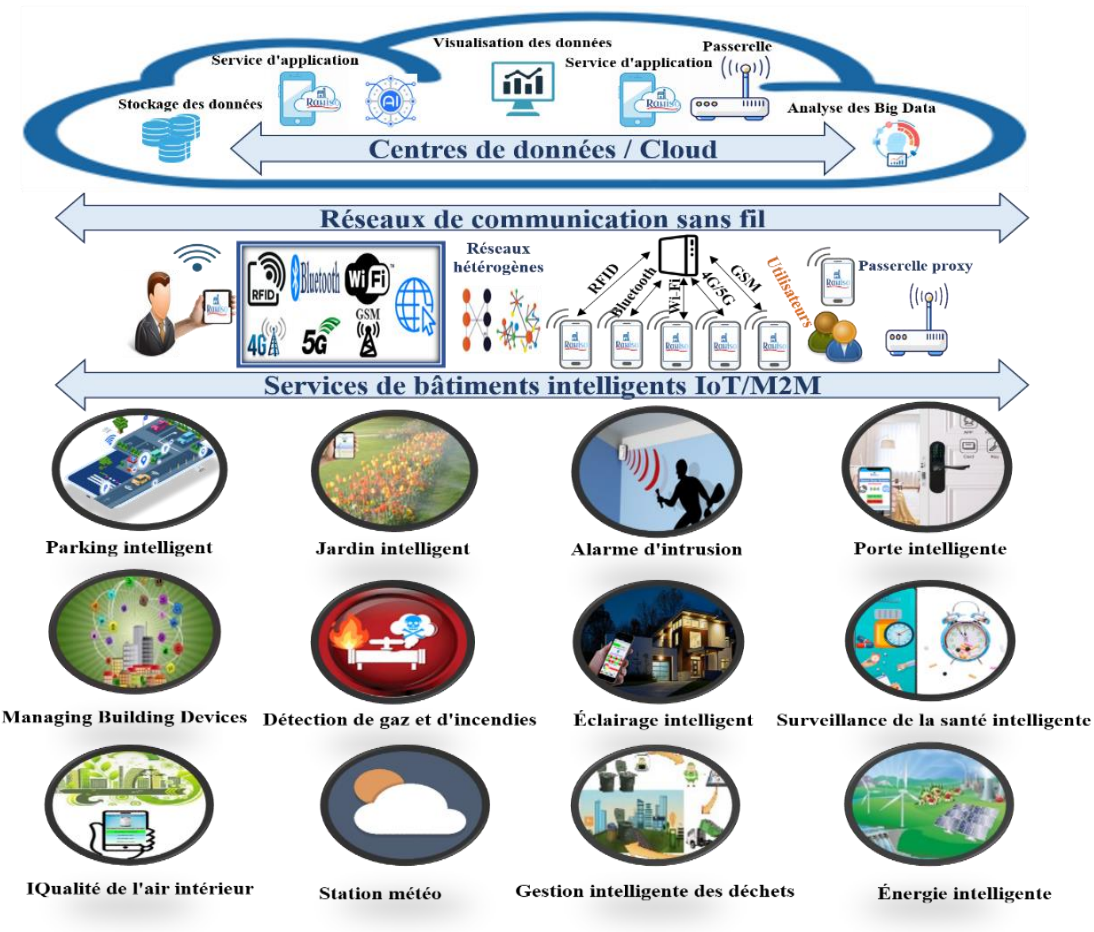

Figure 11. Architecture des bâtiments intelligents IoT/M2M.

Tous les services proposés sont conçus et mis en œuvre pour contrôler et surveiller le bâtiment à distance via l'application Raniso en utilisant la connectivité RFID/Bluetooth/Wi-Fi et les réseaux cellulaires tels que GSM, 4G ou 5G. Cette conception d'infrastructure de bâtiment intelligent IoT/M2M aide les propriétaires, les opérateurs et les gestionnaires d'installations à améliorer la fiabilité et la performance des actifs, et est bénéfique pour prévenir la perte de ressources et de vies dues à des événements indésirables. En outre, le système proposé est économe en énergie et peu coûteux et peut être utilisé dans divers bâtiments tels que les hôpitaux, les hôtels, les universités, les entreprises, etc.

Résultats et discussion

Cette section présente les résultats des tests fonctionnels du prototype du système de bâtiment intelligent IoT/M2M proposé, qui comprend plusieurs services et fonctions innovants, tels que le stationnement intelligent, l'automatisation de l'irrigation du jardin, la détection d'intrusion, la porte intelligente, la gestion des dispositifs du bâtiment, la détection d'incendie et de gaz, l'éclairage intelligent, le rappel intelligent des médicaments, la surveillance de la qualité de l'air intérieur, la station météorologique, la gestion intelligente des déchets et l'énergie intelligente. Dans cette section, l'efficacité du système conçu est confirmée en testant tous ses services et fonctionnalités sur le modèle final de bâtiment intelligent, qui a été créé pour élaborer la performance et la fonctionnalité de l'approche proposée. Notre objectif était de concevoir et de mettre en œuvre un bâtiment intelligent IoT/M2M basé sur la convergence de deux réseaux hétérogènes : les WSNs basés sur la RFID, le Bluetooth, le Wi-Fi et les MCNs tels que le GSM, la 4G ou la 5G. Toutes les données collectées par le système proposé sont stockées dans la base de données en nuage, envoyées au serveur ThingSpeak et visualisées dans quatre canaux. Les canaux reçoivent des données des capteurs du bâtiment toutes les 10 secondes et sont visualisés sous forme de graphiques linéaires sur le site Web de ThingSpeak et l'application Raniso en temps réel (voir Figure 12). En plus de démontrer la capacité de surveiller les données des bâtiments en temps réel depuis n'importe où via Internet, ces graphiques montrent également les bonnes performances et la rapidité de réponse de l'approche proposée. Les résultats que nous avons obtenus sont très satisfaisants, car nous avons atteint l'objectif souhaité, à savoir fournir des relevés précis au serveur. En outre, la latence est très faible, de sorte que les utilisateurs peuvent facilement contrôler et surveiller le bâtiment intelligent à distance, à tout moment et de n'importe où, à l'aide de téléphones mobiles via l'application Raniso. En outre, l'une des réalisations de cette étude est l'utilisation de l'intelligence artificielle pour contrôler les appareils en autorisant les commandes vocales par l'intermédiaire de Google Assistant. Le bâtiment intelligent proposé dans la Figure 13 est personnalisable en fonction des préférences de l'utilisateur. Par exemple, l'utilisateur peut contrôler les lumières à l'aide de boutons-poussoirs, du Bluetooth, du Wi-Fi, des réseaux 4G/5G, de la voix via Google Assistant, ou automatiquement en fonction des informations fournies par le capteur PIR. Il en va de même pour la porte intelligente proposée, où l'utilisateur peut contrôler la porte sans clé à l'aide d'une carte RFID ou d'un mot de passe, ou à distance via l'application Raniso en utilisant la connexion Bluetooth ou l'Internet via les réseaux Wi-Fi, 4G/5G. En outre, afin de vérifier la mesure de performance du taux d'erreur du système proposé, sur la base des données recueillies dans le tableau 2, y compris la température, l'humidité et la qualité de l'air intérieur pendant 15 jours, nous avons pu calculer le taux d'erreur du système proposé, qui était inférieur à 1 %.

Figure 12. Résultats quantitatifs de la détection pour toutes les applications proposées.

Figure 13. Vue de dessus du prototype de bâtiment intelligent IoT/M2M validé.

Le Tableau 2 présente les données collectées, y compris la température observée par le système proposé (T_{ps}), la température observée à partir des données officielles (T_{od}), l'humidité observée par le système proposé (H_{ps}), Données d'humidité observées à partir des données officielles (H_{od}), Données de IAQ observées par le système proposé(IAQ_{ps}), et Données de IAQ observées à partir des données officielles(IAQ_{od}). Les données collectées ont été prises sur 15 jours, ce qui représente le nombre d'observations (N).

Tableau 2. Données collectées sur 15 jours.

Date	T_{ps}	T_{od}	H_{ps}	H_d	IAQ_{ps}	IAQ_{od}
01/11/2022	24°C	25°C	90%	89%	240	239
02/11/2022	27°C	26°C	76%	78%	225	228
03/11/2022	26°C	25°C	84%	83%	279	275
04/11/2022	23°C	24°C	77%	78%	459	470
05/11/2022	17°C	19°C	75%	77%	760	757
06/11/2022	18°C	18°C	77%	76%	500	499
07/11/2022	22°C	23°C	49%	51%	447	450
08/11/2022	23°C	24°C	50%	53%	330	333
09/11/2022	26°C	25°C	54%	55%	109	112

10/11/2022	24°C	24°C	56%	56%	83	85
11/11/2022	24°C	25°C	47%	46%	100	96
12/11/2022	19°C	20°C	61%	59%	69	71
13/11/2022	21°C	20°C	78%	78%	168	163
14/11/2022	20°C	19°C	80%	82%	251	249
15/11/2022	19°C	19°C	99%	98%	270	266

Pour la température, la moyenne de T_{ps} est donnée par l'équation (5), la moyenne de T_{od} est donnée par l'équation (6), et le taux d'erreur de température (e_T) est exprimé par (7).

$$MT_{ps} = \frac{\sum_{i=1}^{N=15} \boldsymbol{T_{ps}}}{\boldsymbol{N}} \quad (5)$$

$$MT_{od} = \frac{\sum_{i=1}^{N=15} \boldsymbol{T_{od}}}{\boldsymbol{N}} \quad (6)$$

$$e_T = \frac{\boldsymbol{MT_{od} - MT_{ps}}}{\boldsymbol{MT_{od}}} * 100 \quad (7)$$

Pour l'humidité, la moyenne de H_{ps} est donnée par l'équation (8), la moyenne de H_{od} est donnée par l'équation (9), et le taux d'erreur d'humidité (e_H) est exprimé par (10).

$$MH_{ps} = \frac{\sum_{i=1}^{N=15} \boldsymbol{H_{ps}}}{\boldsymbol{N}} \quad (8)$$

$$MH_{od} = \frac{\sum_{i=1}^{N=15} H_{od}}{N} \quad (9)$$

$$e_H = \frac{MH_{od} - MH_{ps}}{MH_{od}} * 100 \quad (10)$$

Pour la qualité de l'air intérieur, la moyenne de IAQ_{ps} est donnée par l'équation (11), la moyenne de IAQ_{od} est donnée par l'équation (12) et le pourcentage d'erreur e_{IAQ} est exprimé par (13).

$$MIAQ_{ps} = \frac{\sum_{i=1}^{N=15} IAQ_{ps}}{N} \quad (11)$$

$$MIAQ_{od} = \frac{\sum_{i=1}^{N=15} IAQ_{od}}{N} \quad (12)$$

$$e_{IAQ} = \frac{MIAQ_{od} - MIAQ_{ps}}{MIAQ_{od}} * 100 \quad (13)$$

Sur la base des données recueillies dans le tableau 2 et des équations mathématiques de (5) à (13), nous avons pu calculer le taux d'erreur estimé pour la température à 0,89 %, l'humidité à 0,56 % et la qualité de l'air intérieur à 0,06 %. Ces taux d'erreur sont très faibles, ce qui indique les bonnes performances et l'efficacité du système proposé.

En outre, grâce à l'interface de préférences de Raniso (voir Figure 14), les utilisateurs peuvent entrer leurs préférences telles que la température, l'humidité, le niveau d'éclairage, la couleur de l'éclairage, le type de parfum et le type de musique, et toutes ces préférences entrées sont stockées dans une base de données SQL, comme le montre la Figure 15. Ces résultats nous permettent de dériver plusieurs configurations optimales pour les travaux futurs sur la base du comportement d'interaction de l'utilisateur.

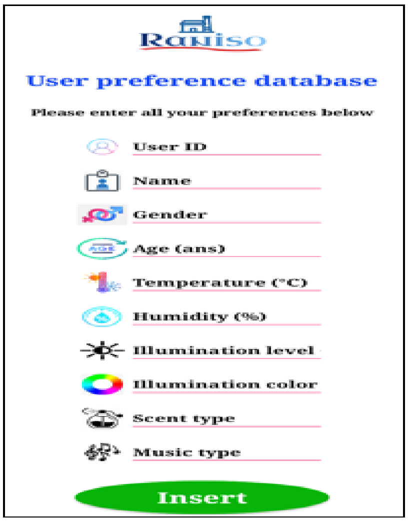

Figure 14. Interface des préférences de l'utilisateur.

User_ID	Name	Gender	Age (ans)	Temperature (°C)	Humidity (%)	Illumination level (Lux)	Illumination_color	Scent_type	Music_type
User 1	Rania	Female	26	25	40	500	Blue	Jasmine	Classical
User 2	Hocine	Male	59	28	50	800	Yellow	Floral	Classical
User 3	Djamila	Female	52	22	30	600	White	Lavender	Soul
User 4	Nadjib	Male	36	27	30	200	White	Jasmine	Soul
User 5	Mounia	Female	34	24	35	350	Red	Lavender	Jazz
User 6	Mohamed	Male	31	23	50	150	White	Lemon	Tango
User 7	Nihad	Female	27	26	45	400	Purple	Floral	Folk
User 8	Assia	Female	27	25	55	200	Green	Lemon	Jazz
User 9	Morad	Male	40	25	30	500	White	Lavender	Classical
User 10	Ammar	Male	75	27	50	700	Green	Jasmine	Classical
User 11	Khoula	Female	27	23	40	250	Red	Jasmine	Folk
User 12	Oussama	Male	30	24	40	300	White	Floral	Salsa
User 13	Abdou	Male	25	22	55	250	Yellow	Lavender	Soul
User 14	Ghania	Female	38	25	40	500	Blue	Lemon	Jazz
User 15	Karima	Female	39	23	30	700	White	Floral	Soul
User 16	Amina	Female	28	22	40	400	Green	Jasmine	Jazz
User 17	Samir	Male	31	27	40	350	Blue	Lavender	Folk
User 18	Youcef	Male	46	24	50	800	White	Jasmine	Tango
User 19	Omar	Male	43	23	35	600	Purple	Floral	Salsa
User 20	Hadjer	Female	22	26	50	600	Blue	Floral	Tango

Figure 15. Base de données des préférences des utilisateurs.

Conclusion générale

Dans cette thèse, nous avons étudié les technologies IoT/M2M et les réseaux mobiles 4G/5G, en analysant différents aspects tels que leur architecture, leurs protocoles et leurs applications. Nous avons également analysé les avantages, les défis et les solutions associés au déploiement et à la convergence de ces réseaux. Nous avons également évalué les méthodes de convergence existantes et présenté des études de cas de mises en œuvre réussies et de réseaux convergents. En outre, nous avons comparé le travail proposé dans cette thèse avec les systèmes existants qui présentent les inconvénients suivants : ils n'intègrent pas les technologies IoT et M2M, reposent sur une ou deux technologies de communication sans fil au maximum, ont une portée de transmission sans fil limitée, une interface peu pratique et un coût excessif. La contribution de cette thèse est résumée comme une conception pour le contrôle adaptatif des dispositifs IoT/M2M dans les systèmes smart-x utilisant deux plateformes IoT bien connues (ThingSpeak et Blynk), ainsi que notre application mobile multiplateforme appelée "Raniso", sur des réseaux sans fil hétérogènes. Cette thèse s'est concentrée sur le développement d'un paradigme smart-x IoT/M2M basé sur la convergence des WSNs et des MCNs. Sur la base des résultats obtenus dans cette thèse, nous prouvons que le mécanisme proposé fournit une nouvelle conception architecturale pour un système flexible et peu coûteux qui peut être utilisé pour divers systèmes IoT/M2M intelligents, y compris les réseaux intelligents, la vente au détail intelligente, les villes intelligentes, etc. À titre d'exemple, la conception architecturale a été fournie plus en détail pour cinq applications intelligentes, à savoir la domotique intelligente, l'environnement intelligent, la ville intelligente, les soins de santé intelligents et le bâtiment intelligent. Toutes ces applications innovantes peuvent être contrôlées et surveillées à distance via ThingSpeak, Blynk et Raniso, un serveur local qui permet de contrôler à distance les systèmes smart-x via différents HetNets, tels que la connectivité RFID/Bluetooth/Wi-Fi et les réseaux cellulaires, tels que GSM, 4G ou 5G. Le système smart-x IoT/M2M proposé a été conçu, mis en œuvre, déployé, testé et a donné les résultats escomptés. En outre, le mécanisme proposé a présenté un système smart-x hybride (local et distant) et peu coûteux basé sur l'IoT/M2M qui permet la connexion efficace, sécurisée et rentable de tous les dispositifs intelligents IoT/M2M. Il permet également la réception de données provenant de systèmes smart-x, le stockage des données dans la base de données en nuage, ainsi que l'affichage et la surveillance à distance de ces données via la page web ThingSpeak et les applications Raniso et Blynk. Ce déploiement et cette convergence des réseaux M2M et des réseaux mobiles 4G/5G améliorent la fonctionnalité et l'accessibilité globales du système.

Perspectives

De nombreux domaines et perspectives intéressants peuvent être étudiés dans le cadre de travaux futurs basés sur cette thèse :

Premièrement, nous pouvons étudier directement de nouvelles perspectives d'intégration des techniques d'apprentissage automatique afin d'améliorer la robustesse et l'avancement de l'approche proposée. Les algorithmes d'apprentissage automatique ont la capacité d'analyser de grandes quantités de données, d'identifier des modèles et de faire des prédictions ou des décisions précises basées sur les modèles appris. En incorporant ces techniques dans l'approche proposée, nous pouvons améliorer ses performances et son adaptabilité.

Deuxièmement, outre les secteurs abordés dans cette thèse, nous pouvons mettre en œuvre l'application du mécanisme proposé par exemple dans l'intégration des systèmes de transport intelligents, qui peuvent atténuer la congestion du trafic, réduire les émissions de carbone et améliorer la mobilité globale. Les véhicules autonomes et les systèmes intelligents de gestion du trafic peuvent révolutionner les déplacements domicile-travail tout en garantissant la sécurité et la durabilité.

Troisièmement, il est essentiel de tenir compte de l'expérience de l'utilisateur lors de l'examen du déploiement et de la convergence de ces réseaux. Il s'agit notamment d'évaluer des facteurs tels que la facilité d'utilisation, l'accessibilité et la satisfaction des utilisateurs. Comprendre comment les utilisateurs interagissent avec les dispositifs M2M/IoT et les nouveaux réseaux mobiles sur lesquels ils s'appuient peut éclairer la conception et la mise en œuvre de solutions centrées sur l'utilisateur.

Quatrièmement, une autre perspective à prendre en compte est celle des cadres réglementaires entourant les réseaux M2M et les réseaux mobiles 4G/5G. Au fur et à mesure que ces technologies progressent, il peut s'avérer nécessaire de mettre à jour les politiques et les réglementations pour traiter des questions telles que l'attribution du spectre, les normes d'interopérabilité, la gouvernance des données et la protection de la vie privée. L'examen du paysage réglementaire peut fournir des indications sur les considérations juridiques et politiques associées à leur déploiement et à leur convergence.

Cinquièmement, la convergence des réseaux M2M avec les réseaux mobiles 4G/5G suscite des inquiétudes quant à la protection de la vie privée et à la sécurité. Avec un nombre croissant d'appareils connectés, il est nécessaire de garantir l'intégrité et la confidentialité des données, ainsi que la protection contre les cyber menaces. L'exploration des défis et des solutions potentielles pour sécuriser ces réseaux en abordant des considérations éthiques telles que la confidentialité des données, la partialité algorithmique et la cyber sécurité dans le déploiement et la convergence de ces réseaux peut être une perspective importante pour la thèse.

Enfin, une autre perspective à considérer est l'impact économique du déploiement et de la convergence des réseaux M2M avec les réseaux mobiles 4G/5G. Il s'agit notamment d'examiner le potentiel de nouveaux modèles commerciaux, de nouvelles sources de revenus et d'économies de coûts. Par exemple, les réseaux M2M peuvent permettre une maintenance prédictive dans les industries, réduisant les temps d'arrêt et optimisant l'allocation des ressources. Comprendre les implications économiques peut aider les organisations à prendre des décisions éclairées sur les investissements dans ces technologies.

Nous espérons que cette thèse inspirera d'autres recherches dans ce domaine et contribuera au développement de solutions innovantes qui tireront parti de la puissance de ces technologies dans nos pays.

List of Publications

This dissertation is submitted for the degree of Doctor at the University Mohamed El Bachir El Ibrahimi of Bordj Bou Arreridj, Algeria. The research described herein was conducted under the supervision of Pr. Salih AIDEL in the Advanced Electronics and Telecommunications Laboratory (ETA), Department of Electronics, Faculty of Science and Technology.

Part of this work, closely related to the research theme, has been presented in the following publications:

International journals

1. **R. Djehaiche**, S. Aidel, A. Sawalmeh, N. Saeed and A. H. Alenezi, "Adaptive Control of IoT/M2M Devices in Smart Buildings using Heterogeneous Wireless Networks," in IEEE Sensors Journal, doi: 10.1109/JSEN.2023.3247007

Chapters Books

1. **Djehaiche, R**., Aidel, S., Belazzoug, M., Saeed, N. (2023). Design, Implementation, and Deployment of IoT/M2M Smart City Applications Based on MCNs. In: Hatti, M. (eds) Advanced Computational Techniques for Renewable Energy Systems. IC-AIRES 2022. Lecture Notes in Networks and Systems, vol 591. Springer, Cham. https://doi.org/10.1007/978-3-031-21216-1_5
2. **Djehaiche R**., Aidel S., Saeed N. (2022) Implementation of M2M-IoT Smart Building System Using Blynk App. In: Hatti M. (eds) Artificial Intelligence and Heuristics for Smart Energy Efficiency in Smart Cities. IC-AIRES 2021. Lecture Notes in Networks and Systems, vol 361. Springer, Cham. https://doi.org/10.1007/978-3-030-92038-8_44
3. **Djehaiche R**., Aidel S., Benziouche N. (2021) Design and Implementation of M2M-Smart Home Based on Arduino-UNO. In: Hatti M. (eds) Artificial Intelligence and Renewables Towards an Energy Transition. ICAIRES 2020. Lecture Notes in Networks and Systems, vol 174. Springer, Cham. https://doi.org/10.1007/978-3-030-63846-7_66

International conferences

1. **R. Djehaiche**, S. Aidel, and K. Benhamimid, “A Smart Home Management based on M2M / IoT Technologies” 2022, pp. 1–10. DOI : https://doi.org/10.6084/m9.figshare.19103315.v1

National conferences

1. **R. Djehaiche** and S. Aidel, “Application of M2M Communication based on ZigBee to Control Smart home automation,” 2021, pp. 114–119. https://doi.org/10.6084/m9.figshare.14748486.v1

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RANIA DJEHAICHE,
12/10/2023,
Bordj Bou Arreridj, Algeria.

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Chapter 5. Adaptive Control of IoT/M2M Devices in Smart Buildings using Heterogeneous Wireless Networks

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List of Acronyms

1G : *1^{st} Generation*
2G : *2^{nd} Generation*
3G : *3^{rd} Generation*
3GPP : *3^{rd} Generation Partnership Project*
4G : *4^{th} Generation*
4GC : *4G Core*
5G : *5^{th} Generation*
5GC : *5G Core*
6G : *6^{th} Generation*
6LoWPAN : *IPv6 over Low-Power Wireless Personal Area Networks*
ADN : *Application Dedicated Node*
AE : *Application Entity*
AI : *Artificial Intelligence*
AMF : *Access Management Function*
AMPS : *Advanced Mobile Phone System*
AP : *Access Point*
APN : *Access Point Names, : Access Point Name*
ARP : *Allocation and Retention Priority*
ASN : *Application Service Node*
B5G : *Beyond 5G*
BAN : *Building Area Network*
BS : *Base Station*
BBU : *Base Band Units*
BDMA : *Beam Division Multiple Access*
BLE : *Bluetooth Low Energy*
BWP : *Bandwidth Part*
CA : *Carrier Aggregation*
CDMA : *Code Division Multiple Access*
CI : *Cloud Infrastructure*
CN : *Core Network*
CoMP : *Ccoordinated Multiple transmission/reception*
CR : *Cognitive Radio*
CSE : *Common Service Entity*
CSF : *Common Service Functions*
CSMA/CA : *Carrier Sense Multiple Access with Collision Avoidance*
CSS : *Chirp Spread Spectrum*
D2D : *Device-to-Device*
DBPSK : *Differential Binary Phase Shift Keying*
DC : *Dual Connectivity*
DLL : *Data Link Layers*
DSSS : *Direct Sequence Spread Spectrum*
E2E : *End-to-End*
EB : *Exabytes*
EDGE : *Enhanced Data for GSM Evolution*
eDRX : *extended Discontinuous Reception*
EHT : *Extremely High Throughput*
EM : *Electromagnetic*
eMBB : *enhanced Mobile Broadband*
eMBMS : *evolved Multimedia Broadcast/Multicast Services*
eMTC : *enhanced Machine-Type Communication*
EN-DC : *E-UTRAN Dual Connectivity*
eNodeB : *evolved Node B*
EPC : *Evolved Packet Core*
ETSI : *European Telecommunications Standards Institute*
E-UTRAN : *UMTS Terrestrial Radio Access Network*
FAN : *Field Area Network*
FBMC : *Filter Bank Multi Carrier*
FDD : *Frequency Division Duplex*
FD-MIMO : *Full-Dimension MIMO*
FHSS : *Frequency Hopping Spread Spectrum*
GBR : *Guaranteed Bit Rate*
GFSK : *Gaussian Frequency Shift Keying*
GPRS : *General Packet Radio Service*
GSM : *Global System for Mobile*
GUI : *Graphical User Interface*
H2H : *Human-to-Human*
HeNBs : *Home eNodeBs*
HetNets : *Heterogeneous Networks*
HF : *High Frequency*
HS : *High Speed*
HSDPA : *High-Speed Downlink Packet Access*
HSS : *Home Subscriber Server*
IAB : *Integrated Access & Backhaul*
IAQ : *Indoor Air Quality*
ICN : *Information Centric Networking*
ICT : *Information and Communications Technology*

IDC : *In-Device Coexistence*
IDE : *Integrated development environmente*
IIoT : *Industrial Internet of Things*
IIT : *Istituto Italiano di Tecnologia*
IoMT : *Internet of Medical Things*
IoT : *Internet of Things*
ISM : *Industrial, Scientific, and Medical*
ITU : *International Telecommunication Union*
KPI : *Key Performance Indicator*
LAA : *Licensed-Assisted Aggregation*
LAN : *Local Area Network*
LCD : *Liquid Crystal Display*
LCSs : *Location Services*
LDPC : *Low Density Parity Check*
LDR : *Light Dependent Resistor*
LE : *Low Energy*
LED : *Light Emitting Diode*
LF : *Low Frequency*
LPWAN : *Low Power Wide Area Networks*
LR-LPWAN : *Low-Rate Wireless Personal Area Networks*
LTE : *Long Term Evolution*
LTE-A : *Long Term Evolution-Advanced*
LTE-M : *Long Term Evolution for Machine*
M2M : *Machine-to-Machine*
MANO : *Management and Orchestration*
MBB : *Mobile Broadband*
MBR : *Maximum Bit Rate*
MCNs : *Mobile Cellular Networks*
MCSs : *Modulation and Coding Schemes*
ME : *Mobile Equipment*
MEC : *Mobile Edge Computing*
MF : *Microwave frequency*
MIMO : *Multiple Input Multiple Output*
mIoT : *massive IoT*
ML : *Machine Learning*
MME : *Mobility Management Entity*
mMIMO : *massive MIMO*
mMTC : *massive Machine Type Communication*
mmWave : *millimeter Wave*
MN : *Middle Node*
MR-DC : *Multi-Radio Dual Connectivity*
MT : *Mobile Termination*
MTC : *Machine-Type-Communication*
NAN : *Neighborhood Area Network*
NB-IoT : *Narrowband-Internet of Things*
NC-OFDM : *Non-Continuous OFDM*
NE-DC : *NR-E-UTRAN Dual Connectivity*
NFC : *Near Field Communication*
NFs : *Network Functions*
NFV : *Network Function Virtualization*
NG : *Next Generation*
NGC : *Next Generation Core*
NGEN-DC : *NG-RAN E-UTRAN-NR Dual Connectivity*
NI : *Network Infrastructure*
NMT : *Nordic Mobile Telephone*
NOMA : *Non Orthogonal Multiple Access*
NPNs : *Non-Public Networks*
NSA : *Non-Standalone*
NSE : *Network Service Entity*
NTN : *Non-Terrestrial Networking*
OFDM : *Orthogonal Frequency Division Multiplexing*
OFDMA : *Orthogonal Frequency Division Multiple Access*
PACS : *Picture Archiving and Communication Systems*
PCEF : *Policy Control Enforcement Function*
PCF : *Policy Control Function*
PCRF : *Policy Control and Charging Rules Function*
PDN : *Packet Data Network*
PDU : *Packet Data Unit*
PPM : *Parts Per Million*
PRBs : *Physical Resource Blocks*
PSAP : *Public Safety Answering Points, : Public Safety Answering Points*
PSM : *Power Saving Management*
QCI : *QoS Class Identifier*
QoE : *Quality of Experience*
QoS : *Quality of Service*
RAN : *Radio Access Network*
RATs : *Radio Access Technologies*
RES : *Renewable Energy Sources*
RF : *Radio Frequency*
RFID : *Radio Frequency Identification*
RRC : *Radio Resource Control*
RTC : *Real Time Clock*
RTLS : *Real Time Locating Systems*
SA : *Standalone*
SBI : *Service-Based Interfaces*
SCA : *Software Composition Analysis*

SCADA : *Supervisory Control and Data Acquisition*
SCS : *Sub-Carrier Spacing*
SDAP : *Service Data Adaptation Protocol*
SDN : *Software Defined Networking*
SDOs : *Standards Development Organizations*
S-GW : *Serving Gateway*
SIG : *Special Interest Group*
SIM : *Subscriber Identity Module*
SMF : *Session Management Function*
SMR : *Smart Medicine Reminder*
SMS : *Short Message Services*
SN : *Secondary Node*
SoC : *System on Chip*
SPHCC : *Shanghai Public Health Clinical Center*
SPP : *Serial Port Protocol*
TACS : *Total Access Communication System*
TBCC : *Tail Bitting Convolution Codes*
TCP / IP : *Transmission Control Protocol / Internet Protocol*
TDD : *Time Division Duplex*
TDMA : *Time Division Multiplexed Access*
TE : *Terminal Equipment*
TSC : *Time Specific Communication*
UAVs : *Unmanned Aerial Vehicles*
UDM : *Universal Data Management*
UDN : *Ultra Dense Networks*
UE : *User Equipment*
uHDD : *ultra-High Data Density*
UHF : *Ultra-High Frequency*
uHSLLC : *ultra-High Speed Low Latency Communications*
UICC : *Universal Integrated Circuit Card*
UMTS : *Universal Mobile Telecommunications System*
uMUB : *ubiquitous Mobile Ultrabroadband*
UPF : *User Plane Functions*
URLLC : *Ultra Reliable Low Latency Communication*
USIM : *Universal Subscriber Identity Module*
V2X : *Vehicle to Everything*
ViLTE : *Video over LTE*
VNF : *Virtualized Network Function*
VoLTE : *Voice over LTE*
WAN : *Wide Area Network*
WANs : *Wide Area Networks*
WCDMA : *Wideband Code Division Multiple Access*
Wi-Fi : *Wireless Fidelity*
WiMAX : *Worldwide Interoperability for Microwave Access*
WLANs : *Wireless Local Area Networks*
WPANs : *Wireless Personal Area Networks*
WSNs : *Wireless Sensor Networks*
XR : *Extended Reality*

List of Symbols

e_H *: Humidity error rate*
e_{IAQ} *: Temperature error rate*
e_T *: Temperature error rate*
H_{OD} *: Humidity Data observed from Official Data*
H_{PS} : *Humidity observed by the proposed system*
IAQ_{OD} *: IAQ observed from Official Data*
IAQ_{PS} *: IAQ Data observed by the proposed system*
MH_{od} : Mean of *Humidity Data observed from Official Data*
MH_{ps} *: Mean of Humidity observed by the proposed system*
$MIAQ_{od}$: *Mean of IAQ observed from Official Data*
$MIAQ_{ps}$: *Mean of IAQ Data observed by the proposed system*
MT_{od} : *Mean of Temperature observed from Official Data*
MT_{ps} *: Mean of Temperature observed by the proposed system*
N *: Number of observations*
P_L : *Packet loss*
T_{DR} *: Total data received*
T_{DS} *: Total data sent*
T_{OD} : *Temperature observed from Official Data*
T_{PS} *: Temperature observed by the proposed system*

General Introduction

The deployment of Internet of Things (IoT) technology and Machine-to-Machine (M2M) communications involves the implementation of a network infrastructure that connects various devices and machines, allowing them to communicate and exchange data. This often includes the use of wireless sensor networks (WSNs) such as wireless fidelity (Wi-Fi), Bluetooth, ZigBee, radio frequency identification (RFID), and mobile cellular networks (MCNs) like global system for mobile (GSM), 4^{th} Generation (4G) and 5^{th} Generation (5G) networks [1]. 4G and 5G mobile networks are the latest generations of cellular networks that provide faster data speeds and improved connectivity for mobile devices. These networks are also used to support IoT and M2M communications by providing a reliable and low-latency connection for connected devices. The convergence of IoT/M2M networks and 4G/5G mobile networks allows for the efficient and effective communication and exchange of data between various devices and machines. However, it also requires a significant investment in network infrastructure and technology to support the increased number of connected devices and the increased demand for data. In addition to the deployment of network infrastructure, the convergence of IoT/M2M networks and 4G/5G mobile networks also involves the integration of various wireless technologies and protocols to enable seamless communication between devices and machines. Among these different wireless communication technologies, ambient backscatter has been emerging for large-scale IoT/M2M applications that can allow the transmission of data without requiring power from the IoT device and facilitates device-to-device (D2D) and even multihop communications. By reflecting far-field Electromagnetic (EM) waves from ambient Radio Frequency (RF) transmitters, a tiny passive gadget can send data with very low power consumption. This cutting-edge technology can effectively solve the battery problem faced by massive low-power devices in large-scale IoT/M2M communications [16]–[19]. The heterogeneous networks (HetNets) operating on different wireless communication technologies, especially WSNs and MCNs, offer numerous applications in many industrial sectors, such as home automation, industry, healthcare, agriculture, and smart cities [20].

However, the deployment and convergence of IoT/M2M networks and 4G/5G mobile networks also bring challenges such as cost, privacy, security, and scalability. Another important aspect of the convergence of IoT/M2M networks and 4G/5G mobile networks is the use of network slicing. Network slicing allows for the creation of multiple virtual networks on top of a shared physical infrastructure. This enables the creation of different networks for different use cases, such as low-latency networks for industrial automation and high-bandwidth networks for video streaming. Additionally, the integration of 4G and 5G with IoT/M2M networks enables the use of cellular technologies like Narrowband-Internet of Things (NB-IoT) and Long Term Evolution for Machine (LTE-M) for Low Power Wide Area Networks (LPWAN). These technologies are designed for IoT devices with low data rates and long battery life, making them well suited for use cases such as smart cities, agriculture, and logistics. Another important aspect is the use of Software Defined Networking (SDN) and Network Function Virtualization (NFV) to manage, control and monitor these converged networks [21]. It allows network operators to program, configure and optimize their networks dynamically and efficiently. Furthermore, the integration of Artificial Intelligence (AI) and Machine Learning (ML) techniques into IoT/M2M networks and 4G/5G mobile networks can enable new capabilities such as self-optimizing networks, predictive maintenance, and intelligent resource allocation.

The objective of our thesis "**Deployment and Convergence of M2M Networks and 4G/5G Mobile Networks**" is to study the deployment and convergence of IoT/M2M networks and 4G/5G mobile networks. Specifically, we aim to explore the challenges and solutions related to the deployment of these networks, as well as the benefits and challenges of their convergence. Additionally, we plan to evaluate existing approaches to convergence and provide case studies of successful deployments and converged networks in practice. Ultimately, our thesis aims to contribute to the understanding of how these networks can be deployed and converged effectively to support various applications in different domains.

Comparing the proposed work in this thesis with existing research works, the drawbacks of smart-x systems include the lack of using IoT and M2M technologies together, reliance on one or two wireless communication technologies at most, a limited wireless transmission range, mostly inconveniently designed user interface, and excessive costs. Therefore, the proposed approach presents a hybrid (local and remote) and a low-cost IoT/M2M-based smart-x system with a user-pleasant smartphone interfaces. Besides, we propose in this thesis five major innovative applications, including smart home automation, smart environment, smart city, smart healthcare, and smart building. All these smart applications can be controlled and monitored remotely by two well-known IoT platforms (ThingSpeak and Blynk), along with our versatile free IoT/M2M platform named Raniso which is used as a local server to control the building via different HetNets, such as RFID /Bluetooth/ Wi-Fi connectivity and cellular networks, such as GSM, 4G, or 5G. Furthermore, with the proposed mechanism, all IoT/M2M smart devices can be connected in a way that is energy-efficient, secure, convenient, and cost-effective, as well as receiving data from the proposed smart-x systems, storing data in the cloud database, displaying it on the ThingSpeak webpage and remotely monitoring it via Raniso and Blynk apps.

CHAPTER 1

THESIS PRESENTATION

Contents of Chapter 1

1.1 Introduction

This chapter explains the motivations behind the research activities focused on the deployment and convergence of IoT/M2M networks and 4G/5G mobile networks. It also aims to provide a comprehensive background on the significance of this topic in ensuring the success of future IoT/M2M applications.

1.2 Context and Research Scope

The context of this thesis is the increasing prevalence of IoT/M2M communications and the need to integrate them with 4G/5G mobile networks. M2M networks are used to connect devices that do not require human intervention, such as sensors, meters, and other IoT devices. These devices generate large amounts of data that need to be transmitted reliably and securely to other devices or cloud-based services for processing and analysis. 4G/5G mobile networks, on the other hand, are designed for human communication and provide high-speed data transmission for voice, video, and data services.

Global M2M subscriptions to global population until year 2030 as depicted in Figure 1.1. The fastest development period of M2M industry and terminals was in the year 2020, and this industry will become saturated no earlier than 2030 [22].

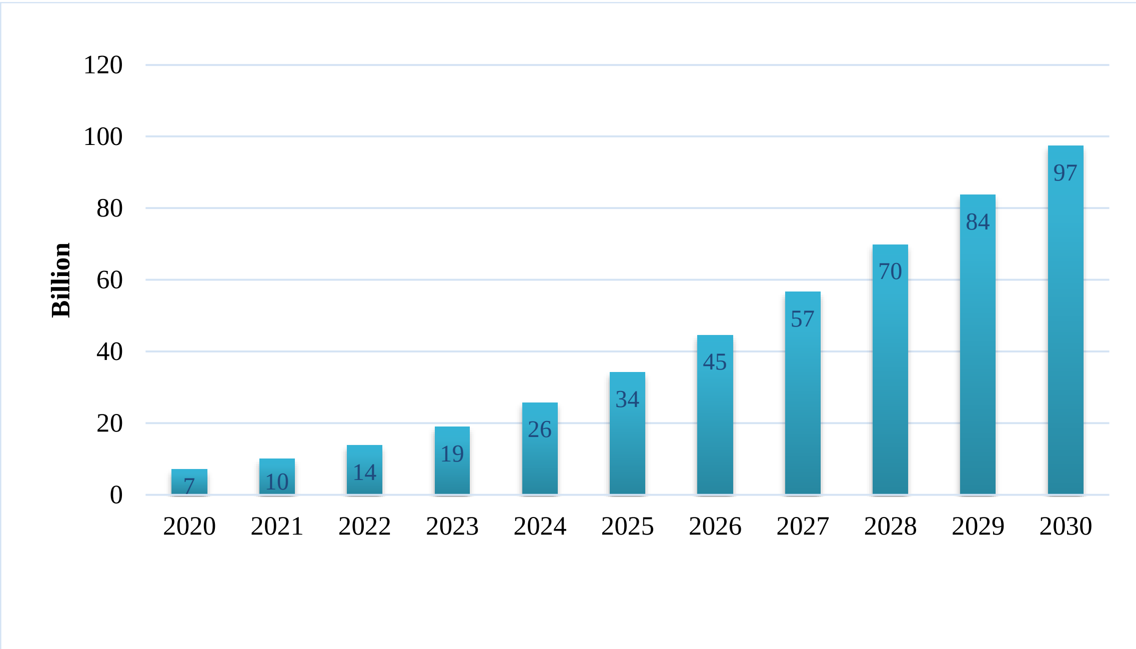

Figure 1.1 Global estimates of M2M subscriptions between 2020 and 2030.

Figure 1.2 below illustrates the growth of mobile traffic, including M2M traffic, at an annual rate of approximately 55% from 2020 to 2030. It is estimated that the global monthly mobile traffic will reach 607 Exabytes (EB) in 2025 and 5,016 EB in 2030 [22].

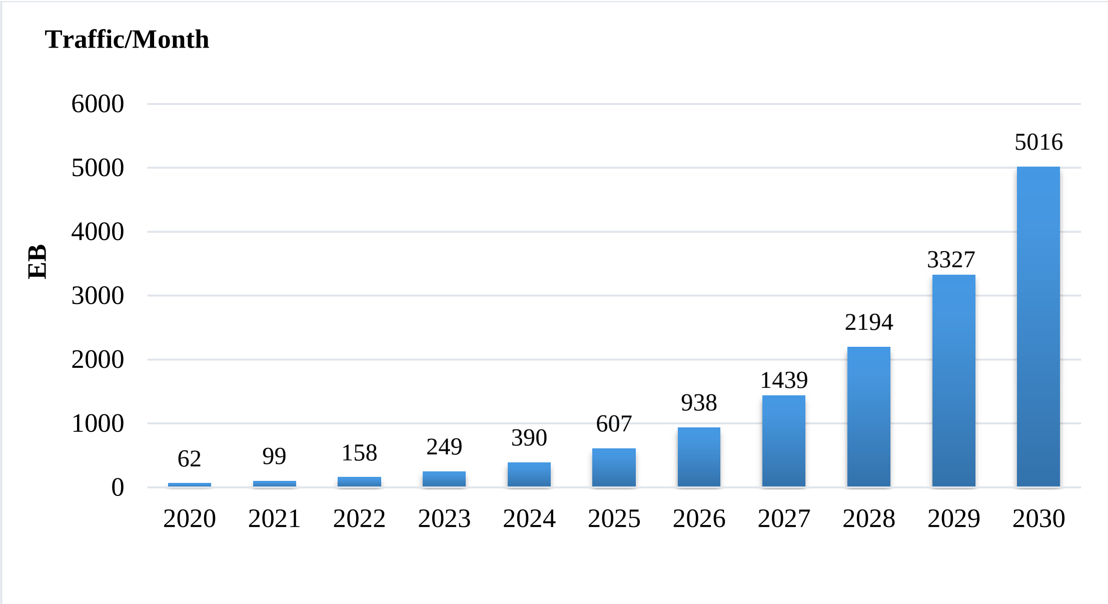

Figure 1.2 Global mobile traffic estimates in 2020-2030 (M2M traffic included).

Mobile traffic by service type was estimated using power function fitting, a form of curve fitting, to calculate year-on-year growth. The estimates were then normalized based on the global mobile traffic estimation shown in Figure 1.3. It was assumed that the proportion of each service type obtained from the respective curve-fitting results remained unchanged [22].

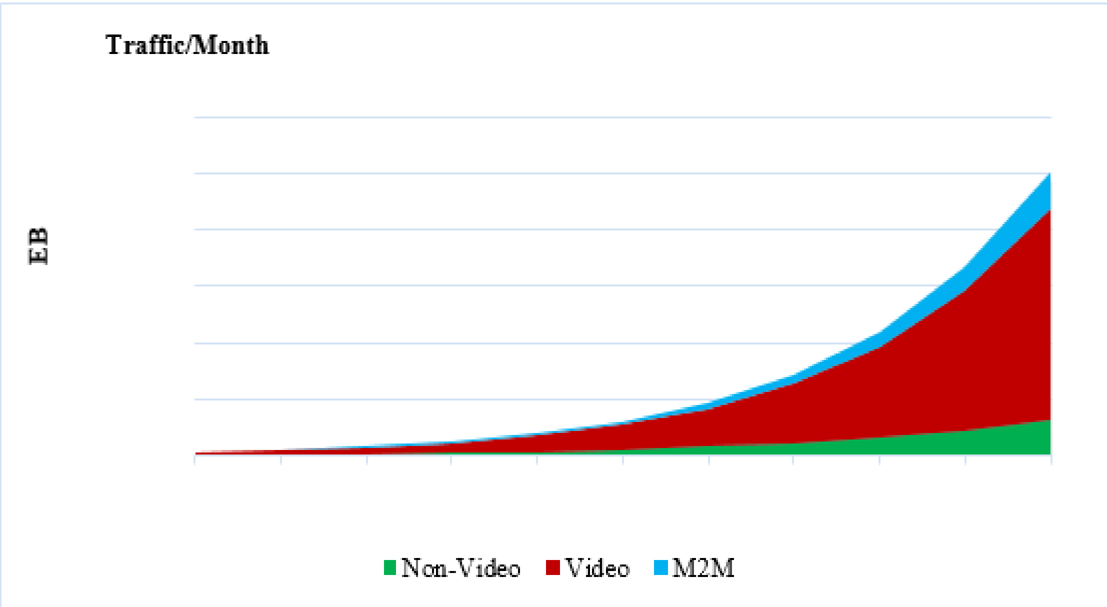

Figure 1.3 Global mobile traffic estimation by service type.

The research scope of this dissertation is to investigate the deployment and convergence of M2M networks and 4G/5G mobile networks. This includes exploring ways to manage interference between these networks, ensuring security in M2M networks, investigating network architecture for seamless communication between devices, and ensuring scalability as the number of connected devices continues to grow.

Overall, the thesis aims to provide solutions to the challenges associated with the deployment and convergence of M2M networks and 4G/5G mobile networks. By addressing these challenges, it is hoped that reliable and efficient communication between devices can be achieved, leading to improved performance and increased adoption of IoT technologies.

1.3 Research challenges

Since the dawn of mobile networks, especially 4G and 5G networks, the majority of operators' services are focused on new application horizons such as Internet of Things technology and Machine to Machine communication. Deploying and converging IoT/M2M communications and 4G/5G mobile networks in the same network means facing new challenges. These new challenges influence the academic world with new research topics that need to find appropriate solutions. In our thesis, we are motivated to investigate and provide solutions to the following challenges:

1.3.1 Supporting a massive number of devices

One of the major challenges of IoT/M2M smart applications based on 4G/5G mobile networks is the ability to accommodate a large number of devices. As more devices get connected, it becomes increasingly challenging to manage and maintain them all. To satisfy the demands of IoT/M2M services, cellular radio networks need to be able to support multiple devices per cell. However, current cellular networks are intended for Human-to-Human (H2H) Mobile Broadband (MBB) services, which only allow for a limited number of concurrent access opportunities. To accommodate a greater range of services, it is important to enhance the abilities of the evolved Node B (eNodeB) to handle IoT devices' traffic and concurrent connections. Recent studies have focused on enhancing wireless systems and architectures to support connected devices along with existing H2H traffic within networks like Long Term Evolution-Advanced (LTE-A), LTE-A Pro, and 5G. As a part of these efforts, we are eager to study the primary challenges of accommodating a massive number of devices per cell from the perspective of a cellular system's access control plane.

1.3.2 Interference management

As many IoT/M2M devices are connected to heterogeneous networks consisting of wireless sensor networks and mobile cellular networks, they can interfere with each other, leading to degraded performance or even complete failure of communication. We investigate in this thesis the way to manage interference between these networks by using frequency hopping or beamforming techniques.

1.3.3 Network architecture

The integration of IoT/M2M networks with 4G/5G mobile networks requires careful consideration of network architecture. In the thesis, we investigate how different devices can communicate with each other and how data can be transferred between them by using gateways or routers.

1.3.4 Scalability

As the number of connected devices continues to grow, scalability becomes an essential consideration. We explore ways to ensure that IoT/M2M communications and mobile cellular networks can scale up effectively without compromising performance or reliability, by using cloud-based solutions and distributed computing architectures.

1.4 Motivations and Research Contributions

In response to the rapid development of wireless communication technology, the deployment and convergence of IoT/M2M technologies and 4G/5G cellular networks are becoming increasingly important for many industries including homes, buildings, cities, healthcare systems, etc. Among the benefits of IoT/M2M smart applications based 4G/5G mobile networks is their ability to provide real-time data and analytics. By connecting devices and sensors to the internet, these applications can collect and analyze data on everything from traffic patterns to energy usage, enabling businesses and individuals to make more informed decisions. For example, a smart city could use IoT sensors to monitor traffic flow and adjust traffic lights in real-time to reduce congestion. Another benefit of IoT/M2M smart applications based 4G/5G mobile networks is their ability to automate processes and improve efficiency. By connecting machines and devices to the internet, these applications can streamline workflows and reduce the need for human intervention. For example, a factory could use IoT sensors to monitor equipment performance and automatically schedule maintenance when needed, reducing downtime and improving productivity. In addition, IoT/M2M smart applications based on 4G/5G mobile networks can improve safety and security. By connecting devices such as cameras and alarms to the internet, these applications can provide real-time monitoring and alerts in case of emergencies. For example, a home security system could use IoT sensors to detect intruders and automatically notify authorities. Also, IoT/M2M smart applications based 4G/5G mobile networks can improve quality of life by providing new services and experiences. For example, a healthcare provider could use IoT sensors to monitor patients remotely, enabling them to receive care from the comfort of their own homes. Similarly, any smart building system could use IoT devices to control lighting, temperature, and other settings, providing a more comfortable and convenient living environment. Despite the great applicability of IoT/M2M communications and 4G/5G mobile networks in the implementation of smart applications, there is a lack of strategies in existing systems that include limited wireless range connectivity, poorly designed user interfaces, security concerns, high costs, complexity, interoperability issues, privacy concerns, and reliability issues. As more devices become connected to the internet and more data is collected and analyzed, it is important to weigh the benefits against the potential risks and drawbacks when deciding whether to adopt these technologies.

This thesis proposes adaptive control of IoT/M2M devices in smart-x systems (homes, buildings, cities, and healthcare) using heterogeneous wireless networks as a means to address these issues and reduce the existing limitations of current systems. By selecting the appropriate connection, whether WSN or MCN, through a user-friendly interface using smartphones via the Raniso app or Blynk app, regardless of time and location, users can control their systems easily and efficiently. Costs are reduced through the use of efficient and affordable components and the free Raniso App to manage, monitor and control building equipment and conditions across different heterogeneous networks.

This research contribution involves the use of our developed mobile application Raniso to control IoT/M2M devices in smart-x systems over heterogeneous wireless networks to achieve adaptive control. The main contributions of this thesis (illustrated in Figure 1.4) are outlined as follows:

1. **1.** Development, implementation, and design of adaptive control for IoT/M2M devices connected to heterogeneous networks in smart-x systems using Arduino and NodeMCU boards with heterogeneous low-cost and small-sized sensors and actuators.
2. **2.** Dynamic deployment and intelligent management of IoT/M2M devices to facilitate monitoring and control of smart applications via the ThingSpeak IoT platform, the Blynk app, and our free Raniso mobile app.
3. **3.** Development of a methodology to customize smart applications based on user preferences using Artificial Intelligence (AI) techniques such as image recognition, speech recognition, and decision-making.
4. **4.** Offering several innovative smart applications, including smart home, smart environment, smart city, smart healthcare, and smart building.
5. **5.** Analyzing and evaluating the functionalities of the proposed systems in terms of adaptability, control, automation, comfort, energy efficiency, and effectiveness.

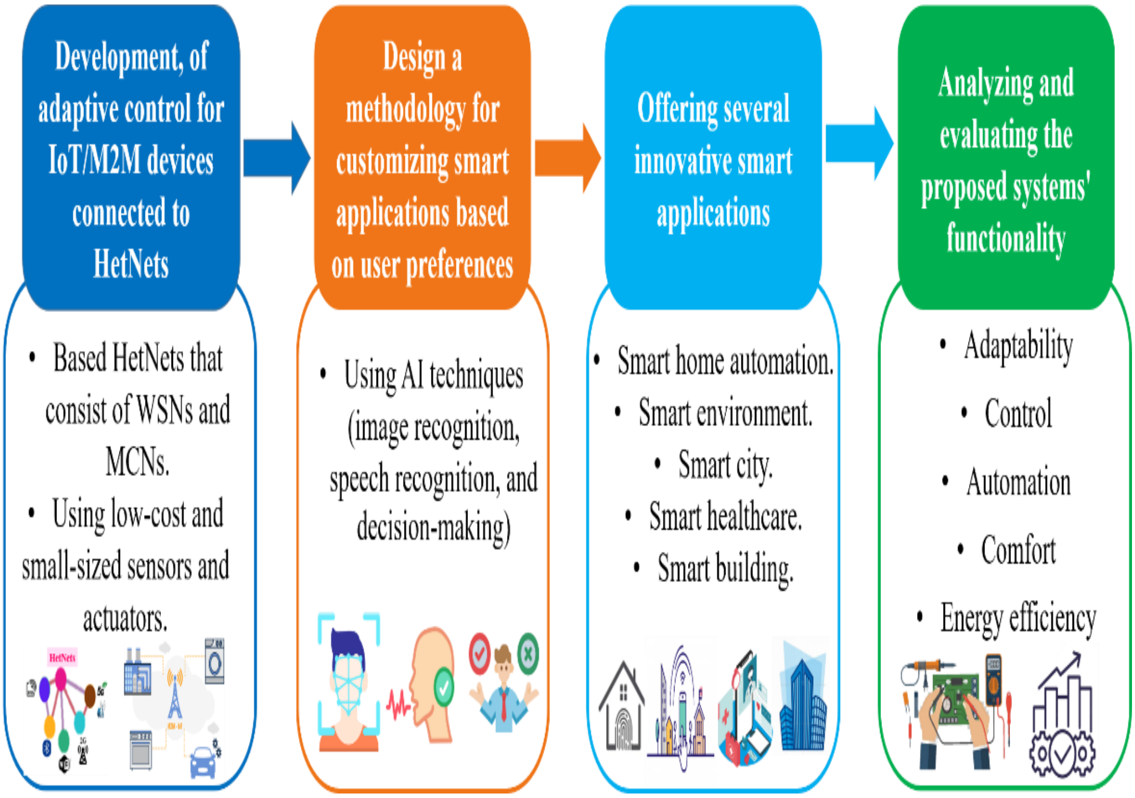

Figure 1.4 Thesis Contributions.

1.5 Thesis Organization

The remainder of this thesis is divided into four chapters and is organized as follows:

- Chapter (2) provides a comprehensive explanation of M2M communication, IoT technology, and 4G/5G mobile networks, highlighting their building blocks, architecture, characteristics, and requirements.
- Chapter (3), provides a comprehensive analysis of the deployment and convergence of IoT/M2M communications and MCNs/WSNs, exploring the challenges and opportunities associated with this emerging field.
- Chapter (4), deals with the design, implementation, and deployment of IoT/M2M technologies in various Smart-X systems, including healthcare, homes, offices, and cities.
- Chapter (5), focuses on the Adaptive Control of IoT/M2M Devices in Smart Buildings using Heterogeneous Wireless Networks consisting of WSNs and MCNs.

Figure 1.5 illustrates the thesis organization.

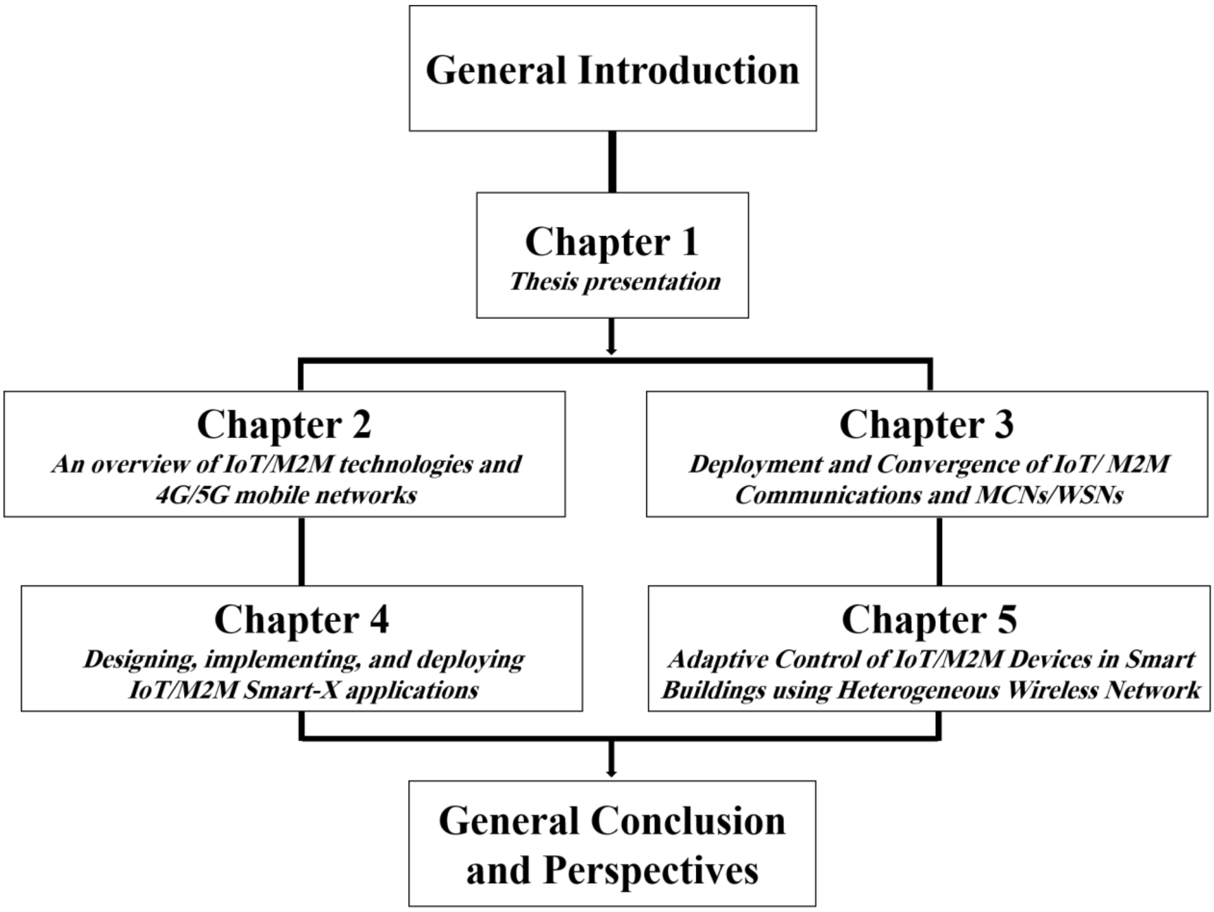

Figure 1.5 Thesis organization.

CHAPTER 2

An overview of IoT/M2M technologies and 4G/5G mobile networks

Contents of Chapter 2

2.1 Introduction

The Internet of Things and machine-to-machine communications are becoming increasingly popular as they enable connection and communication between different devices and networks. The number of connected devices is ever-growing and the need for reliable and secure data transmission is increasing. In this chapter, we aim to provide an overview of IoT/M2M communications, including its evolution, current needs, and connectivity technologies. Then, we summarize and discuss some IoT/M2M application domains. Wireless sensor networks and mobile cellular networks are two enabling technologies that are ideal for IoT/M2M devices. We will discuss the characteristics of each technology, as well as their potential applications in the context of IoT/M2M communications. Finally, we then focus on 4G and 5G mobile networks, which are the main technologies used in this thesis. Their definitions, specifics, and characteristics are provided.

2.2 Internet of Things Technology

Since the term was coined by Kevin Ashton in 1999, the Internet of Things has become a rapidly growing technology that has been transforming our lives through its various applications. The term "Internet of Things" consists of two words: "Internet" and "Things", where "Internet" can be defined as "A globally connected network system that uses Transmission Control Protocol / Internet Protocol (TCP / IP) to transfer data", while "Thing" is "An object or entity not precisely designated". Therefore semantically, the concept of the Internet of Things refers to the ability of devices to communicate over the Internet through mobile devices, sensors, and actuators [2], which allows for the collection of information and knowledge, providing a way to make faster and smarter decisions [3]. The International Telecommunication Union (ITU) defines the IoT as a global infrastructure for the information society, enabling advanced services by interconnecting physical and virtual things based on existing and evolving interoperable information and communication technologies [23]. The IoT can be expressed through a simple formula such as:

$$IoT = Services + Data + Networks + Devices \qquad (2.1)$$

There is a wide range of IoT use cases, and the market is now expanding toward massive IoT deployment. Massive IoT is about massive scale, the billions of devices, objects, and machines that require connectivity even in the most remote locations and that report to the cloud regularly. On the other hand, it refers to those applications, which are less latencysensitive, and have lower throughput requirements but requires a huge volume of low-cost and low-energy consumption devices on a network with excellent coverage. Massive IoT applications could see an introduction in the future years, depending on the development and release of supporting modules. It promises new developments in connectivity for all sorts of "things" around the world, while Industrial IoT (IIoT) is a type of M2M communication, mainly focused on real-time machine monitoring, business environment, smart manufacturing, delivery and quality control, and electronic data management [24].

2.2.1 IoT Building Blocks

The IoT can be clearly explained by looking at the concept of the building blocks presented in Figure 2.1.

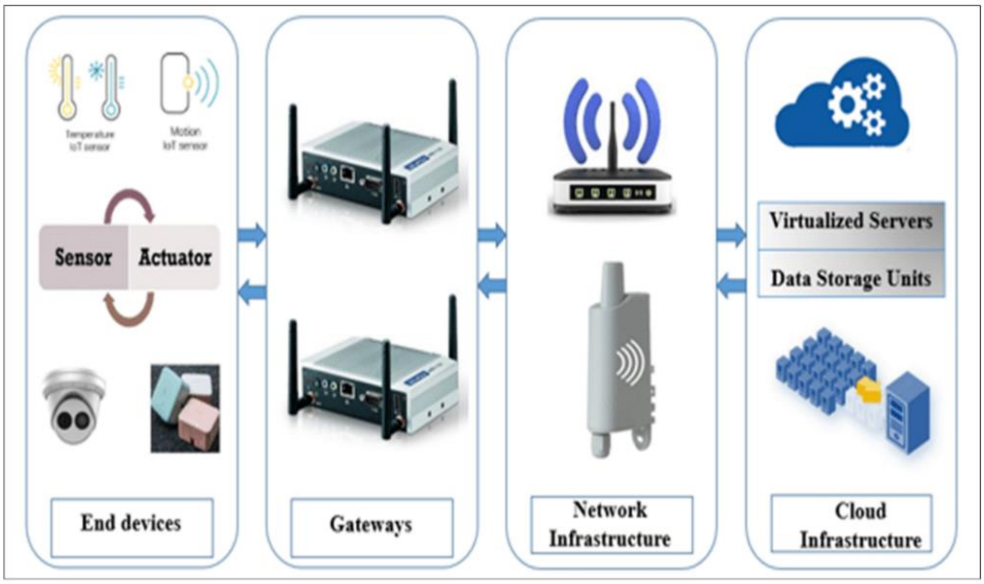

Figure 2.1 Building blocks of IoT.

The building blocks of IoT include:

- **End devices:** Consist of sensors and actuators that gather important information about objects in the target areas without human intervention.
- **Gateways:** Acting as an intermediate block and enabling strong connectivity between things and the cloud infrastructure. This block also provides security and management capabilities during data flow.
- **Network Infrastructure (NI):** The devices represented are routers, aggregators, repeaters, etc., which control the flow of data between objects and the cloud infrastructure. The connectivity in this infrastructure can operate in a wireless or wired mechanism.

- **Cloud Infrastructure (CI):** The primary function of this block is to compute and analyze data received from end devices and gateways. It also enables analytics, logic, and advanced computing capabilities.

2.2.2 IoT Architecture Layers

As the number of IoT deployments rises, it is important to consider the architectures used to support them. IoT architectures consist of different layers of technologies that can be either three-layered or five-layered. This section will evaluate these two approaches to IoT architecture, with a focus on the three-layer design (application layer, network layer, and perception layer) and the five-layer design (business layer, application layer, processing layer, transport layer, and perception layer).

2.2.2.1 Three-layer design

A three-layer architecture is a common and generally known structure for IoT studies as presented in Figure 2.2.

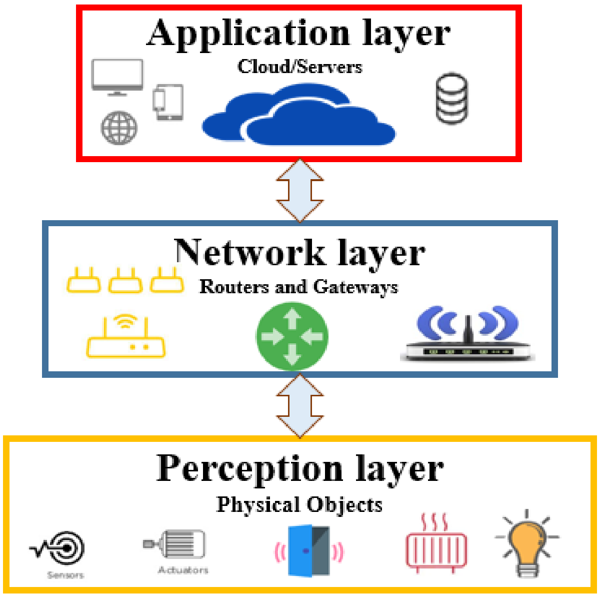

Figure 2.2 Three-Layer IoT Architecture.

The three-layer design consists of three levels: perception, network, and application. Each layer is described below.

- Perception layer is the same in the three-layer design and the five-layer design. It is also called a recognition layer. In both designs, it is the lowest layer of the conventional IoT architecture. This layer's main objective is to collect data/information from things or devices [25].

- Network layer is the middle layer that provides the connection between the perception layer and the application layer. Data is efficiently transferred from the perception layer to the application layer, making it the brain of this architecture [25].
- Application layer is the topmost layer in three-layer modular designs that provides good service to customers. This layer is responsible to link the gap between the user and devices.

2.2.2.2 Five-layer design

When research focuses on the finer aspects of integrating various technologies and broad parametric application domains, the current three-layer architecture is not sufficient, so researchers have developed a five-layer IoT architecture presented in Figure 2.3. The five-layer design is an extension of the three-layered architecture. It adds two additional layers to the basic design: the business layer and the middleware layer.

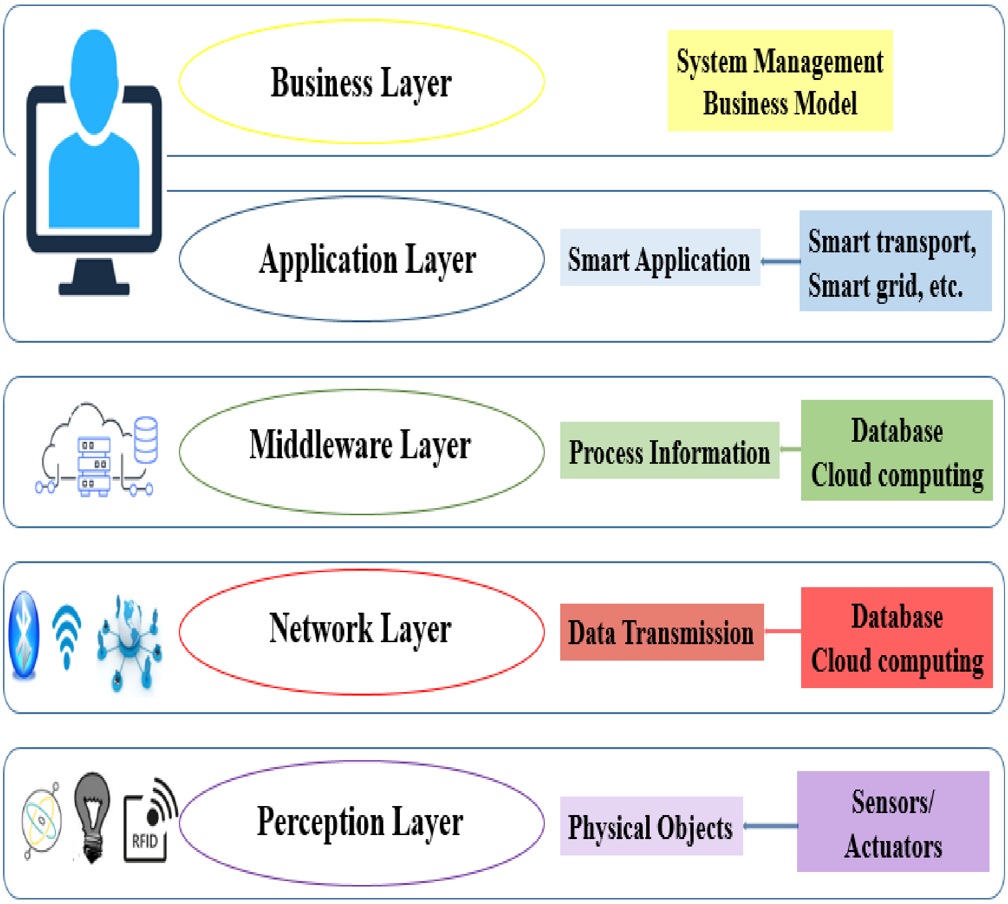

Figure 2.3 Five-Layer IoT Architecture.

The presented five-layered architecture is similar to three-layered architecture but with an extra two layers added. The role and the functioning of each layer shown in the five-layered IoT architecture are presented in Table 2.1 [25].

Table 2.1 Role and functional features of five-layer IoT architecture.

Perception layer	This layer can sense and collect information about the environment where smart things are available.
Transport layer	This layer transfers data from the perception layer to the processing layer and vice versa via any type of network.
Processing layer	This is the middleware layer that has special features such as information storage, analysis, and data processing to enable vendors to provide various types of services.
Application layer	Its main feature is to provide the user with a specific service based on the type of application.
Business layer	As the name suggests, it works in business. It manages the entire IoT system where all applications will be managed, especially business and profit models in a user-friendly manner with privacy.

2.3 Machine-to-Machine Communication

In today's digital world, Machine-to-Machine communication has become increasingly popular. The abbreviation M2M can be used to refer to two other main concepts, namely: Man-to-Machine communication, which involves communication between a human-powered device and a machine, and Machine-to-Mobile communication, which involves communication between machines and mobile devices. However, the most common is Machine-to-Machine which it is originated as a part of supervisory control and data acquisition (SCADA) systems, where sensors and other devices are connected to computers to monitor and control industrial processes. Machine-to-Machine is also known as Machine-Type-Communication (MTC) in the 3rd Generation Partnership Project (3GPP), which is an integral part of the IoT ecosystem and a major contributor to its development. M2M is defined as communication that allows devices to connect across a wired or wireless communication network without the need for human intervention. Sensors, RFID, Bluetooth, Wi-Fi, and other wireless technologies, as well as cellular communications lines and autonomic computing software, are used to assist a network device in understanding and transmitting data and making decisions in an M2M system [4]. M2M is typically deployed to boost production, cut expenses, and improve security.

In 2008, the European Telecommunications Standards Institute (ETSI) created the M2M Technical Committee to standardize the rapidly growing field of M2M communication. The goal of this committee was to develop a common architecture for M2M applications and devices to accelerate their adoption. Over time, the scope has expanded to include the IoT. Recognizing this need, and to ensure the most efficient deployment of IoT/M2M communications systems, several of the world's leading Information and Communications Technology (ICT) Standards Development Organizations (SDOs) founded oneM2M in July 2012 as a global initiative designed to promote efficient M2M communication systems and IoT. This new global organization seeks to develop technical specifications and reports to ensure that M2M devices can successfully communicate on a global scale, i.e. common Service Layer.

2.3.1 M2M Building Blocks

To realize any M2M-based smart network, M2M communication is considered a building block to deploying a wide-scale communication, monitoring, and control infrastructure. The choice of communication technology for M2M would be based on the use case, and ability to address the challenges. A typical M2M network consists of the following building blocks presented in Figure 2.4.

- **Wide Area Network (**WAN**) / Field Area Network (**FAN**):** Cellular M2M technology using 2G/3G/4G plays an important role in M2M WAN FAN communications [11].
- **Neighborhood Area Network (NAN) / Building Area Network (**BAN**) / Local Area Network (LAN):** There are large-scale wireless sensors and actuators deployed in a typical M2M network to carry out the monitoring task. These sensors have an important role to play in realizing various functionalities needed in the M2M network. The various communication technologies available are [IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN), Wi-Fi, ZigBee, Bluetooth, Near Field Communication (NFC), RFID, etc.] [11].

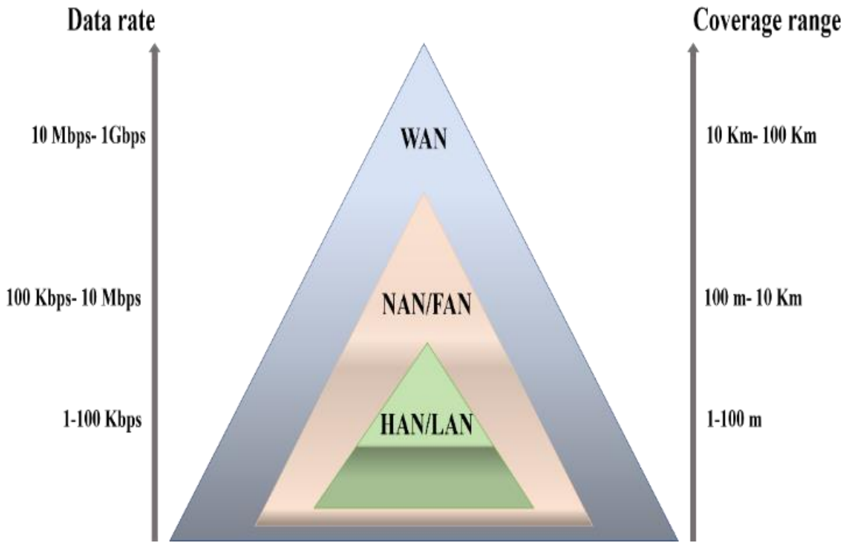

Figure 2.4 Building blocks of M2M.

2.3.2 M2M Communication Architecture

The European Telecommunications Standards Institute (ETSI) suggested three domains for a generic end-to-end architecture of the M2M system paradigm, namely: the M2M device domain, the network domain, and the application domain. We explain each of the mentioned domains one by one below. We have designed the M2M architecture as depicted in Figure 2.5.

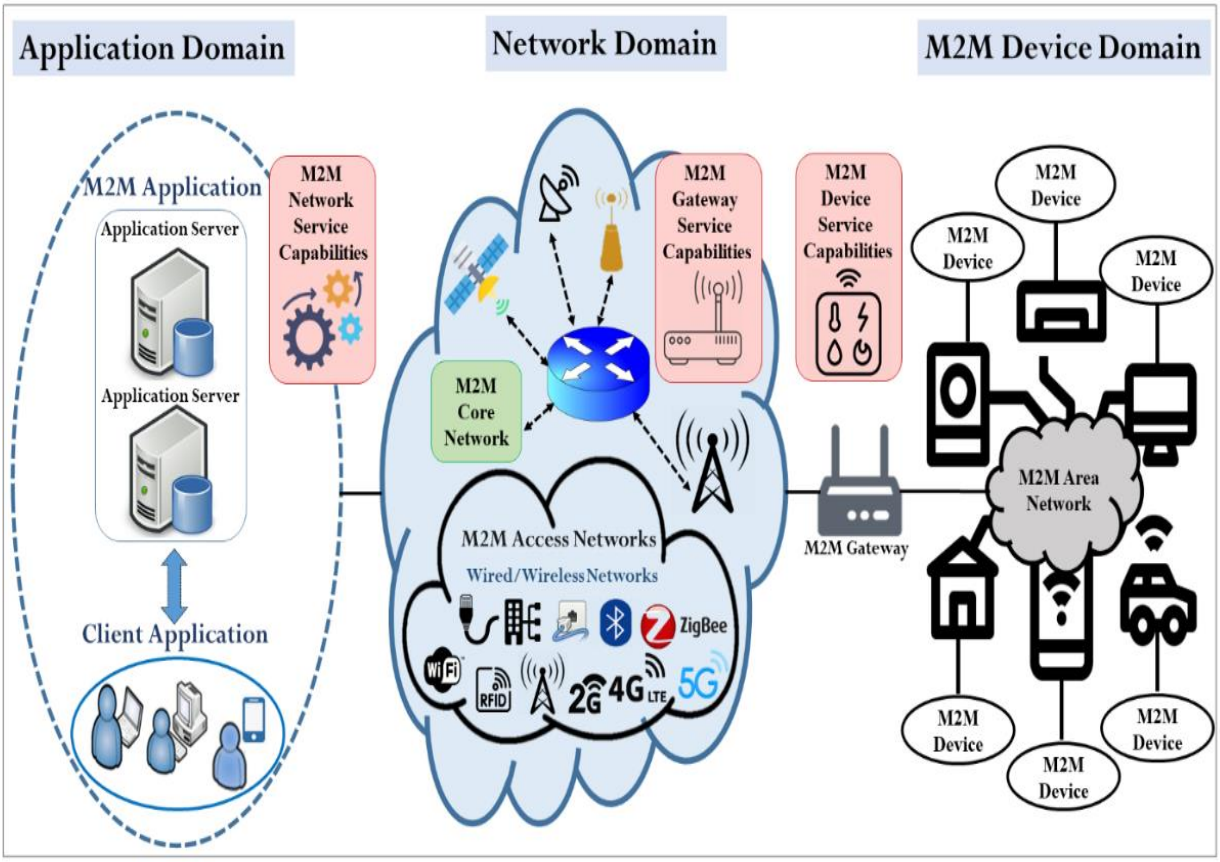

Figure 2.5 The architecture of M2M communication.

2.3.2.1 M2M device domain

This domain's role is to transmit data from M2M devices to the Network domain. M2M devices are the system endpoints that can connect to a Network domain either directly using an embedded Subscriber Identity Module (SIM), Wide Area Networks (WANs) connection (4G/ 5G) or via a gateway, which receives, manages and aggregates data, then delivers it to the Network domain. In addition, the use of an M2M LAN is preferable when the cost is a determining factor. In this case, several WPANs can be adopted, via which these devices can communicate [26].

2.3.2.2 Network domain

This domain acts as a bridge between the M2M device domain and the M2M application domain. In this domain, long-range wired/wireless network protocols [e.g. Worldwide Interoperability for Microwave Access (WiMAX), and 4G/5G networks, telephone networks, etc.] are utilized to provide cost-efficient and reliable channels with wide coverage to convey the sensory data from the M2M device domain to the application domain [27]. Besides, the M2M platform generally includes other tools, such as object administration and operation. There is usually a middleware whose role is to orchestrate the data flows with the different objects. Its features are to manage queues, and archive messages exchanged.

2.3.2.3 Application domain

This domain consists of a back-end server and M2M application clients. The back-end server is the primary component of the M2M system and acts as an integration point to store all the sensory data transmitted from the M2M device domain. It also provides real-time monitoring data to various client applications including e-health care, smart metering, etc [27].

2.3.3 OneM2M standard

The oneM2M is a global standard for M2M communication and IoT technology, which is a technical specification that provides a common framework for interoperability between different IoT/M2M devices and platforms. It provides a set of specifications that define common service layer protocols, data models, and security mechanisms. These specifications enable IoT/M2M devices to discover each other, exchange data in a standardized manner, and provide services such as device management, data storage, and application enablement [28], [29].

The architecture of oneM2M (see Figure 2. 6) divides M2M/IoT environments into two domains, namely the infrastructure domain and the field domain. It also defines four types of nodes that are present in each domain, namely Infrastructure Node (IN), Middle Node (MN), Application Dedicated Node (ADN), and Application Service Node (ASN). The IN is located in the network infrastructure and provides M2M service. The MN acts as a gateway between the devices and the network infrastructure. The ADN is a constrained device with limited functionality, specifically focusing on M2M service logic. The ASN is a generic node that includes both Common Service Functions (CSFs) and M2M applications.

The architectural model of oneM2M consists of three main entities: the Application Entity (AE), the Common Service Entity (CSE), and the underlying Network Service Entity (NSE). The AE represents the application logic for an end-to-end IoT solution and can be found in devices, gateways, or servers. The CSE acts as a platform that provides CSFs, which are M2M service functions utilized by various application entities. These CSFs cover a wide range of functions, including registration, security, application, service, data, and device management. The NSE, on the other hand, delivers network services to the CSE [30].

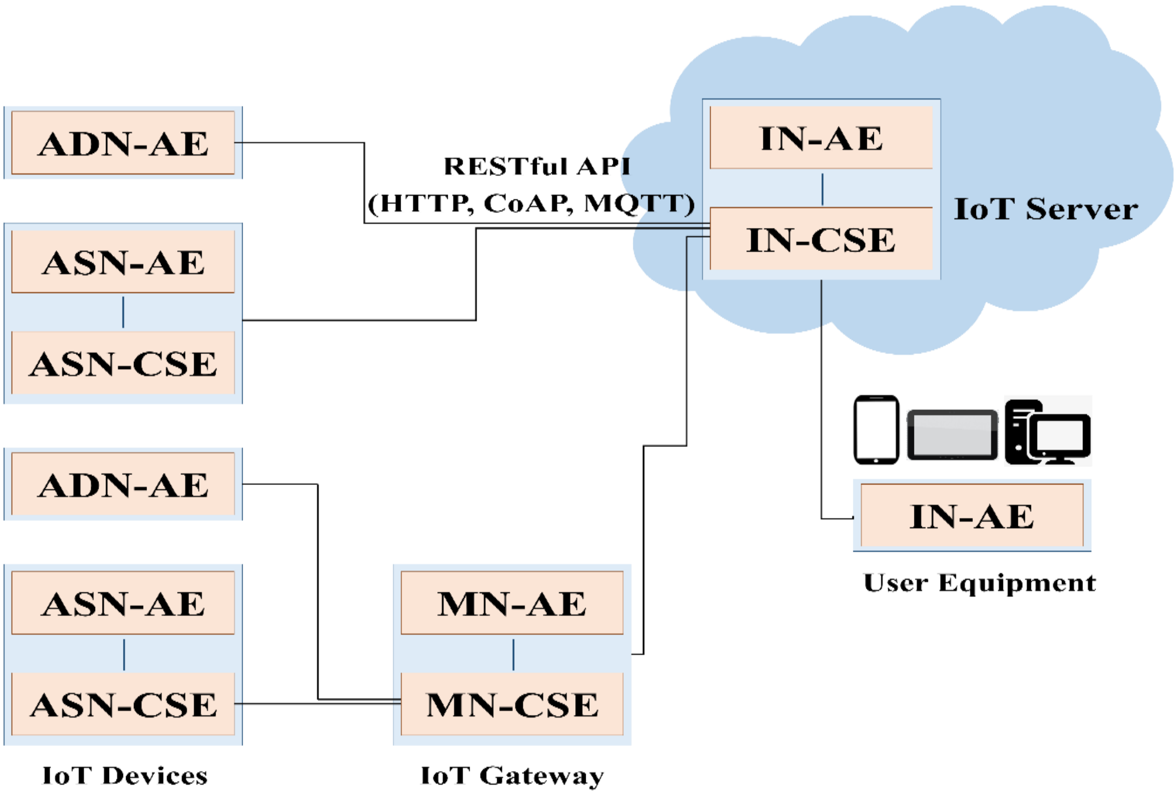

Figure 2. 6 OneM2M reference architecture model.

2.4 IoT/M2M Wireless Communication Technologies

Connectivity is one of the main pillars of the IoT/M2M paradigm. The variety of data types and applications requires different communication protocols to meet the specific functional requirements of an IoT/M2M system. In this section, we will review the IoT/M2M communication parameters as well as the main features of the currently prominent communication technologies for IoT/M2M, categorizing them into short-range wireless communication, including wireless personal area networks (WPANs) and wireless local area networks (WLANs), LPWANs and MCNs shown in Figure 2.7

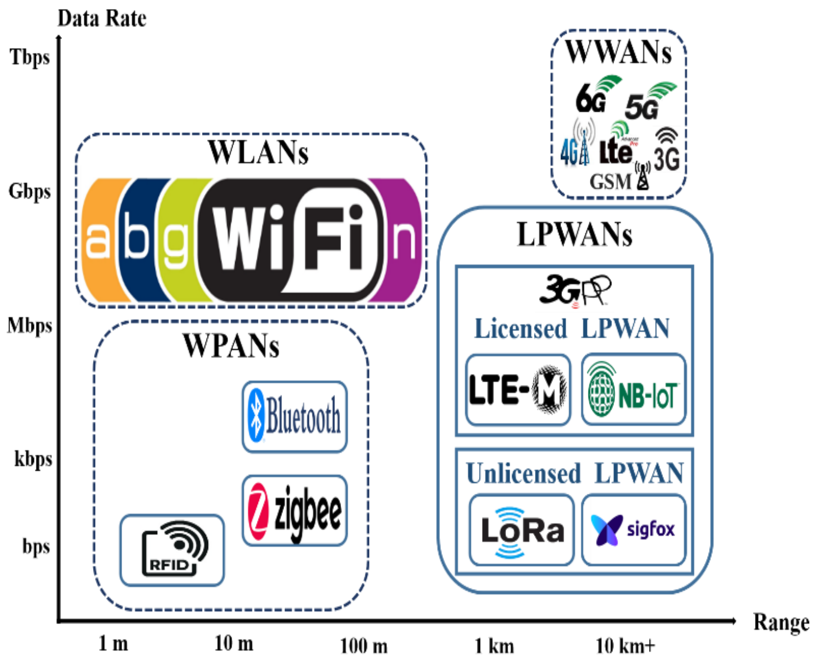

Figure 2.7 IoT/M2M communication technologies.

2.4.1 IoT/M2M Communication Parameters

Before taking the leap and deploying an IoT/M2M solution, it is critical to know the communication parameters. IoT/M2M communication protocols include the following aspects:

- **Data Rate:** It is the amount of transmitted information within a time duration.
- **Range:** It is the maximum distance between two intercommunicating nodes. It depends upon the transmitting power, the frequency band used, and the type of modulation. Additionally, it may be impacted by the nodes' actual locations or the weather.
- **Power Consumption:** It is the quantity of energy that a node needs to function within its lifetime. This parameter defines the need for permanent power or the use of a battery.
- **Interoperability:** It is the capacity for information flow between nodes, regardless if they are of different types.
- **Scalability:** the challenge of deploying a higher number of nodes, increasing the number of end-users, as well as the amount of data to store and process without the need of migrating the technology.
- **Cost:** This is the price of implementing and maintaining a certain technology. The cost of the network is strongly influenced by energy consumption, maintenance, and scalability.
- **Network Topology:** It is the mode of inter-nodes communication. Examples of topologies include star, mesh, point-to-point, point-to-multipoint, etc.

- **Security and privacy:** It is the way of securing data transmission and reception. It is essential to guarantee that the communication sent between nodes only reaches the intended nodes.

2.4.2 Wireless Personal Area Networks

2.4.2.1 Bluetooth and Bluetooth Low Energy

Bluetooth is designed based on the IEEE 802.15.1 wireless personal area communication standard and can be used for short-range ad hoc communication (master and slave configuration) between devices operating in the 2.4 GHz ISM (Industrial, Scientific, and Medical) band. In 2010, the Bluetooth SIG (Special Interest Group) released Bluetooth v4.0+LE (Low Energy), or simply Bluetooth Low Energy (BLE). This new technology contains two sub-specifications: Bluetooth smart, further known as BLE single mode; and Bluetooth smart ready, known as BLE dual mode. BLE dual mode implements the classic Bluetooth stack, which is used in Bluetooth v1.1 to Bluetooth v3.0+HS (High Speed), as well as the Bluetooth smart stack. BLE single mode implements only the Bluetooth smart stack [31], [32]. BLE has a low power mode that considerably lower power consumption by shortening the time the radio is active, making it especially ideal for embedded M2M devices with demanding battery life requirements. In comparison to the original Bluetooth standard, BLE is claimed to consume 10–20 times less power and transmit data 50 times faster.

2.4.2.2 ZigBee

ZigBee is a standard for Low-Rate Wireless Personal Area Networks (LR-LPWAN) that was developed about twenty years ago to address the need for low-cost, low-power wireless sensor and control networks across a range of market sectors. The standard is invented by the ZigBee Alliance in 2004 and it is based on the IEEE 802.15.4 standard. The ZigBee PRO standard is optimized for low power consumption and to support large networks with thousands of devices. Three different frequency bands can be used with IEEE 802.15.4 standard: 868 MHz, 914 MHz, and 2.4 GHz which support 1, 10, and 16 channels respectively, each with a bandwidth of 2 MHz. It is capable of reducing the frequency of battery replacement (up to two years) and provides connection speeds of up to 250 kbps for a coverage radius of up to 1,000 meters. Direct Sequence Spread Spectrum (DSSS) is used as a modulation scheme for ZigBee and it is only defines physical and data link layers (DLL). IEEE 802.15.4 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for channel access. This is particularly important from an IoT/M2M perspective since a large number of connected devices can try to communicate at the same time [33].

2.4.2.3 RFID

Radio Frequency Identification (RFID) is a low-cost wireless technology that encodes digital data in an RFID "tag" affixed to a product and allows a radio wave device to read it remotely. It is one of the fundamental technologies for implementing IoT/M2M applications such as smart shopping, healthcare, national security, agriculture, etc. The typical RFID systems consist of tags, readers, and back-end computer systems. There are two types of tag: active and passive tag, where the active tag has a battery and can send the information at hundreds of meters, and the passive tag depends on the emitted energy of the reader's antenna instead of using the battery to transmit information [34]. The four main frequency ranges that RFID devices use are as follows:

- Low Frequency (LF) —125~134 kHz. Very short range (a few cm) and low transfer rate, usually used for smart cards, tickets, animal tagging, etc.
- High Frequency (HF) —13.56 MHz. Range up to 1.5 meters, medium to high transfer rates. Extensively utilized in NFC devices, smart labels, and cards.
- Ultra-High Frequency (UHF) —433~956 MHz. A range of several meters, a fast scanning rate that allows for simultaneous reading of hundreds of tag IDs.
- Microwave frequency (MF)—2.45 GHz. Primarily for active tags for toll collection or Real Time Locating Systems (RTLS).

2.4.3 Wireless Local Area Networks

2.4.3.1 Wi-Fi

Wireless fidelity (Wi-Fi) is defined by a family of IEEE 802.11 standards as the most popular WLANs used for data transmission, which operates within 5 GHz and 2.4 GHz ISM spectrum bands. Wi-Fi users can surf the Internet at broadband speeds by connecting to an access point (AP) or ad hoc mode. To improve the network performance and throughput while considering dense and congested areas enhanced features were introduced into the 802.11ac/802.11ax/802.11be releases. To extend the Wi-Fi network applications to meet the needs and requirements of modern IoT/M2M connectivity, the IEEE proposed and established Low-power Wi-Fi, which is also called IEEE 802.11ah as an amendment to the legacy standard. It aims to achieve a low energy consumption of down to 100's milliwatts which is suitable for IoT-based devices, provides a large coverage area, and can achieve a data rate of up to 347 Mbps [33], [35]. One indicator of this progression is the rapid rise in nominal data rates, which have gone from the legacy 2 Mbps of IEEE 802.11-1997 to over 10 Gbps in the most recent

802.11ax, also known as Wi-Fi 6. Modern Wi-Fi achieves such a performance gain thanks to faster Modulation and Coding Schemes (MCSs), wider channels, and the adoption of Multiple Input Multiple Output (MIMO) technologies [36]. The next generation Wi-Fi standard is Wi-Fi 7, also known as IEEE 802.11be Extremely High Throughput (EHT).

2.4.4 Low power wide area Networks

LPWANs are a new type of wireless communication technologies that are designed to offer a set of features including wide-area and massive scale connectivity for low power, low cost, and low data rate devices. This type of technology is proposed to support IoT/M2M applications. There exist several implementations of LPWAN schemes, which can be classified into two categories. The first one is 3GPP LPWAN which introduced two standards in its LTE Release 13: Enhanced Machine-Type Communication (eMTC) and NB-IoT. The second category is non-3GPP LPWAN, which includes LoRa and Sigfox.

2.4.4.1 LoRa

LoRa, standing for (Lo)ng (Ra)nge, defines two different layers: the physical layer (LoRa modulation) and the MAC layer (LoRaWAN protocol) based on ALOHA. It is an open standard governed by the LoRa Alliance, it was developed by a company called Semtech. LoRa offers a very compelling mix of long-range, low power consumption, and secured data transmission [37]. This technology uses unlicensed ISM bands, i.e., 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia, for communication at a maximum data rate of 50 kbps, which is sufficient for most IoT/M2M applications. The Chirp Spread Spectrum (CSS) modulation, which disperses a narrow-band signal over a wider channel bandwidth, facilitates bidirectional communication. The resulting signal has low noise levels, enabling high interference resilience, and is difficult to detect or jam [38].To mitigate the effect of interference, LoRa uses a Frequency Hopping Spread Spectrum (FHSS) which enables access to available channels. It has been shown that long communication ranges (15 km+) are achievable in urban and suburban areas [33]. LoRaWAN is based on LoRa and adds a network layer to manage communication between LPWAN gate and end node devices as a routing protocol. Each message transmitted by an end device using LoRa is received by all the base stations in the range. To address the different requirements of a wide range of IoT applications, LoRaWAN provides three classes of devices.

2.4.4.2 Sigfox

Sigfox is a low-power network technology for wireless communication of a diverse range of low-energy objects such as sensors and IoT/M2M applications. It contributes to the IoT by allowing interconnection via a gateway and offers a complete end-to-end connectivity solution by using Ultra-Narrowband. Sigfox deployed with two main modulations: the Differential Binary Phase Shift Keying (DBPSK) and the Gaussian Frequency Shift Keying (GFSK). This proprietary technology supports unidirectional and bidirectional communication over an unlicensed spectrum. Like LoRa, Sigfox uses unlicensed ISM bands, for example, 868 MHz in Europe and 915 MHz in North America, and 433 MHz in Asia. This technology allows the transportation of small amounts of data ranging up to 50 kilometers. It uses the frequency bandwidth efficiently and experiences very low noise levels, leading to very low power consumption, high receiver sensitivity, and low-cost antenna design at the expense of maximum throughput of only 100 bps [33], [38].

2.4.4.3 Enhanced Machine-Type Communications

Enhanced Machine-Type Communications is a cellular Low Power Wide Area (LPWA) technology developed by 3GPP in Release 13. It reduces modem complexity and power consumption while providing extended coverage over existing legacy handset modems. This technology is an enhancement for LTE networks to support MTC for the IoT. Enhanced Machine-Type Communications, also known as LTE Cat-M1, or Cat-M operates within a limited bandwidth of 1.08 MHz from the available 1.4 MHz, allowing it to use only six physical resource blocks (PRBs) from the eight available 180 kHz LTE physical resource blocks that coexist in a general legacy-purpose LTE system. With the support for 1.08 MHz band (narrowband channel) for both radiofrequency and baseband, it is expected to achieve maximum throughputs of up to 1 Mbps in both uplink and downlink operations for massive IoT. To ensure effective utilization, eMTC is standardized with power saving management (PSM) and extended discontinuous reception (eDRX) as its power savings mechanisms, enabling it to support long battery life of about 10 years with a 5 Watt-Hour battery system [33].

2.4.4.4 Narrowband-Internet of Things

In the 3GPP Release-13 specification, the narrowband-internet-of-things was introduced as an evolution of eMTC as a low-power wide area cellular technology. It is designed to facilitate the massive deployment of IoT devices by allowing existing operators to utilize small portions of their existing networks and available spectrum. NB-IoT supports ultra-low-end IoT applications and is optimized for coexistence with legacy GSM, GPRS, and LTE technologies. It operates with a minimum system bandwidth of 180 kHz for both downlink and uplink operations. This makes it possible for a GSM operator to replace one GSM carrier of 200 kHz with an NB-IoT application. An LTE network operator can also deploy NB-IoT applications into an LTE carrier by allocating one of its PRBs of 180 kHz to NB-IoT. The NB-IoT air interface is designed to ensure harmonious coexistence with LTE so that the performance of LTE or Cat-NB1 is not compromised [33]. Table 2. 2 Summary of some current IoT/M2M wireless technologies.summarises some of current wireless IoT/M2M technologies.

Table 2. 2 Summary of some current IoT/M2M wireless technologies.

Technology	Modulation	Frequency Band	Range	Data Rate	Channel Bandwidth
Bluetooth	GFSK	2.4 GHz	50 m	2 Mbps	125,250 or 500 kHz
ZigBee	DSSS	868, 914 MHz, and 2.4 GHz	Less than 1 km	250 Kbps	2 Mhz
RFID	ASK, FSK , PSK/OOK	(LF) —125~134 kHz (HF) —13.56 MHz (UHF) —433~956 MHz (MF)—2.45 GHz	LF/HF —10~20 cm UHF/MF—3 m	4 Mbps	LF, HF,UHF, MF
Wi-Fi	MCS	2.4 GHz, 5 GHz, 6GHz	100 m	40 Gbps (Wi-Fi 7)	20/22 MHz
LoRa	CSS	433,868 and 915 MHz	15 km	50 Kbps	125,250 or 500 kHz
Sigfox	BPSK	433,868 and 915 MHz	20 km +	100 bps	100 Hz
eMTC	QPSK, 16-QAM	Licensed LTE frequency band	Urban:~5km Suburban:~ 17 km	1 Mbps	1.08 MHz
NB-IoT	BPSK, QPSK	Licensed LTE frequency band	Urban:1~ 8 km Suburban:~ 25 km	200 Kbps	200 kHz

2.4.5 Mobile Cellular Networks Evolution

The beginning of mobile cellular networks can be traced back to the 1st Generation (1G) of mobile phone technology, which launched in the early 1980s, based on analog frequency-division multiplexed technology, with a peak data rate of up to 2.4 Kbps. Many 1G network standards have been used around the world since its inception, including advanced mobile phone system (AMPS), Nordic Mobile Telephone (NMT), Total Access Communication

System (TACS), etc. The 1G system had many drawbacks, including poor security, lower transmission efficiency, low battery life, large size, poor sound quality, and frequent interruptions. The 2nd generation (2G) era was ushered in with GSM utilizing digital modulation technologies, including the Time Division Multiplexed Access (TDMA) and Code Division Multiple Access (CDMA), which were employed to develop the 2G systems with digital transmissions, better voice, short message services (SMS) and data rate of about 64 Kbps. GSM quickly replaced the 1G technology and it continues to be a business opportunity and generates revenues even today. This was followed by 2.5G General Packet Radio Service (GPRS) and 2.75G Enhanced Data for GSM Evolution (EDGE) which both increased the connection speed, utilizing packet-switched data, and allowing for access to certain mobile Internet content. Moving forward, the year 2000 saw the introduction of the 3rd Generation (3G) technology in the form of Universal Mobile Telecommunications System (UMTS), operating on the 1900-2000 MHz frequency band and providing a data transfer rate of at least 2 Mbps. UMTS is based on Wideband Code Division Multiple Access (WCDMA) that provides better video applications on mobile phones and improved Quality of Service (QoS) for Multimedia. This technology was designed to increase wireless data traffic and it quickly took over the market, though it did not completely replace 2G. Followed by 3.5G HSDPA (High-Speed Downlink Packet Access) and 3.75 G (HSPA+) which are mobile telephony protocols that provide download speeds of 8-10 Mb/s in the downstream direction. In 2010, the 4G era started with two competing systems, LTE and WiMax, both based on the Orthogonal Frequency Division Multiple Access (OFDMA) modulation scheme. WiMAX had a short commercial life and was quickly replaced by LTE. Long Term Evolution-Advanced (LTE-A) is considered as 4G standard which integrates existing and new technologies such as coordinated multiple transmission/reception (CoMP), Multiple-Input Multiple-Output (MIMO), and orthogonal frequency division multiplexing (OFDM). With many mobile network operators (MNOs) investing in the rollout of LTE networks across the world, the development of long-term evolution technology has been integral to the transition from the 2nd Generation (2G), 3G to 4G, which provides high-speed data rates up to 1Gbps in the downlink and 500 Mbps in the uplink. This deployment has been instrumental in enhancing the MBB proposition and improved coverage, as well as offering more attractively priced data tariffs, greater availability, and affordability of higher-speed devices. As the LTE evolution continues to introduce new features and improvements, the generational shift is gaining momentum, making it the fastest-growing mobile technology of all time. In the coming months, the 5G will be commercially available as the initial basic tests, the construction of hardware facilities, and the standardization processes have almost been completed. In addition to speed improvements, 5G is expected to unleash a massive ecosystem where networks can serve the communication needs of billions of connected devices while balancing speed, latency, and cost. The fifth generation networks offer higher data rates of up to 10 Gbps due to the use of a new spectrum of the microwave band (3.3-4.2 GHz) and advanced technologies like Beam Division Multiple Access (BDMA) and Filter Bank Multi-Carrier (FBMC). To improve the performance of the 5G network, numerous developing technologies, such as Massive MIMO (mMIMO), Software Defined Networks (SDN), Device-to-Device (D2D) and Information Centric Networking (ICN), are integrated into the network to allow rapid deployment of different services. As 5G networks have entered the commercial deployment phase, various global research institutions have turned their attention to 6^{th} Generation (6G) networks. The 6G networks aim to enhance performance by providing peak data rates of about 1 Tbps and ultra-low latency (microseconds) [6], [39].

Throughout the years and up to today, only 1G has completely disappeared. While GSM/GPRS/UMTS/HSPA/LTE are all still very much alive and kicking and cover a wide range of business sectors for different industries covering data rate, cost, power consumption, data speed, latency, etc. This evolution of technologies over the decades is outlined in Figure 2.8

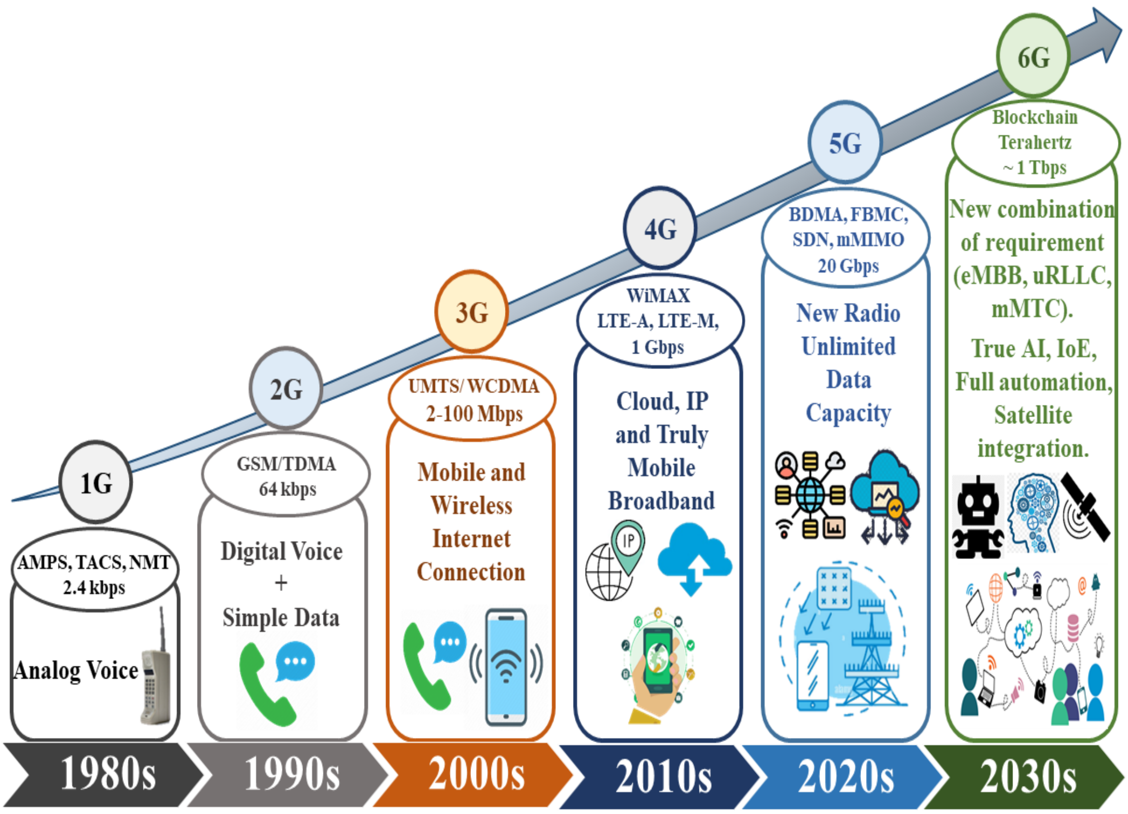

Figure 2.8 Existing and expected mobile cellular networks evolution till 2030.

2.5 Fourth-Generation Technology for Mobile Networks

The fourth generation was first introduced by Telia Sonera in Finland in 2010. This mobile network, standardized by 3GPP as a long-term evolution, offers faster speed and greater capacity for cellular devices than its predecessors [40]. LTE is developed to interconnect heterogeneous communication systems, offering increased bandwidth and enabling increased coverage of 4G. It replaces the 3.75 G (HSPA+), 3.5 G (HSPA), and 3G (UMTS) families of standards to achieve a high system capacity and coverage, high peak data rates, low latency, decreased operational costs, multi-antenna support, and flexible bandwidth operations. It uses Multi carrier CDMA or OFDM. The frequency range used in 4G is from 2000 MHz to 8000 MHz and uses a frequency spectrum of 5 MHz to 20 MHz. Maximum downlink speed of around 100 Mbps and uplink speed of around 50 Mbps is achieved in LTE systems. The core network type used in 4G is IP based. 4G network has very low latencies, wider channels, and carrier aggregation up to 100 MHz. The two common modes of LTE are LTE frequency division duplex (FDD) and LTE time division duplex (TDD) [41], [42]. The basic key challenges in turning to 4G are Multimode User Terminals, Wireless System Discovery, Wireless System Selection, Terminal Mobility, Network Infrastructure, and QoS Support, Security and Privacy, Fault Tolerance and survivability, Multiple Operators and Billing Systems, as well as Personal Mobility.

2.5.1 4G LTE Architecture

Figure 2.9 provides an overview of the LTE network and its elements.

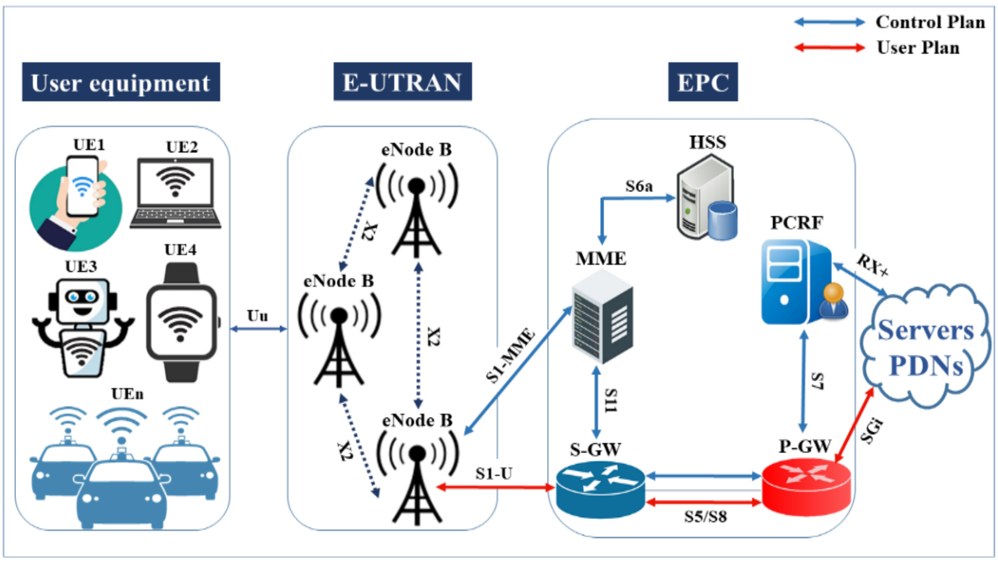

Figure 2.9 4G LTE Architecture.

The high-level 4G LTE network architecture consists of three main components: the user equipment (UE), the evolved UMTS terrestrial radio access network (E-UTRAN), and the evolved packet core (EPC). The roles of each element are explained below [5].

1. **The user equipment:** this is the mobile equipment (ME), which can be either a mobile phone, a laptop, a vehicle, or any other such device used by end users for wireless communication. The ME consisted of the following modules:

- **Mobile Termination (MT):** This is responsible for handling all the communication functions.
- **Terminal Equipment (TE):** This is responsible for terminating the data streams.
- **Universal Integrated Circuit Card (UICC):** This is the SIM card for LTE equipment. It runs an application known as the Universal Subscriber Identity Module (USIM).

2. **The E-UTRAN:** is responsible for ensuring radio communications between the UE and the EPC network. The E-UTRAN consists of only one component, the evolved base stations, also known as the eNodeBs or eNBs, which are interconnected with each other through an interface known as X2. The eNB supports two main functions including transmission and reception of radio waves by all mobiles using the LTE air interface's analog and digital signal processing functions. In addition, it sends signaling messages, such as handover commands, to all its mobiles to control their low-level operation.
3. **The Evolved Packet Core:** also known as Core Network (CN) is responsible for the overall control of the user equipment and establishment bearers. The EPC comprised of the following components:

- **The Home Subscriber Server (HSS):** is a central database that contains information about all the network operator's subscribers.
- **The Packet Data Network (PDN) Gateway (P-GW):** communicates with the outside world ie. PDN, using SGi interface. Each PDN is identified by an access point name (APN).
- **The serving gateway (S-GW):** connects the PDN gateway with the eNB by acting as a router. Serving and PDN gateways are connected via the S5/S8 interface. There are two slightly different implementations, namely S5 if the two devices are in the same network and S8 if they are in different networks.
- **The mobility management entity (MME)**: controls the high-level operation of the mobile system using signaling messages and a Home Subscriber Server.

- **The Policy Control and Charging Rules Function (PCRF):** controls the flow-based charging functionality of the Policy Control Enforcement Function (PCEF), which resides in the Policy Control Gateway.

2.5.2 QoS monitoring in 4G LTE systems

Quality of Service in cellular networks is handled in an end-to-end (E2E) manner. E2E connectivity is established using an E2E bearer service, which connects the UE to a specific entity, via the 4G components. The bearer profile includes the following QoS parameters QoS Class Identifier (QCI), Allocation and Retention Priority (ARP), Guaranteed Bit Rate (GBR) and Maximum Bit Rate (MBR). To guarantee a certain QoS, E2E bearer service is into small bearers. Each bearer connects two main entities, for example, the radio bearer, which handles the communication between the UE and the eNB over the LTE air interface. Such decomposition of the E2E bearer allows QoS monitoring over each small bearer. Therefore, the fulfillment of the E2E required QoS is achieved on each part (bearer). And, it has been recognized that a key determinant of QoS is the resources allocated. Apart from the EPC and cloud resources, which could be over-provisioned, the allocation of radio resources at the eNB side remains a challenge. Radio resources are scarce and the number of UEs is increasing with high throughput demands. Also, the amount of resources required to achieve a given data rate depends on the quality of the radio channel, e.g. if the channel conditions are poor, many more radio resources are required to achieve a given data rate. This implies the need to consider the channel conditions when into account when monitoring throughput in cellular networks [43]–[45]. Figure 2.10 presents end-to-end QoS scheme in 4G LTE network.

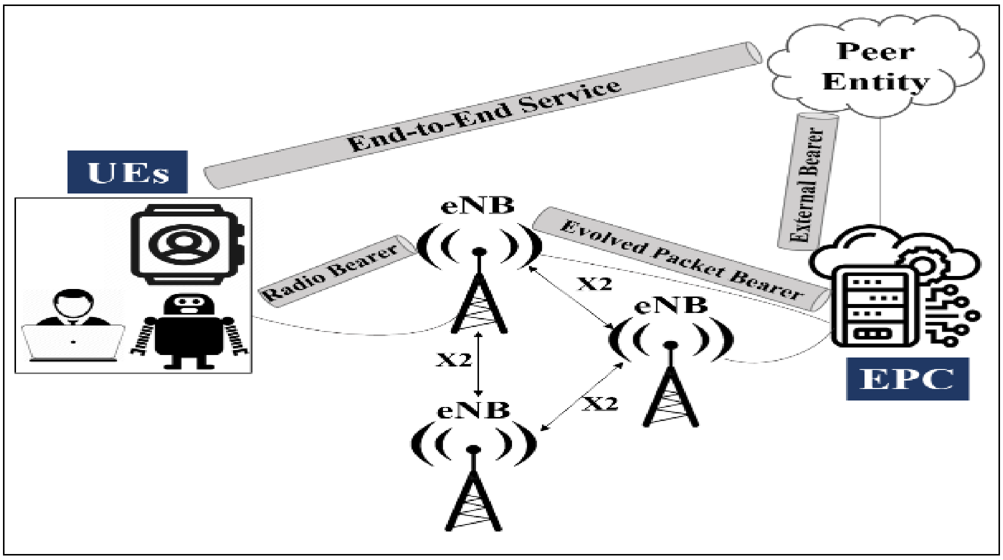

Figure 2.10 End-to-End QoS scheme in 4G LTE network.

2.6 Fifth Generation New Radio Access Technology

Fifth Generation wireless system is the future standard of mobile communication networks that are said to offer speed performance of up to 20 Gbps [6]. The first version of 5G networks is based on Release 15 by 3GPP, composed of 5G Core (5GC) and 5G New Radio (5G NR), which will be deployed throughout the world at frequencies ranging from less than 6GHz (0.45GHz-6GHz) to millimeter wave (mmWave) (24.2-52.6 GHz). To fully implement 5G NR, entirely new hardware is needed, but the existing infrastructure can still be utilized. 5G NR architecture supports both Non-Standalone (NSA) and Standalone (SA) deployment modes. NSA relies on existing networks and existing infrastructure, making it easier to rollout new technologies, while SA architectures are dependent solely on the Next Generation Core (NGC) or 5^{th} Generation Core that operates on 5G specifications [46]. 5G NR is designed with various features that enable enhanced data rates, massive connectivity of UE and machines with reliable communication, and low latency. It uses OFDM waveform for data transmission, as in LTE, and is equipped with flexible spectrum and numerology, features that were not part of LTE systems. 5G New Radio implements FDD for low-frequency bands and TDD for high-frequency bands. NR also provides dynamic TDD to allocate dynamic slots based on data traffic. For providing higher data rates, 5G NR utilizes Low Density Parity Check (LDPC) coding as opposed to turbo coding and polar coding instead of Turbo Codes and Tail Bitting Convolution Codes (TBCC), which is used in traditional networks. Interworking is another feature of NR systems that supports the coexistence of different Radio Access Technologies (RATs) to maintain the mobility and flexibility of the NR architecture. Enhanced Carrier Aggregation (CA) is used to enable Dual Connectivity (DC) by combining LTE and 5G NR carriers to enhance data rates and throughput [47]. The wide range of 5G network deployment is due to the inclusion of many new features like scalable numerology, flexible spectrum, forward compatibility, and an ultra-lean design. The term 5G simply means the fifth technological generation of cellular networks, while 5G NR refers specifically to the radio access technology (RAT) developed for 5G networks. It's the radio standard for 5G deployments.

2.6.1 Use cases of 5G New Radio

There are three primary use cases specified for the 5G New Radio as the Next Generation Key Performance Indicator (KPI) which are enhanced mobile broadband (eMBB), massive machine type communication (mMTC), and ultra reliable low latency communication

(URLLC). The 5G NR takes advantage of the diverse spectrum to offer unprecedented services and massive deployments. Figure 2.11 shows the services and features offered by the three 5G NR use cases.

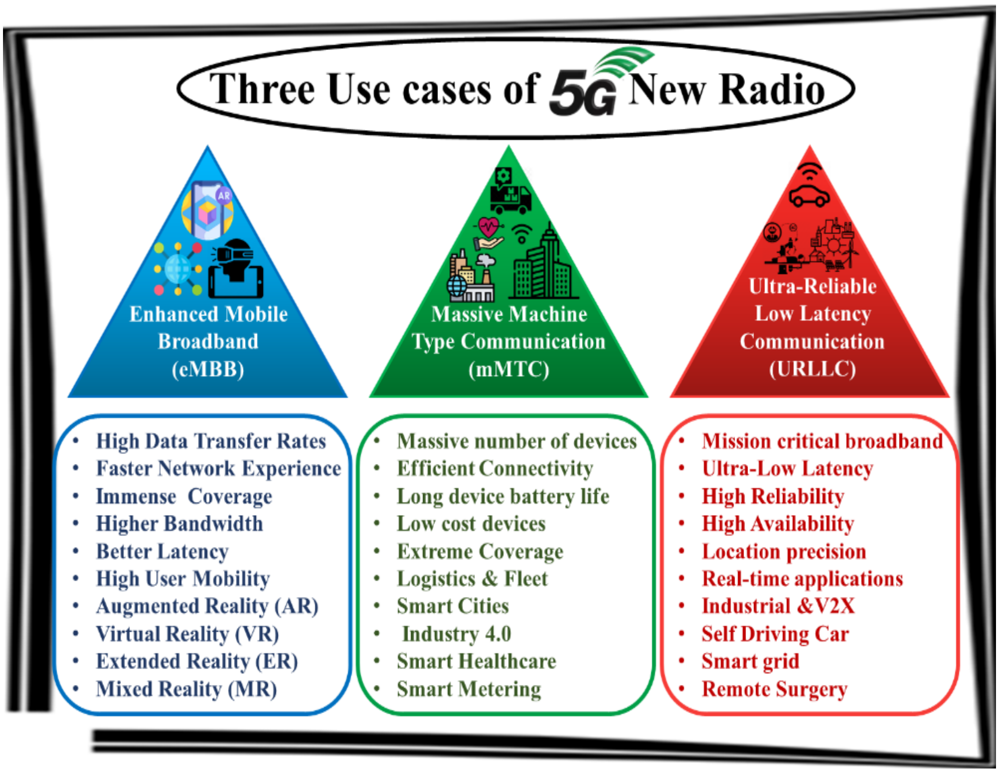

Figure 2.11 Various services and features provided by three use cases of 5G NR.

Various use cases are described below, along with their features and enabling services:

2.6.1.1 Enhanced Mobile Broadband

Enhanced Mobile Broadband is an extension of LTE systems' existing services, and one of the key use cases for 5G new radio. At the moment, 4G has been supporting video resolutions lower than 720pHD and mobility interruptions of 50 ms. While 5G NR systems support 1080p, 2K, 4K, and 8K HD video resolutions with less than 1 ms mobile latency. The eMBB services ensure faster data rates for a better user experience and aim to provide the required QoS that we currently enjoy from fixed broadband Internet services. The eMBB service enables enhanced broadband access in high-density areas such as stadiums, offices, conference centers, and special venues. In moving vehicles or high-speed trains, eMBB provides users with consistent access anywhere, anytime. In highly mobile scenarios and crowded locations, eMBB helps to solve several problems related to connection termination. Various services that are enabled by eMBB include AR, VR, MR, 360◦ video streaming, immersive videoconferencing, real-time virtual interactions, and HD screen display [46]. The 5G eMBB use case supports the following features:

- The peak data rate is 20 Gbps for DL and 10 Gbps for UL.
- The area traffic capacity is 10 Mbits/s/m².
- Increase energy efficiency by a factor of 100 times.
- Provide a peak spectral efficiency of approximately 30b/s/Hz for DL and 15b/s/Hz for UL.
- The user experienced a data rate of 100 Mb/s for DL and 50 Mb/s for UL.
- Supports high mobility of around 500 Kmph and 1000 Kmph.

2.6.1.2 Massive Machine Type Communication

The total number of connected devices is expected to reach up to 50 billion in the future. For communication between this massive number of connected devices, mMTC is presented as one of the primary use cases of 5G NR. The mMTC can be used in a wide range of applications, including fleet management, logistics management, autonomous driving, health monitoring, factory automation, smart metering, surveillance, and security. In mMTC, the data from the input device is automatically interpreted by smart devices and the appropriate response is generated based on the input. The uplink flow of the data packet is generally much larger than the downlink flow, which contains only the request information. The size of the data packets is very small, but the connectivity of multiple devices increases the total traffic volume. Massive IoT (mIoT) is also categorized under mMTC services, which deals with the connection of numerous devices using the Internet to perform autonomous functions [46]. The 5G mMTC use case supports the following features:

- High connection density of 1M devices/Km2.
- Wider coverage.
- High mobility of 10km/h indoors, 30km/h in dense urban areas, and 500km/h in rural areas.

2.6.1.3 Ultra-Reliable Low Latency Communication

The uRLLC is one of the most critical use cases of 5G NR, which brings innovation to the entire infrastructure of the next-generation system. It improves the quality of the network and makes it potentially sufficient to support multiple applications. It allows the traditional limits of existing devices to be extended and their functionalities to be improved. In 4G, the network is associated with lower reliability and higher latency, making it unable to support various advanced applications. In 5G NR, the uRLLC service ensures lower latency and higher system reliability, typically less than 1 ms per packet with 99.999% reliability. The uRLLC services can be enabled in two ways: by replacing existing wired links and by native uRLLC applications. In the case of link replacement, the existing links are replaced with a new uRLLC-enabled link to improve the quality of communication. For example, in Industry 4.0 devices, traditional wired links are replaced by uRLLC-enabled wireless links, such as in cooperative robots. However, the native uRLLC links are not the replaced links. They are fully designed for uRLLC applications [46]. The different requirements that the 5G uRLLC use case focuses on are as follows: User plane latency of up to 1 ms for Urllc, Control plane latency of up to 10-20 ms, Reliability of 99.999% success probability, Mobility interruption time less than 1 ms.

2.6.2 Network Architecture for 5G

Figure 2.12 shows a general 5G Cellular Network Architecture.

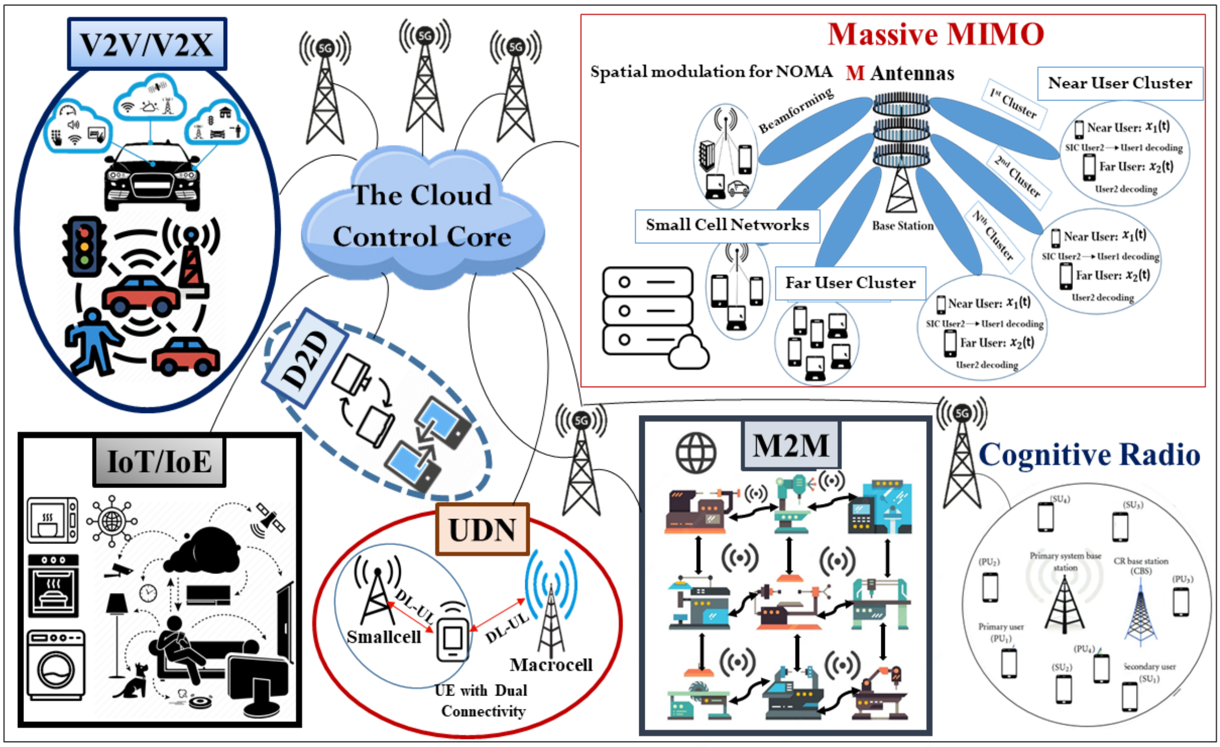

Figure 2.12 A general 5G Cellular Network Architecture.

The general 5G network architecture consists of various essential technologies such as D2D, Non Orthogonal Multiple Access (NOMA), Ultra Dense Networks (UDN), Software Composition Analysis (SCA), MIMO, Massive MIMO, and Cognitive Radio (CR). These technologies will focus on meeting all the requirements of 5G. UDN helps handle the ultra-high density of users and increases the capacity of the network. SCA network increases coverage and offloads traffic. MIMO helps to increase the diversity gain to handle the maximum number of users. Massive MIMO is an extension of traditional MIMO systems and helps enable massive connectivity in the network. Cognitive Radio is another useful technology that helps to utilize the available bands in the spectrum by varying different parameters for simultaneous communication.

2.6.3 Beyond 5G with the advent of 6G

As 5G is commercialized around the world, research institutions around the world have started to look beyond 5G and 6G is expected to evolve into green networks that deliver high QoS and energy efficiency. To meet the demands of future applications, significant improvements in mobile networks in the architecture of mobile networks. The anticipated 6G as an unprecedented breakthrough, integrating traditional terrestrial mobile networks with emerging space, air, and undersea networks to provide anytime, anywhere network access. The sixth generation is different from the preceding generations, as it will be characterized by a high degree of heterogeneity in multiple aspects, like network architecture, application types, computing and storage resources, etc. So it has the potential to change the world in all its aspects like our perception of life, lifestyle, and business. This communication technology is all about sixth-sense communication. There are three new 6G service classes: ubiquitous mobile ultra-broadband (uMUB), ultra-high-speed low latency communications (uHSLLC), and ultra-high data density (uHDD) [39]. The rapid development of advanced applications and novel service requirements are the driving force behind the think of utilization of 6G. Figure 2.13 presents the potential six key requirements for future 6G systems.

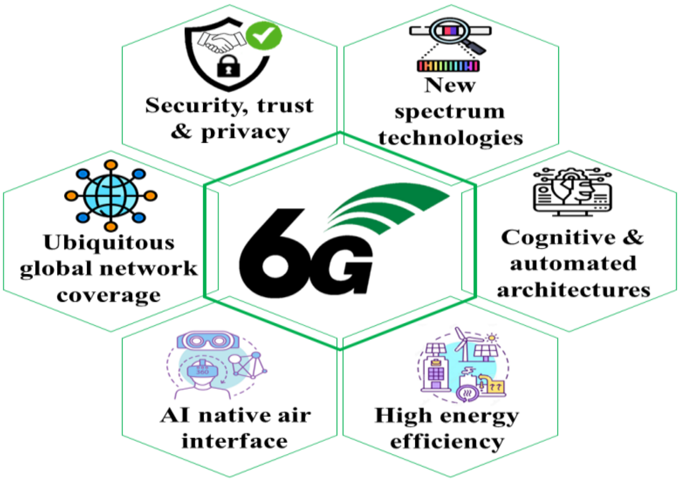

Figure 2.13 The six key requirements for future 6G systems.

A detailed comparison between cellular networks is presented in Table 2.3 [6].

Table 2.3 Summary of some current IoT/M2M mobile cellular technologies.

Specifications	1G	2G	3G	4G	5G	6G
Data rate	2.4 Kbps	64 Kbps	2 Mbps	1 Gbps	20 Gbps	~ 1 Tbps
End-to-end (E2E) latency	20–200 s	10–100 s	1 s	100 ms	10 ms	1 ms
Maximum spectral efficiency	1 bps/ HZ	0.5 bps/ HZ	2.5 bps/Hz	15 bps/Hz	30 bps/Hz	100 bps/Hz
Network mobility support	Up to 15 m/hr	Up to 50 km/hr	Up to 150 km/hr	Up to 350 km/hr	Up to 500 km/hr	Up to 1000 km/hr
Satellite integration	No	No	No	No	No	Fully
Artificial intelligence	No	No	No	No	Partial	Fully
Autonomous vehicle	No	No	No	No	Partial	Fully
XR	No	No	No	No	Partial	Fully
Extreme Reality	No	No	No	No	Partial	Fully
Haptic Communication	No	No	No	No	Partial	Fully
THz communication	No	No	No	No	Very limited	Widely

2.7 Conclusion

More recently, with the rapid evolution of mobile networks, including 4G/5G networks, IoT technology and M2M communications are becoming essential for many of the smart services and applications that are currently flooding the market. This chapter has provided an overview of IoT/M2M communication technologies and 4G/5G mobile networks. First, the general IoT technology and M2M communication system were introduced and their building blocks, architectures and requirements were explained. We then summarised and discussed some IoT/M2M application areas including security and public safety, industrial, transport and logistics, smart grid, smart environment, smart healthcare, robotics and utilities. It also highlighted some of the key IoT/M2M communication technologies, including WPANs, WLANs, LPWANs and MCNs. Finally, we focused on 4G and 5G mobile networks, which are the main technologies used in this thesis. Their evolution, characteristics and architectures were presented.

CHAPTER 3

Deployment and Convergence of IoT/ M2M Communications and MCNs/WSNs

Contents of Chapter 3

3.1 Introduction

In recent years, there has been a growing interest in the convergence of IoT/M2M communications and MCNs/WSNs. This convergence has the potential to create new opportunities for data collection and analysis, leading to more efficient and effective decision-making processes. However, deploying these technologies together poses several challenges, including interoperability, security, scalability, etc. The third chapter of this thesis aims to provide a comprehensive analysis of the deployment and convergence of IoT/M2M communications and MCNs/WSNs, exploring the challenges and opportunities associated with this emerging field. To achieve this aim, this chapter is organized as follows. In the second section, we provide an overview of deployment strategies for IoT/M2M communications and 4G/5G mobile networks, highlighting 4G/5G releases evolutions, 4G-5G interworking architecture, deployment considerations, and challenges that need to be addressed for successful deployment. In the third section, we discuss the various migration strategies from 4G to 5G and beyond. The fourth section is devoted to converging solutions for wireless heterogeneous networks, focusing on types of converged mobile networks, converged WSNs and MCNs, network architecture convergence, air-interface convergence, protocol convergence, M2M in mobile converged networks, and WSN and 5G MCN convergence scenario. In the final section, we conclude the chapter.

3.2 Exploring Deployment Strategies for IoT/M2M Communications and 4G/5G mobile networks

IoT/M2M communications in cellular network deployments involve several technical and operational considerations, such as network architecture, spectrum availability, cost, etc. Several deployment strategies for 5G balance the trade-off between reliability and throughput including standalone 5G, non-standalone 5G, and dual connectivity or hybrid deployment scenarios using both 5G and LTE components, and a variety of combinations of 5G NR, 5GC, LTE Core, and LTE Access (E-UTRA). Each option has its benefits and challenges, and the optimal deployment strategy will depend on factors such as market needs, regulatory requirements, and existing infrastructure. A thorough exploration of deployment strategies will help operators and service providers make informed decisions and effectively deploy 5G mmWave communication systems that meet the evolving needs of the market. A thorough understanding of the various deployment options is essential to make informed decisions and effectively deploy 5G mmWave communication systems that meet the evolving needs of the market.

3.2.1 4G LTE releases Evolutions

Rel-8 LTE is launched in December 2004 as part of 4G LTE project work. It is initially referred to as Evolved Universal Terrestrial Radio Access (E-UTRA) for the radio access part, but it differs significantly from the UMTS system. Some of the important aspects covered were higher data rates, low latency, the introduction of MIMO, etc. OFDMA waveform, FDD/TDD operation, and an all-IP core network were its main features. In Rel-9, femtocells are added in the form of Home eNodeBs (HeNBs), Location Services (LCSs), evolved Multimedia Broadcast/Multicast Services (eMBMS), and Voice over LTE (VoLTE). Rel-10 (2011) was brought as LTE-Advanced, to expand the limits and features of Release 8 and to meet the requirements of the International Mobile Telecommunications Advanced (IMT-Advanced) for the 4G. The LTE-A system enhances LTE systems to support much higher data usage, lower latencies, and better spectral efficiency. Hence, 3GPP's efforts have continued through Rel-11, 12, 13, etc. Rel-11 (2012) includes HetNet, in-device coexistence (IDC), advanced IP interconnection of services, and basic functionality for CoMP transmission and reception. While Rel-12 (2015) was largely completed on time in March 2015. A major improvement has been made to the performance, efficiency, and capabilities of Release 12 compared to Release 10 and Release 11. Among the presented improvements are Interference coordination and management, Dynamic TDD, Frequency separation between macro and small cells, Inter-site carrier aggregation and macrocell-assisted small cells, and Wireless backhaul for small cells. Rel-13 (2016) marked the beginning of LTE Advanced Pro which enhances LTE-A technologies and it includes Licensed-Assisted Aggregation (LAA), LTE enhancements for MTC, Full-Dimension MIMO (FD-MIMO), and Indoor positioning projects. Rel-14 (2017) and beyond saw further enhancements to the specifications [48]. There are slight differences in the dates in Figure 3.1 due to commercial deployment dates.

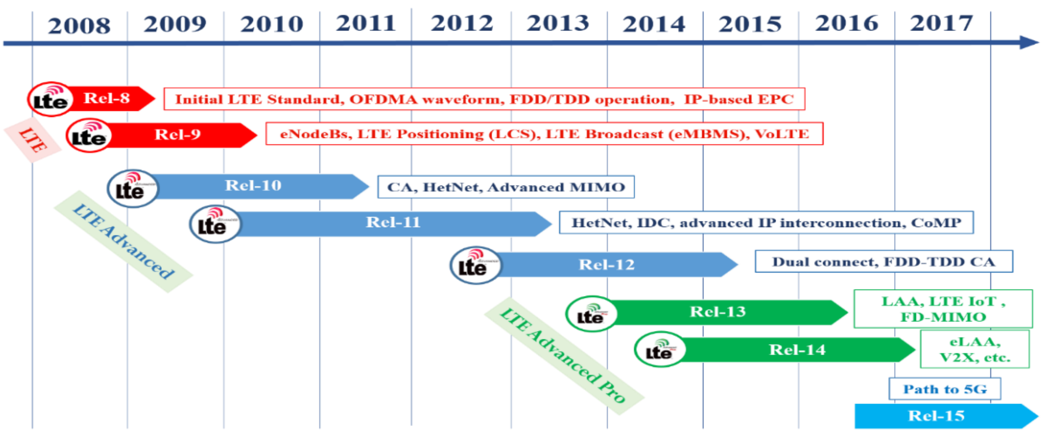

Figure 3.1 4G LTE releases evolutions.

3.2.1.1 LTE Enhancements for IoT/M2M

LTE is a key component of an IoT/M2M future that places new requirements on connectivity. By offering spectral efficiency, longevity, and scalability, LTE is becoming more viable for IoT/ M2M applications. LTE MTC specifically addresses the dramatic increase in the number of devices expected to be deployed for IoT/M2M applications. The introduction and development of LTE MTC chipsets and modules represent a significant step for the cellular IoT/ M2M market. The widespread accessibility of LTE cellular networks provides a significant edge over other network options. Improved support for low-cost, energy-efficient IoT/M2M devices will be facilitated by LTE's expansion into diverse use cases through diminished RF bandwidth. Anticipated applications for LTE IoT/M2M consist of metering, environmental and industrial monitoring, object location tracking, e-health, wearables, and sensor technology. Furthermore, reduced latency will empower the addition of new applications and services involving traffic safety management, critical infrastructure control, industrial process regulation, VoLTE, and video over LTE (ViLTE). These services are becoming increasingly important for IoT/M2M applications that require real-time communication capabilities. LTE radio access network enhancements for IoT/ M2M communications address the issues of overload control, network support for IoT and M2M devices, device cost reduction, power saving for ultra-long battery life, signaling overhead, and coverage enhancement [49]. Some of these key enhancements are as follows:

- **Device Power Saving:** IoT/M2M devices often have limited battery life and may need to operate for extended periods without being recharged. To address this, LTE has introduced several power-saving modes such as PSM and eDRX. These modes allow devices to conserve power by reducing the frequency of network interactions when they are not actively transmitting or receiving data.
- **Mobility management:** IoT/M2M devices may need to move between different coverage areas while maintaining their network connection. LTE has introduced several features such as eDRX and Radio Resource Control (RRC) idle mode signaling to support seamless handovers between different cells.
- **Lower Cost:** IoT/M2M applications often require low-cost devices that can be deployed in large numbers. To address this, LTE has introduced several optimizations such as reduced complexity and lower data rates that enable low-cost devices to be used in IoT/M2M applications.

- **Extended Coverage:** LTE has introduced several enhancements to extend coverage and improve connectivity in these areas. One such enhancement is the use of CA which allows multiple LTE carriers to be combined to provide higher data rates and better coverage. This is particularly useful in areas where there may be limited spectrum available for LTE. Another enhancement is the use of small cells, which are low-power base stations that can be deployed in areas where traditional macrocells may not be practical. They can provide better coverage and capacity in indoor and outdoor environments, as well as in rural or remote areas. LTE has also been optimized for satellite communications which can provide connectivity in areas where terrestrial networks are not available or practical.

These enhancements have made LTE a more suitable technology for IoT/M2M communication, enabling a wide range of applications.

3.2.2 Leading 3GPP evolution of 5G

The 3GPP Releases for 5G provide different specifications for the implementation of 5G NR. Release 15 of 2017 provides the initial specifications for 5G NR. It mainly focuses on Non-Standalone deployments, where LTE EPC is the core network. Release 15's main drop of 2018 introduces Standalone deployments that are not dependent on LTE and operate solely on NGC as their core network. The late release 15 outlines the modified architecture of 5G NR, focusing on backward compatibility and dual connectivity functionalities. Release 15 of 3GPP, also known as phase 1 of the 5G NR system, covers a wide range of topics, including 5G system deployment scenarios NSA and SA (see Figure 3.2 that highlights the differences between NSA and SA deployments), numerology, waveform, synchronization procedures, and modulation. The technical specifications defined in Release 15 are regularly adjusted in new Releases to meet the needs of different applications and use cases [46]. In addition, Release 16 is referred to as phase 2 of 5G NR, which includes the extensions of the existing release 15 features and enables full support for Vehicle to Everything (V2X) connectivity, and IIoT for Industry 4.0. This includes improvements to URLLC for Time Specific Communication (TSC), support for Non-Public Networks (NPNs), operations in unlicensed spectrum, and deployment enhancements via Integrated Access & Backhaul (IAB) operation mainly for mmWave networks. According to 3GPP reports, release 17 will include features such as Non-Terrestrial Networking (NTN), Extended Reality (XR), edge computing in 5G core, network slicing, network automation, enhanced V2X services, and radio access network (RAN) slicing [50]. While release 18, the fourth standard for 5G, is the first to be dubbed "5G Advanced", indicating that it will significantly advance 5G in the areas of artificial intelligence/machine learning and extended reality, which are the most prominent rel-18 projects and the top category for defining "Advanced" aspects, in contrast to Release 16 and 17 which mainly extended 5G to new industries. It includes advanced downlink/uplink MIMO, enhanced mobility, mobile integrated IAB and smart repeaters, evolved duplexing, green networks, drones, and enhanced satellites and multicast enhancements. The current 5G systems are the basis for the new technologies beyond the 5G/6G network. Figure 3.3 presents 5G releases evolutions.

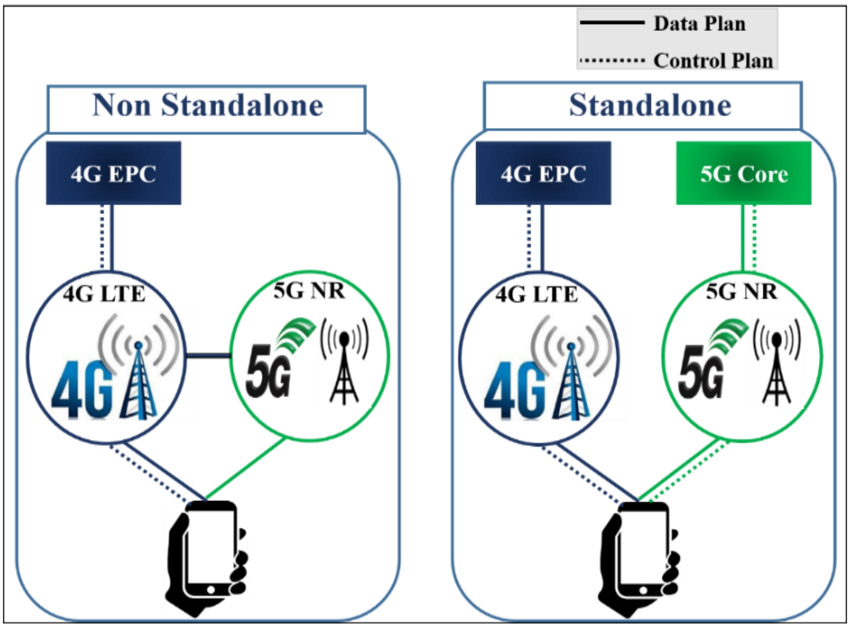

Figure 3.2 Non-Standalone and standalone deployment.

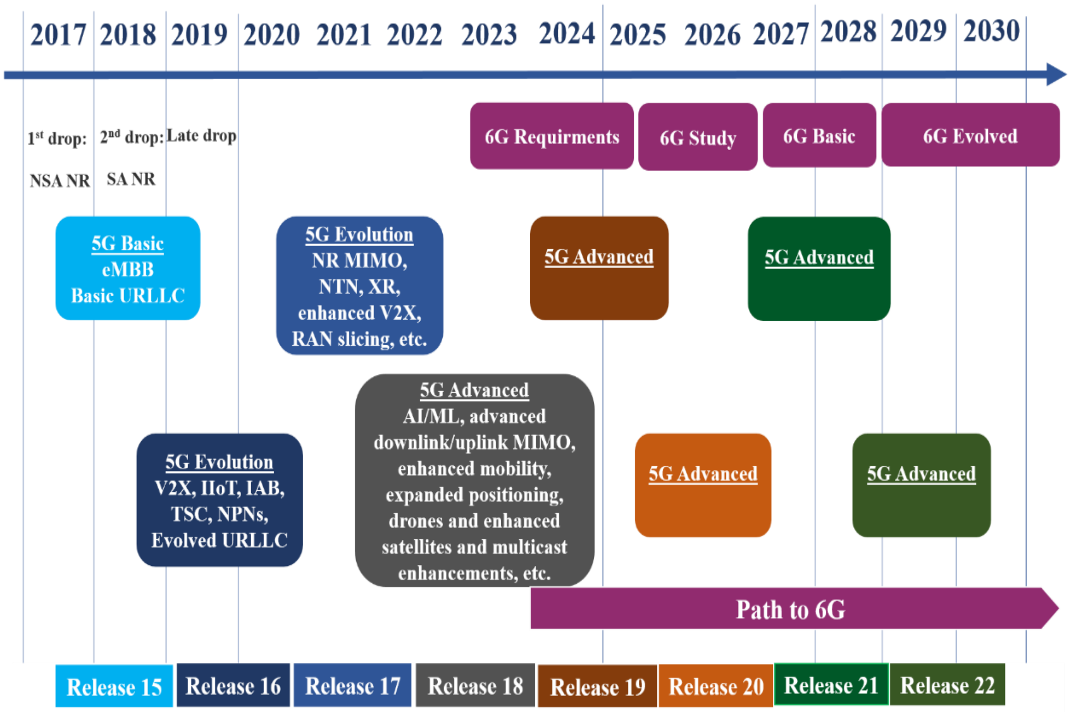

Figure 3.3 5G releases evolutions.

3.2.3 4G-5G interworking architecture

The 4G-5G interworking architecture is a set of standards and protocols that enable the interworking of 4G and 5G mobile cellular networks. It enables the two networks to communicate with each other, allowing users to switch seamlessly between the two networks. The architecture also enables the development of new applications and services that can be used across both networks. The benefits of 4G-5G interworking include increased network coverage and capacity, improved user experience, and the ability to develop new applications and services. Figure 3.4 provides a high-level overview of the interworking between the 4G and 5G networks, with key network functions (NFs) interworking to provide seamless services to mobile subscribers. All the NFs on the left (in blue) are part of a 4G core and the NFs on the right (in green) are part of a 5G core.

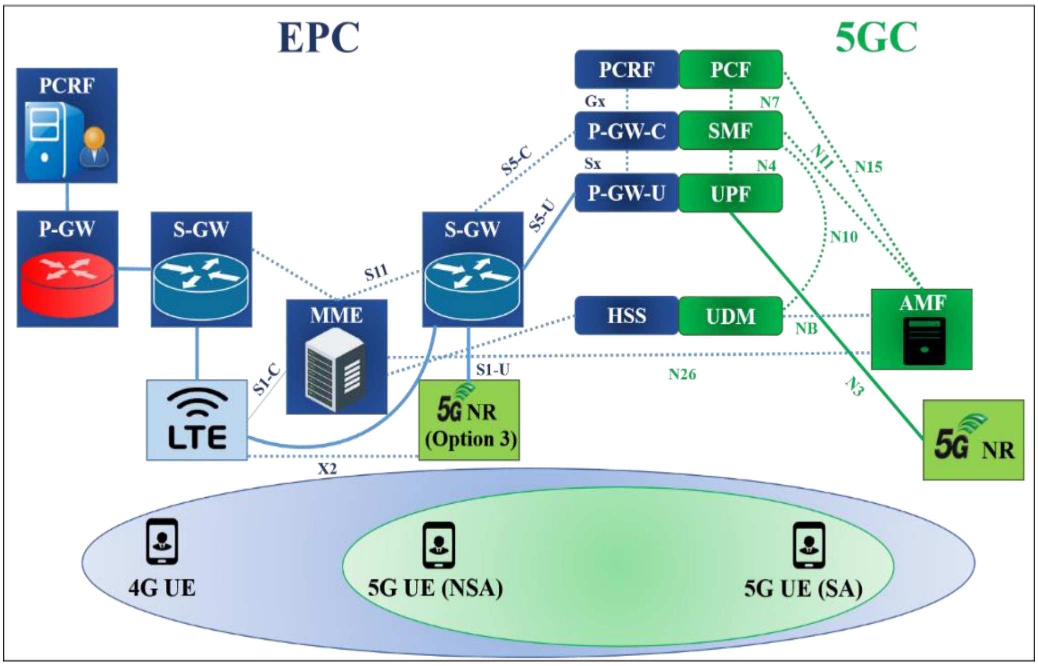

Figure 3.4 4G-5G interworking architecture.

We have simplified the 4G-5G interworking architecture with a top-down explanation to make it easier to understand, as detailed below [51].

- 5G technology is not just about high bandwidth, it's also about providing differentiated services and Quality of Experience (QoE). In 5G, subscriber services are managed by Policy Control Function (PCF), so we need a seamless user experience by managing, notifying, and charging for 5G network usage.
- The network architecture of the 5G system is divided into control and user plane separation because they can scale independently. 5G subscribers are terminated in the Session

Management Function (SMF). SMF manages subscribers from the time they connect to the network until they disconnect or leave the network.

- 5G provides much higher bandwidth to subscribers and supports low latency services, so User Plane Functions (UPF) are typically deployed at the edge. In Mobile Edge Computing (MEC), UPF and low latency applications are typically deployed at the edge.
- When users power on their devices, they go through a signaling phase in which they are authenticated with the correct credentials. In 4G, this is handled by MME, and in 5G this is handled by the Access Management Function (AMF). To ensure interworking between 4G and 5G, the N26 interface is used.
- Subscriber data for 4G is stored in the HSS, while for 5G, it is stored in the Universal Data Management (UDM). To ensure successful interworking between HSS and UDM, subscriber information must be matched between 4G and 5G.
- The greatest change with the 5G technology is at the edge. The NR provides capability, allowing users to utilize the 5G network. In addition, existing 3G and 4G radio stations must be taken into consideration to limit interference and provide handover mechanisms, so that the user can access any service available based on their device capabilities and subscription. 5G NSA provides the ability to connect 5G NR sites to existing 4G Core (4GC). 5G SA only allows 5G New Radio to connect to 5G Core.
- When 4G was deployed, the virtualization technology was not mature enough, so it was initially launched on standalone physical devices and then transitioned into standardized ETSI Management and Orchestration (MANO) based Virtualized Network Function (VNF) architecture on private/public cloud. On the other hand, 5G network functions are deployed as micro-services on cloud-native, container-based clusters e.g. Kubernetes. To summarize, there is a distinct difference between the 4G and 5G network functions and the underlying cloud technologies.

3.2.4 5G Deployment Considerations

Deployment of 5G technology requires careful consideration of several factors, including:

3.2.4.1 Optimal slice selection during UE mobility towards 4G and NSA

Network slicing is a crucial solution for operators who aim to reduce costs while offering differentiated QoS to different classes of subscribers. After deployment, 5G Standalone networks will coexist with Non-Standalone and 4G networks for a considerable period. This hybrid scenario presents significant mobility challenges for subscribers, particularly in terms of selecting the right slice or node for seamless connectivity in overlapping coverage regions for NSA, SA, and 4G networks [51].

3.2.4.2 Roaming partner N26 interface

Operators deploying 5G services will need to address the disadvantages or limitations of the following issue in roaming partner networks that may not be fully compatible with home network capabilities (e.g. certain roaming partners may not support the N26 interface), impacting seamless service continuity and mobility between the 5G home network and a roaming network [51].

3.2.4.3 UE APN Mapping

Operators offering 5G services will perform an incremental firmware upgrade to their customers' handsets, changing the subscription from 4G to NSA to 5G. This leads to a complex scenario where the end user may use multiple Access Point Names (APN), i.e. 5G APN/4G APN while connecting to the 4G network and vice versa. This also requires enhancement of the existing node selection algorithm in both 4G and 5G networks [51].

3.2.5 4G-5G Dual Connectivity

The communication for 5G and beyond will be driven by the need to meet a diverse set of challenging 5G requirements, including providing very high throughput to meet the growing demand for wireless data. The mmWave frequency bands have been identified as potential enablers of ultra-high throughput. However, the use of frequencies above 6 GHz presents several challenges, such as high isotropic path loss, moisture and foliage attenuation, limited range, and blockage from common objects and infrastructure. Although mmWave links may provide high throughput, the quality of these links may vary due to factors such as path loss, deafness, and blockage. In contrast, the widely deployed LTE system provides reliable coverage over a larger distance. The 5G-NR requires not only a new radio access network but also a new core network, and the 3GPP has defined a 5G core network and 5G radio access. Several deployment options consider different combinations of 5G NR, 5GC, LTE core, and LTE access. Not all options will be practical, and some configurations involve the use of only one radio access technology in a standalone scenario, while others involve the use of both 5G-NR and LTE radio cells in a non-standalone scenario through dual connectivity. The core network in such a dual connectivity scenario can be either the 5GC or the LTE evolved packet core [52].

Figure 3.5 and Table 3. 1 show that E-UTRAN Dual Connectivity (EN-DC) corresponds to option 3 of the deployment scenario. Similarly, NG-RAN E-UTRAN-NR Dual Connectivity (NGEN-DC) corresponds to option 4, while NR-E-UTRAN Dual Connectivity (NE-DC) corresponds to option 7 of the deployment possibilities. Given the popularity and widespread deployment of LTE networks, it is natural for the initial 5G mobile network to be built in NSA mode based on the fundamentals of EN-DC.

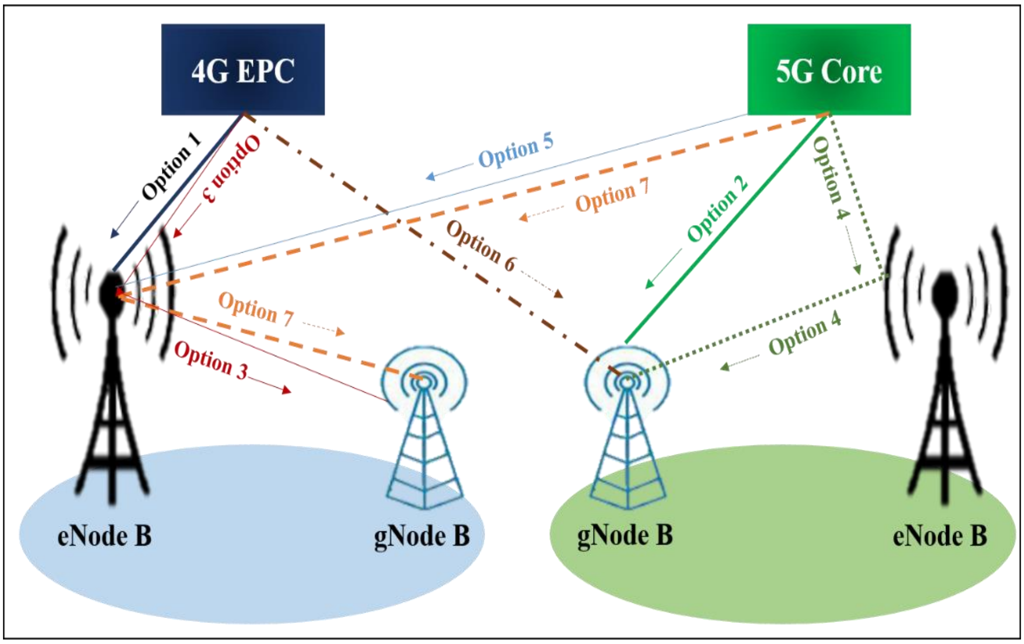

Figure 3.5 Deployment options.

Table 3. 1 Deployment options.

Option	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
Core	EPC	5GC	EPC	5GC	5GC	EPC	5GC
MN	eNB	gNB	eNB	gNB	eNB	gNB	eNB
SN			gNB	eNB			gNB

3.2.5.1 4G-5G Deployment Flexibility

Deployment flexibility refers to the ability of a wireless network to adapt to changing requirements and conditions. The deployment flexibility of a 4G-5G dual connectivity system enables it to be deployed in various scenarios and environments providing a seamless and efficient user experience. With deployment flexibility, operators can quickly respond to changing demands, optimize network performance, and offer reliable and cost-effective services to users.

The 3GPP defines Multi-Radio Dual Connectivity (MR-DC), which allows UEs to use the resources of two different nodes (eNB or gNB) connected by non-ideal backhaul using the Xx interface. In MR-DC, one node provides NR access, while the other can provide either NR access or E-UTRA. One of the nodes acts as the Master Node (MN) and is connected to the core via the S interface. The other is the Secondary Node (SN). When the eNB connected to the EPC acts as the MN, the MR-DC is referred to as EN-DC. In EN-DC, the gNB may or may not connect to the EPC. Given the widespread deployment of LTE and the high capital cost of 5GC and 5G-NR, EN-DC appears to be the choice of mobile operators for initial 5G demonstrations and subscriptions. In the future, the 5G core is expected to be connected to a gNB or enhanced eNB that can act as an MN. There are three configurations for such MR-DCs defined by 3GPP [52]:

- NGEN-DC where the enhanced eNB acts as an MN and is connected to the 5GC. The gNB acts as an SN.
- NE-DC where the gNB connected to 5GC acts as an MN while the enhanced eNB acts as an SN.
- NR-DC in which the NR-NR dual connectivity is supported such that both MN and SN are gNBs only.

3.2.6 Challenges for the deployment of IoT/M2M communications and 4G/5G networks

While IoT/M2M communications and 4G/5G mobile networks offer many benefits, several challenges need to be addressed for their successful deployment. The challenges of their deployment are complex, with several obstacles that need to be overcome to ensure a successful deployment. One of the main challenges is to ensure that networks are secure and protected from hackers and other types of malicious attacks. IoT/M2M devices may be vulnerable to cyber-attacks, which can compromise their functionality and data security. This is particularly important in applications such as healthcare, where patient data must be protected at all times. 4G/5G networks also face security challenges such as network slicing vulnerabilities and increased attack surface due to virtualization. Another challenge is to ensure that the networks are reliable and can operate efficiently under a wide range of conditions. In addition, there can be challenges associated with configuring and managing massive devices that make up the network, as well as ensuring that the network can scale to meet the needs of the users who rely on it, ensuring compatibility with existing systems and adapting to heterogeneous networks.

Other challenges include managing the power consumption of devices, managing data storage and access, and ensuring that devices can operate in a variety of different environments and conditions. Furthermore, the cost of deploying and maintaining IoT/M2M networks and 4G/5G mobile networks is another key challenge. While these technologies offer many benefits, they also require significant investment in infrastructure, hardware, and software. This can be a barrier to entry for smaller companies or organizations that may not have the resources to invest in these technologies. Overall, these challenges need to be addressed for IoT/M2M communications and 4G/5G networks to reach their full potential. This will require collaboration between industry stakeholders, governments, and regulatory bodies to ensure that these technologies are deployed in a secure, interoperable, and cost-effective manner.

3.3 Migration Strategies from 4G to 5G and Beyond

To smoothly transition to 5G, network operators must offer a variety of deployment options that maximize both service and monetary benefits during this migration period. According to [53], important considerations when selecting a migration path may include time to market, capital cost, operating cost, future compatibility, business trends, and current network conditions/architecture. To simplify deployment and control capital costs, it would be reasonable for LTE operators to deploy 5G NR at the existing LTE sites. However, the expected mmWaves frequencies of SA NR are much higher than current LTE frequencies, leading to higher path loss and spotty coverage. If the operation is restricted to the same site, it would be challenging for the operators to maintain the required level of quality (at least equal to that of LTE). Additionally, NSA is not expected to have SA capabilities for fine QoS treatment and network slicing [54].

3.3.1 Migrating from 4G to 5G

Migrating from 4G to 5G poses a significant challenge for many operators since it disrupts many areas, and each of these areas has to be planned and transitioned carefully to be able to reap the potentials that the 5G network provides. The 5G architecture is very different from the 4G architecture and requires readiness on multiple aspects listed below [51]:

- **Data center and infrastructure readiness:** a distributed data center approach is necessary to meet the demands of 5G. This includes several central data centers hosting many core and signaling network functions as well as multiple regional data centers hosting Multi-access MEC nodes with a few hosted applications. Additionally, there may be several smaller data centers (e.g. Far Edge centers) hosting distributed RAN nodes.

- **Radio network readiness:** the 5G radio network must be virtualized and segregated for optimal readiness. This network contains both distributed and central components.
- **IP transport readiness:** IP transport planning should be taken into account when considering the distributed data centers, virtualized RAN with multiple components representing the Base Band Units (BBU), and the different types of haul (backhaul, fronthaul, and midhaul) that need to be planned and designed. Furthermore, advanced features such as segment routing and transport slicing may be necessary when dealing with multiple slices with different QoS requirements.
- **Core network readiness:** 5G core requires a different approach compared to previous generations such as 4G. This is due to the majority of network elements being cloud-based and featuring Service-Based Interfaces (SBI). It is therefore necessary to update messaging infrastructure to support this cloud-native solution.
- **Automation readiness:** Considering the virtualization of all the network functions in 5G, including RAN, and the complex distributed data center approach, it is critical to have automation readiness for deploying various network functions and for their monitoring, management, upgrading, and testing.

Here are some strategies organizations can consider when migrating from 4G to 5G:

3.3.1.1 Transitioning from 4G to 5G

As technology continues to evolve, 4G networks have begun to be replaced by 5G networks. There can be several intermediate steps in the transition from 4G (Option 1) to 5G (Option 2). The following are some of the most popular transitions adapted by most service providers [51]:

- Option1LT E → Option7xNSA → Option2SA
- Option1LT E → Option3xNSA → Option2SA
- Option1LT E → Option4NSA → Option2SA

Figure 3.6 shows the transition from 4G to 5G in which the radio network is first upgraded, wherein NR gNB is connected to the current 4G core to provide higher speeds for 5G capable UEs. The core network is then upgraded to connect the gNB to the 5G core and the 4G coverage is slowly phased out.

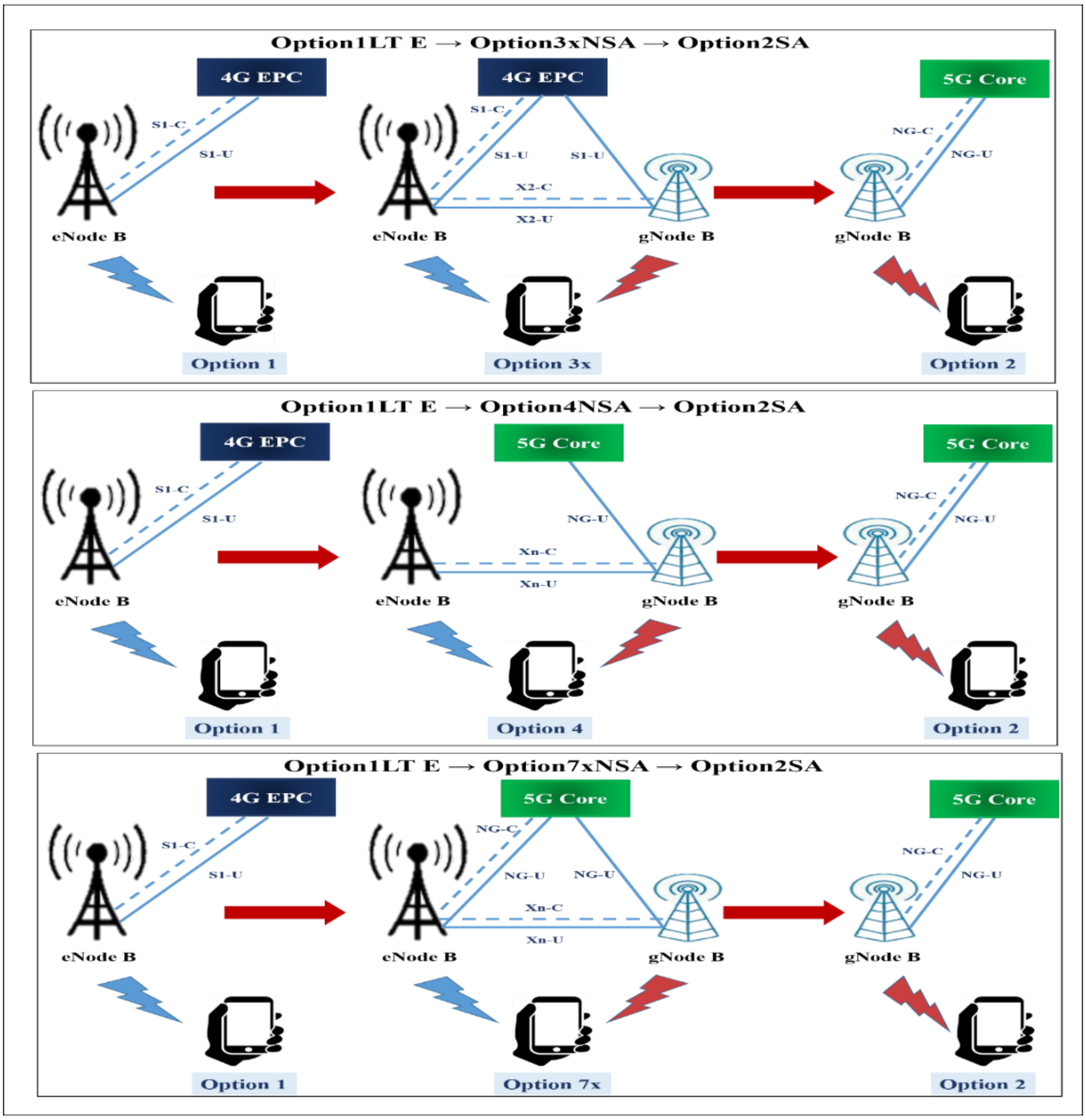

Figure 3.6 4G to 5G Migration Path.

3.3.1.2 5G Readiness Options

There are many approaches to 4G-5G interworking:

- **Non-disruptive approach:** In this approach adopted by a major operator in the North American region, the transition from 4G to 5G is planned in a manner that ensures the existing 4G infrastructure is not interrupted immediately. Instead, 5G radio and core network nodes are added alongside 4G as standalone units providing 5G coverage and service in specific regions, resulting in 5G service provided quickly to end-users, limited to enhanced Mobile Broadband use case. To provide complex use cases, such as support for multiple slices and implementation of MEC use cases, a plan is required for the distributed data center, IP core enhancements, automation readiness, and virtualized and distributed radio network readiness in such a network [51].

- **Greenfield approach:** Another approach to deploying 4G that several major greenfield operators in the Asia Pacific region have adopted involves considering the readiness of data centers, IP backbones, and automation for 5G as part of the planning process. During the deployment of 4G, all network components, including radio network elements, are virtualized through automated deployment and distributed across different data centers. Such operators have an easier and more efficient transition to 5G, as the infrastructure is in place to handle multiple slices, MEC use cases, and other 5G use cases. Additionally, in such scenarios, monitoring, troubleshooting, and life cycle management systems can be developed more quickly [51].

3.3.1.3 UE Mobility Network Selection from 4G to 5G

5G core architecture and slice-based design offer a choice of core network elements and application mapping to user-subscribed slices during Packet Data Unit (PDU) establishment to ensure the anticipated QoE for the PDU sessions. As a result, the network elements are efficiently utilized and planned based on the application types. When UE performs an initial attach to the EPC in the 4G network, the slicing concept is unknown by UE and MME, resulting in the inability to select the appropriate network and slice [51]. This can prevent a 5G capable UE to seamlessly handover from 4G to 5G network as shown in figure 3.7 on the left. While a specific mechanism to select the proper network (e.g.EPC or 5GC) and the correct network slice based on the UE's slice subscription and application mapping is required. MME needs to select a proper network slice when the 5G UE is in a 4G network coverage area, as shown in the right of Figure 3.7.

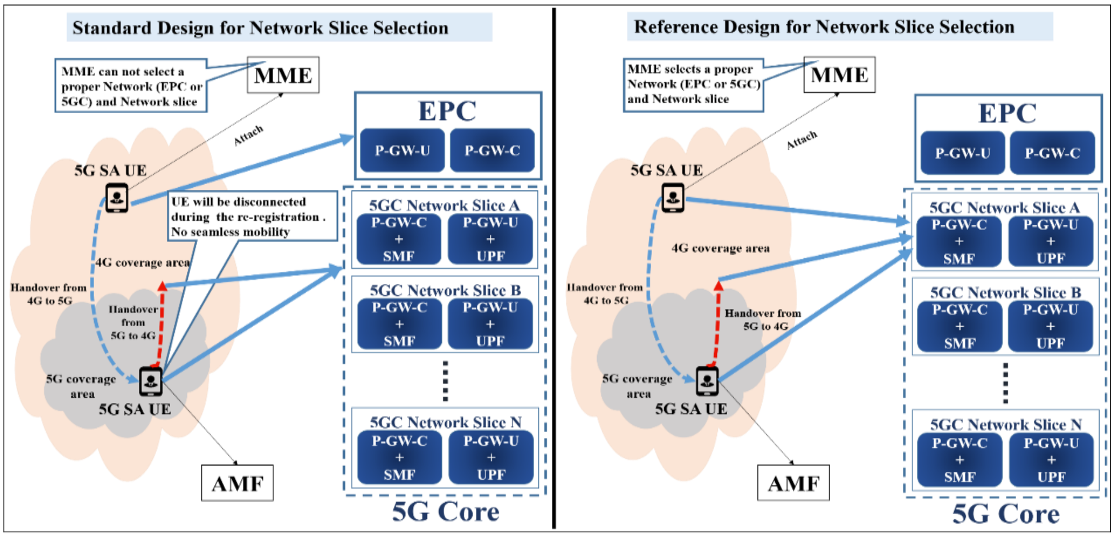

Figure 3.7 Standard and Reference Designs for Network Slice Selection.

3.3.1.4 5G NSA UE Traffic Offloading

In the deployment of 5GC, both 4G UE and 5G (NSA) UE are served by the EPC. However, since the 5GC will have 5GC SMF/ UPF in addition to EPC PGW features like PGW-C and PGW-U, it's crucial to design the 5GC to allow operators to flexibly plan NSA UE traffic offloading according to the capacity and load status on the EPC node [51]. Standardly, 5G NSA Authorized traffic is routed to the 4G EPC core in an NSA deployment, as indicated in Figure 3.8 on the left. Meanwhile, the right side of Figure 3.8 depicts an optimal 5GC design that considers the offloading capability of 5G NSA UE traffic.

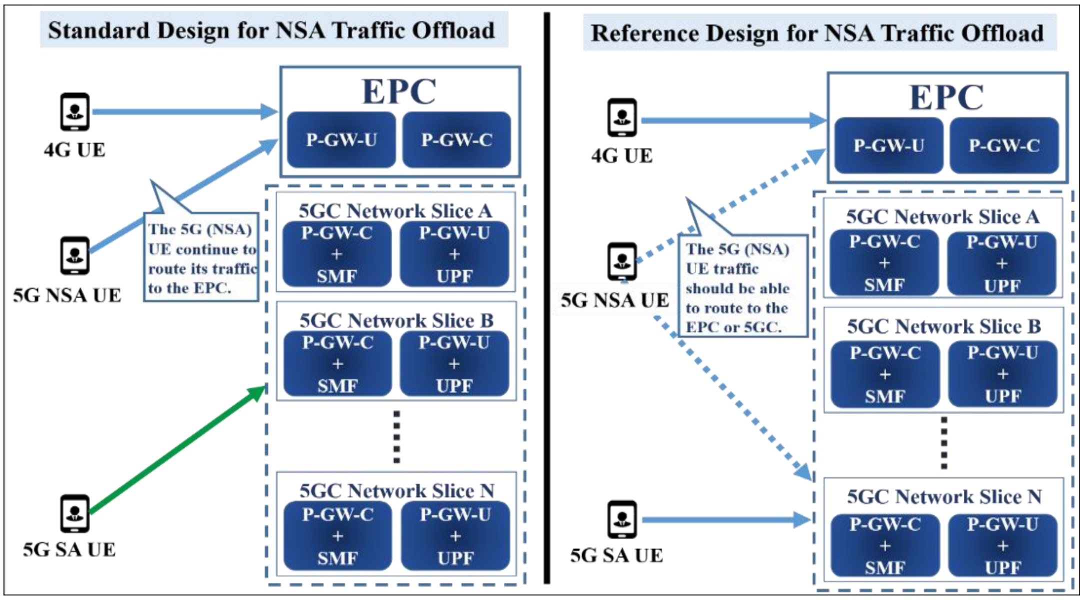

Figure 3.8 5G NSA UE Traffic Offloading.

3.3.1.5 Overlapping NSA and SA Coverage

There may be cases where a single gNB is used for both 5G NSA and 5G SA deployments, resulting in overlapping coverage areas. This can lead to situations where a single gNB may be connected to both the 4G core and 5G core to accommodate secondary RAT additions for NSA users, as well as handovers for 5G SA users. When considering cases where there may be overlapping instances of NSA and 5G SA subscriptions, it is important to plan and prioritize one over the other. Efficiency considerations should also factor in any fallback upon failure and the specific types of services that are being utilized by the user [51].

3.3.1.6 UE capability subscription and APN mapping

UE capability subscription and APN mapping can be implemented as a solution to the scenarios outlined in sections 3.3.6.1, 3.3.6.2, and 3.3.6.3. This solution introduces new APNs for 5G users for data usage, which are distinct from the APNs used by 4G users for the same service. With the introduction of 5G SA nodes, changes to the logic on MME/DNS will be necessary to select the correct node from either the 4G network (i.e. SGW & PGW) or 5G (i.e. PGW+SMF combo node) for a 5G SA capable UE attempting to establish a connection with an appropriate APN in 4G. This solution allows the UE to seamlessly move from the 4G network to the 5G network by selecting the right 5G PGW/SMF node. As the UE moves from 4G to 5G coverage areas and vice versa, the new network/node selection algorithm should take into account UE capability (4G / 5G NSA / 5G SA), UE subscription, APN selected by the UE (all possible APNs including default) [51].

3.3.2 From 5G SA to 6G

On a high level, the technical points of difference between legacy LTE and SA 5G can be majorly considered as Scalable numerology and multiple Sub-Carrier Spacing (SCS), adaptive bandwidth parts, the introduction of the Service Data Adaptation Protocol (SDAP) layer and slot based scheduling.

As 5G SA supports multiple numerologies based on exponentially scalable SCS $\Delta f = 2^{\mu} * 15$ kHz with μ={0,1,3,4} [55], while LTE only supports 15 kHz SCS. From a radio perspective, 5G NR provides a new access layer sublayer in the Service Data Adaptation Protocol Sublayer (PDCP) [56] that manages the radio bearer concept, which is missing in LTE. It also allows UEs to be configured with a carrier Bandwidth Part (BWP) to indicate their working bandwidth within the cell bandwidth; multiple Carrier BWPs can be set up for a UE, but only one can be active within a given component carrier. The creation of a slot in the basic transmission unit, as opposed to subframe-based scheduling in LTE, opens up a scheduling unit much shorter than 0.5 ms. These features add enhancements to 5G SA that make it much more flexible than existing LTE. These flexibilities would be very important in moving Beyond 5G communications (B5G) and 6G communications, which are already being explored. As the Industrial IoT gains momentum, the requirements for B5G and 6G are much more stringent than for legacy systems - in particular, the need for 99.9999% reliability. To achieve this level of reliability, B5G systems will require greater flexibility. One proposed technology to facilitate this required flexibility is artificial intelligence; however, as there are multiple small cells in 5G, the data and training sets for AI modeling will be an immense overhead. This is where dual connectivity could be explored, helping to overcome the challenge of distributing the AI models and inference on those models across multiple sites [52].

3.4 Converging solutions for Wireless heterogeneous networks

Wireless heterogeneity in converged networks has been proposed as a key approach to 4G/5G and beyond communication goals. Multiple wireless access technologies, such as Wi-Fi, Bluetooth, cellular networks, and optical wireless networks, are integrated into convergence [7], [57]. Each of these technologies has its unique characteristics such as range, bandwidth, power consumption, and security features. Managing wireless heterogeneity in converged networks is a challenging task due to the complexity of the network architecture and the variety of wireless technologies involved. It requires careful planning and coordination to ensure seamless integration and optimal performance of all components, taking into account factors such as performance, security, interoperability, and cost-effectiveness to ensure the successful deployment and operation of these complex networks. One approach to managing wireless heterogeneity is the use of SDN and NFV. SDN enables centralized control and management of the network, while NFV enables the virtualization of network functions such as routing, switching, security, etc. This approach provides greater flexibility and scalability in managing heterogeneous networks. Using cognitive radio technology, converged mobile networks can significantly improve IoT/M2M communications by sharing unlicensed spectrum bands in cellular networks, such as LTE-A. Therefore, converged mobile networks will become a popular research topic in the future, as mobile users generally accept mobile multimedia content services. IoT/M2M communications using WSNs have been identified as a promising converging solution for improving overall performance in 4G/5G systems and beyond.

3.4.1 Four main types of Converged Mobile Networks

The convergence of heterogeneous networks enhances M2M communication and IoT technology. Converged networks can be divided into four categories: device convergence, protocol convergence, service convergence, and full convergence of any user’s devices, communication protocols, and network services. Device convergence was the first step, based on the integration of multiple communication interfaces within a single device. This type of convergence involves the simultaneous use of different types of separate communication sessions by one device. For example, a user can use an LTE-A network for voice communication while simultaneously transferring data from a smartphone to a laptop via Bluetooth. However, in this convergence, the user controls each separate communication session. In the second type, that is protocol convergence, different network protocols (Bluetooth, Wi-Fi, LTE, etc.) are used within a single heterogeneous network. As an example of this scenario, consider an LTE-A network with Wi-Fi access points that supports provider-controlled soft handover between cellular and wireless networks. The third type is service convergence, where the goal is continuous mobile content service, regardless of device change and network handover. Full mobile convergence is a type in which the other three types are integrated [7] and can be expressed as the equation (3.1).

$$Full_{Convergence} = Device_{Convergence} + Protocol_{Convergence} + Service_{Convergence} \quad (3.1)$$

Achieving comprehensive full convergence presents a promising avenue for future research due to its technical complexity and potential to deliver exceptional quality of service for users. To attain complete convergence within mobile networks, numerous technical challenges must be overcome. This includes the development of innovative data transmission methods across wireless channels, such as energy-efficient modulation and coding techniques, enhanced spectrum sensing, and radio resource management algorithms. New wireless transmission protocols must be created for each network (LTE-A, Wi-Fi, M2M, etc.) to ensure seamless interoperability. The current leading air interfaces, founded on OFDMA and MIMO antennas, need further improvement to meet the requirements of future unified networks. A single signaling layer is also necessary for the entire converged network, ensuring consistent quality of experience even for users with high mobility [7].

The different types of convergence and their characteristics are summarised in Table 3.2.

Table 3.2 Comparison of four different types of convergence.

Type of convergence	Objectives	Subjects	Features	Stage of development
Device Convergence	Integration of multiple communication interfaces into a single-end device	Users' devices and their interfaces	Simultaneous holding of separate user-controlled communication sessions by a single device	Completely achieved
Protocol Convergence	The convergence of different communication protocols within a logical network	Communication protocols	Soft handover between different communication protocols without session interruption	Completely achieved
Service Convergence	Convergence of network services in a heterogeneous mobile network	Network services and users' devices	Continuous service is maintained regardless of the user device and connection type Independence	Almost completely achieved

Full Convergence	The full convergence of the user devices, the communication protocols, and the network services.	Network services and users' infrastructures	Independence from user devices, communication networks, and service providers	Partially achieved

3.4.2 Converged Wireless Sensor Networks and Mobile Cellular Networks

In wireless sensor networks, the smart mobile user equipment gateway moves into the coverage area of the sensor nodes, broadcasts beacon packets to these nodes, and provides backhaul access to these WSN nodes. Mobile Cellular Networks can send the detected WSN data directly to a central data center [58]. The main disadvantages of WSNs are less robustness to mobility, small coverage, and weak terminals. MCNs, on the other hand, provide more layer control, longer network lifetime, and quality of service for WSN applications and have the advantages of reliable mobility, wide coverage, and powerful user terminals, but are expensive and difficult to deploy and manage [10]. The convergence of MCNs and WSNs can be mutually beneficial: MCNs provide a higher level of layer control and optimization to increase network lifetime and WSN performance, and to provide better QoS when using WSNs; WSNs can act as cognitive and intelligent enablers of MCNs; wireless services and increasingly data-centric applications are enabled by the architecture of WSN and MCN convergence networks; MCNs have the potential to make WSNs more energy efficient and improve network performance; and mobile MCN terminals act as both sensor nodes and gateways to WSNs [8]. In addition, sensor nodes in WSN and MCN convergence networks collect data and send it to a data server via MCN [9], where total data sent (T_{DS}) is the sum of total data received (T_{DR}) and packet loss (P_L) as explained in equation (3.2).

$$T_{DS} = T_{DR} + P_L \quad (3.\ 2)$$

3.4.3 Network Architecture Convergence

Network Architecture Convergence of WSNs and MCNs can be described as the integration of WSNs and MCNs to create a unified network architecture. In the conventional network architecture combining MCNs and WSNs is hierarchical, as shown in the left part of Figure 3.9, in which a set of wireless sensor nodes is utilized for data detection [59]. All gateways operate in dual-mode, equipped with both WSNs and MCNs interfaces. Data detection occurs in the wireless sensor node group, while system control involves the gateway and base station. The base station indirectly manages WSN through the gateway, which only grants access for WSN nodes and sends detected data to backhaul network servers.

Communication between WSNs and MCNs happens through a data channel at the gateway, but this lowers overall system efficiency. With the updated convergence approach, the merging of MCNs and WSNs architectures progresses from layered to flat to reduce hierarchical signaling between both networks. As depicted in Figure 3.9's right portion, the converged architecture enables sensor nodes to receive downlink signaling from the MCN base station. This results in a flat network structure, which allows MCN to directly control and manage WSN, ultimately enhancing its efficiency. For instance, base stations can assist sensor nodes in selecting the most suitable transmission paths for routing traffic. However, due to the limited range of sensor nodes' transmissions, uplink data continues to be routed by the gateway. Although integrating downlink receivers increases complexity in sensor nodes, contemporary device capabilities minimize this impact significantly. In the unified network architecture, it is essential to assess the impact on the MCN and the increased complexity for sensor nodes, to strike a suitable balance between cost and performance enhancement. The authentication process for sensor nodes at the MCN must be scrutinized. Authorization information can be transmitted through the WSN gateway, which already possesses authorization within the MCN. Furthermore, novel time coordination strategies should be developed for this integrated architecture. As the multi-access approach in WSN is contention-based and scheduling-based in MCN, their timings remain separate in the combined scenario. Consequently, a co-optimized coordination plan needs to be devised to enable sensor nodes to establish an optimal balance between energy usage and system performance [10].

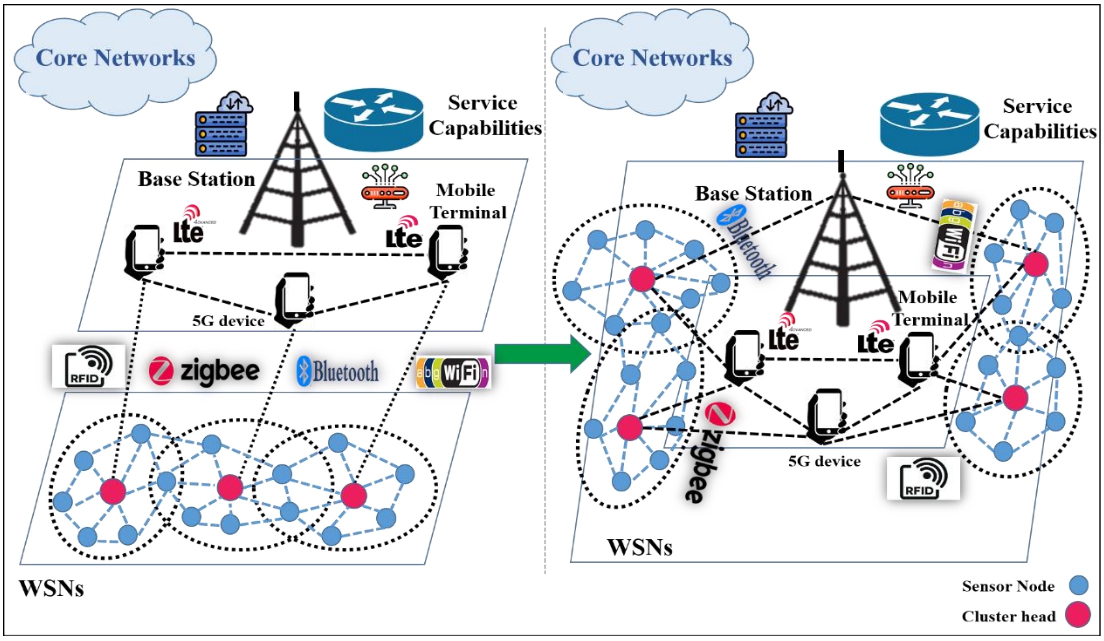

Figure 3.9 Converged network architecture for WSNs and MCNs.

This proposed network architecture convergence aims to enhance communication efficiency, optimize resource utilization, and improve overall network performance by leveraging the strengths of both WSNs and MCNs. Key aspects for achieving this convergence may include:

- **Interoperability:** Developing protocols and standards to ensure seamless communication between WSNs and MCNs devices.
- **Cross-layer optimization:** Optimizing the layer interactions between WSNs and MCNs for improved performance, energy consumption reduction, and resource allocation enhancement.
- **Heterogeneous network deployment:** Mixing diverse network technologies such as 5G, Wi-Fi, Bluetooth, Zigbee, etc., within the converged architecture to support various use cases like IoT devices, wearables, and other smart devices.
- **Mobility management:** Efficiently managing mobile sensor nodes in the converged network for seamless connectivity and maintaining accurate location information.
- **Scalability:** Ensuring that the converged network can accommodate a large number of devices without compromising its performance or security.
- **Security & Privacy:** Addressing security and privacy issues arising due to converging heterogeneous networks to safeguard data integrity, confidentiality, and user privacy.
- **Quality of Service:** Ensuring that end-to-end connectivity meets desired performance metrics such as latency, reliability, and availability for different application requirements.
- **Energy efficiency:** Implementing power-saving mechanisms into the converged network architecture to prolong the lifespan of energy-constrained sensor nodes in WSNs.
- **Integration with cloud/fog/edge computing paradigms:** Utilizing distributed computing infrastructure to perform data processing closer to data sources for faster decision-making while reducing latency in real-time applications.

3.4.4 Air Interface Convergence

Air-interface convergence for WSNs and MCNs primarily relies on narrowband technologies or spread spectrum transceivers. A crucial challenge lies in designing a unified air interface that benefits both MCNs and WSNs. One simple approach involves introducing dual-mode mobile terminals, depicted in the left part of Figure 3.10. However, this solution's main drawback is the frequent switching of modes required to transmit data from WSNs to the base station. In MCNs, OFDM and OFDMA have emerged as primary air-interface solutions. Research has demonstrated that OFDM/OFDMA effectively shares radio resources among systems with varying bandwidths, such as implementing Non-Continuous OFDM (NC-OFDM) [60] as an OFDM-based spectrum pooling technique. As WSNs adapt to higher data rate applications, the OFDM-based air interface emerges as a viable alternative, enabling full air-interface convergence, such as with NC-OFDM, shown in the right part of Figure 3.10. Each WSN cluster shares a subset of MCN's OFDM subcarriers/carriers, allowing sensor nodes multiple access within that subset of subcarriers/carriers. Designing a unified air interface presents a challenge. For instance, the distinct coverage and channel conditions of MCNs and WSNs necessitate a joint design for their cyclic prefixes. Moreover, the two networks have different signal processing capabilities, and they are allocated different bandwidths, i.e. large bandwidth for MCNs and small bandwidth for WSNs. In the case of two networks operating at different frequencies, adaptive filters must be designed to aggregate different amounts of subcarriers. Otherwise, in the case of two networks sharing the same frequency bandwidth, the converged radio frame needs to be designed to mitigate the multi-access interference between the links from mobile terminals to sensor nodes and the links from mobile terminals to the base station [10].

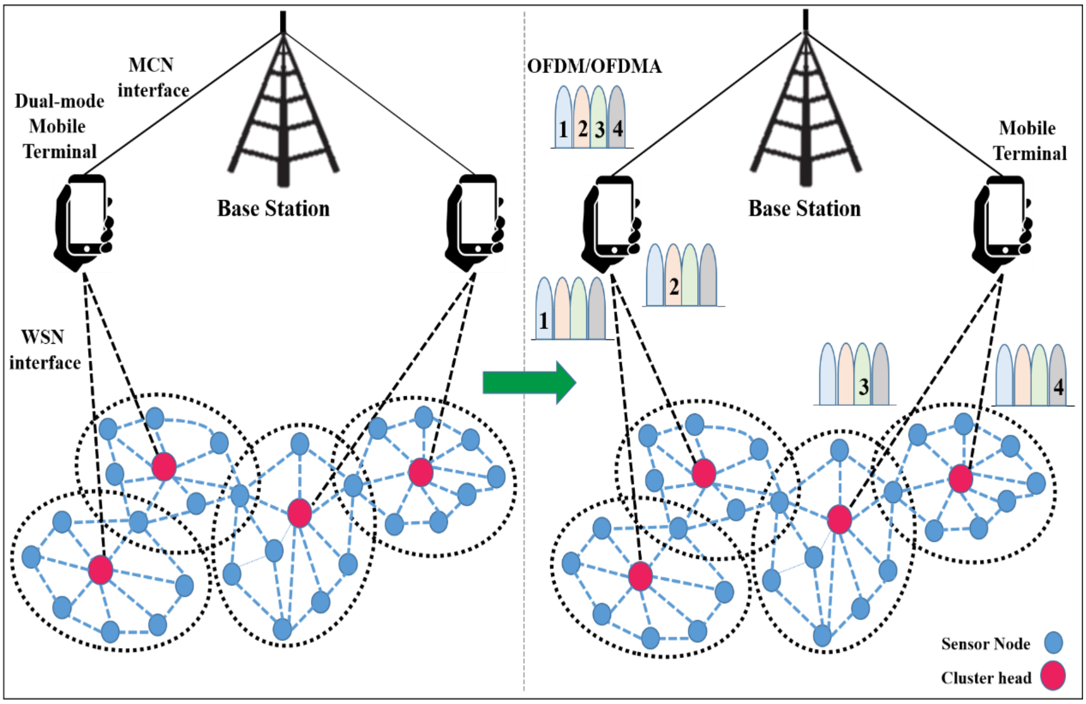

Figure 3.10 Converged air interface for WSNs and MCNs.

3.4.5 Protocol Convergence

In a converged WSN and MCN scenario, the data collected from the sensor nodes can be routed to the base station through the gateway. As shown in the left part of Figure 3.11, the data channel between the two protocol stacks is usually implemented in the gateway. Data channels are implemented to exchange information between the independent stacks. The network architecture and air interface for WSN and MCN are highly converged, so the protocol and control signaling should also be highly converged. In such a converged network, the MAC and network layer protocols in the two stacks should be jointly optimized either to achieve some performance gains for the WSN or to extend the applications of the MCN. As shown in the right part of Figure 3.11, the two protocol stacks are not independent. There is shared data and algorithm between the two stacks. In the converged networks, the downlink and uplink control signaling should be designed and some "cross-MAC" designs need to be implemented at the gateway. The new signaling may affect current WSN and MCN standards. For the downlink, the entry/exit of WSN nodes and gateways can be managed by the BS, while for the uplink, the signaling from WSN nodes, e.g. requests to transmit data, which can be triggered in a periodic, on-demand, or event-driven manner, is also coordinated by the BS. Furthermore, at the PHY/MAC layer, the gateway needs to communicate sufficient/efficient control information to and from the BS to optimize convergence. The gateway needs to request the resources from the BS for uplink and downlink transmission, and forward some system information to the sensor nodes. At the MAC layer, a two-stage resource allocation scheme should be considered for the converged networks, especially for scenarios where there are a large number of WSN nodes with heavy traffic. For example, the gateway can map the data and resource requests of sensor nodes to the MCN and report to the BS; then the BS allocates a different WSN channel group to each gateway for intra-WSN communication according to the requested information from different gateways. At the network layer, when a mobile gateway enters the coverage area of the WSN, it may cause gateway re-selection or even re-clustering of the wireless sensor nodes. How to achieve a balanced trade-off between complexity, performance gain, and energy consumption through robust re-selection and re-clustering algorithms is an important issue for further study [8], [10], [58]. While 4G/5G systems aim to establish convergence between all IP-based networks. To achieve this goal, network management, security, and QoS must be integrated. LTE-A networks meet the requirements applicable to convergence networks. It is backward compatible with previous versions of 3GPP standards, non-3GPP networks, and most IP-based networks, such as the Internet [61].

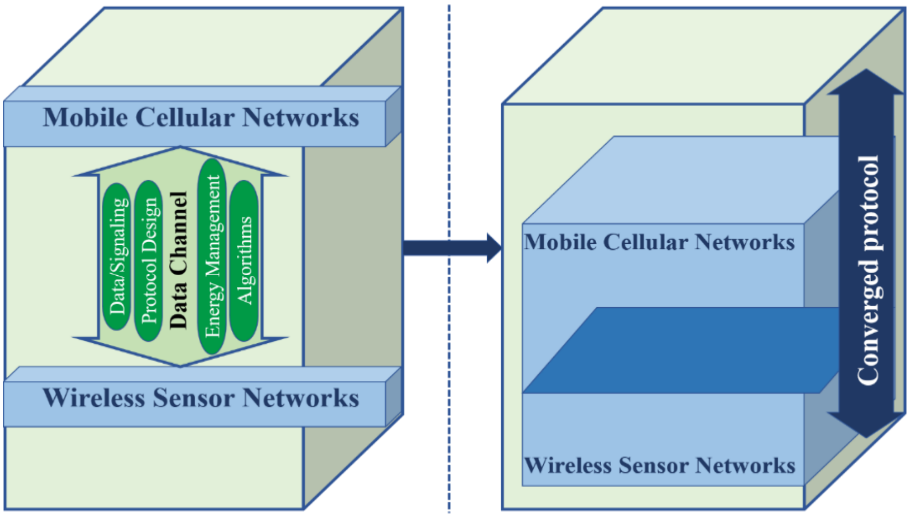

Figure 3.11 Protocol stack for WSN and MCN convergence network.

3.4.6 M2M in Mobile Converged Networks

Through M2M, users can share network access with other users while utilizing multiple communication interfaces[62]. M2M networks usually use WSN protocols, which provide quite a lot less transmission capacity than MCNs. Due to this limited capacity problem with M2M network protocols, the M2M and cellular convergence network are one of the prospective hot research topics in recent years. As cellular networks utilize unlicensed spectrum, new spectrum reforming methods and algorithms were proposed. As M2M and cellular convergence networks continue to develop, devices in the M2M network can share the unlicensed spectrum of cellular networks like LTE-A. In this way, M2M reduces transmission load and significantly increases performance [7]. Figure 3.12 illustrates our proposed architecture for the four scenarios for M2M and cellular network convergence.

Figure 3.12a illustrates the hotspot-based approach to M2M and cellular convergence network, which is the simplest and most straightforward approach. In this scenario, the selection of the M2M master node is based on maximum performance and battery level criteria. The master device creates an M2M area, which provides network access to other devices. In this type of M2M/cellular convergence network, the master M2M node uses all cellular resources and shares them with other M2M devices. However, this approach lacks any QoS control mechanisms. Consequently, if many devices are simultaneously connected to the master device, the likelihood of M2M network overload is relatively high. The mesh-based approach to M2M and cellular convergence network, as depicted in Figure 3.12b, is preferred over the hotspot-based approach due to its ability to provide better quality support. This approach uses multi-hop connections to ensure efficient network access. In this scenario, the master device connects to a limited number of devices, and each device can act as a secondary master to provide multi-hop access to other devices. This mode allows for balanced traffic flow between users by managing data flows in the master M2M device. In this type of converged network, the M2M master device uses all the resources from the cellular network base station and shares them, especially between M2M devices, through the unlicensed spectrum of cellular networks such as LTE-A. The hybrid M2M and cellular convergence network, as illustrated by the mesh topology in Figure 3.12c, is the third scenario that can be implemented. This approach supports hotspot-based M2M subnetworks with a master node connected by a multi-hop communication channel. Essentially, the scenario depicted in Figure 3.12c is a combination of the hotspot-based approach in Figure 3.12a and the mesh-based approach in Figure 3.12b. This type of cellular/M2M convergence network assumes that data flows can be distributed according to the users' type of service. The most advanced scenario for M2M and cellular convergence networks is a fully connected M2M network, as shown in Figure 3.12d, which allows multiple M2M connections to be used for a single data stream. This feature ensures that optimal paths are selected for each transmission, resulting in full utilization of the unlicensed spectrum. This scenario differs significantly from the previous ones in that all M2M devices can simultaneously act as cellular consumers and M2M providers, resulting in increased session reliability.

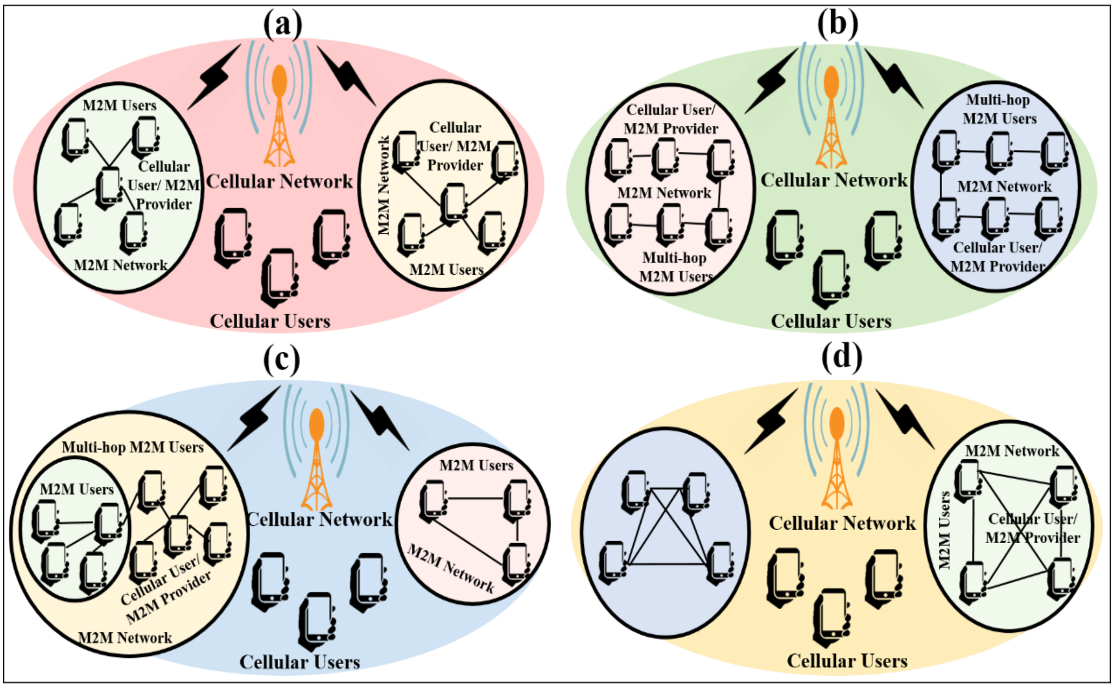

Figure 3.12 Converged mobile networks, including WSNs, MCNs, and M2M networks.

Table 3.3 summarizes the comparison of four possible scenarios of M2M and cellular convergence networks.

Table 3.3 Comparisons of four different M2M/cell convergence network scenarios.

M2M/Cell network convergence scenario	Advantages	Disadvantages
Hotspot-based M2M network	- Simple deployment - Simple session control - Dynamic channel utilization	- Possibility of overloading - Absence of quality control mechanisms - Low reliability
Mesh-based M2M network	- Traffic balancing Multihop routes - Possibility of simple quality control	- Only static routes - Low reliability - Low channel utilization - Quality control mechanisms
Hybrid M2M network	- Dense traffic balancing - Multihop routes - Dynamic channel utilization	- Difficult deployment - Relatively low reliability - Only static routes
Fully connected M2M network	- Multipath traffic control - Precise quality control - Dynamic multihop routing algorithms - High reliability	- Difficult deployment - Complex session control - Complex routing control - Interference problem

3.4.7 WSN and 5G MCN Convergence Scenario

The swift advancement of smart technology has given rise to an environment that encourages the deployment of sensor nodes that are becoming more and more commonplace in our daily lives. The new 5G MCN plays a crucial role in transforming this sensor network into a smart sensor network for M2M communications. The high data rates, lower latency, and other breakthrough technologies of 5G support WSNs and provide better service, allowing for the use of smart devices in new applications. However, to foster the use of WSNs in 5G, it is necessary to ensure that the fundamental properties of WSN devices, such as low data rate, a massive number of devices, and minimum data rates in virtually all circumstances, are compatible. One possible solution to make this convergence possible is to enhance the performance of ZigBee networks, which connect all sensor nodes in the 5G environment as depicted in Figure 3. 13. With the help of 5G, a technology that provides M2M communications, terminals within the range of the ZigBee network can connect to the ZigBee network. Compared to ZigBee sensor nodes, 5G terminals offer more energy, storage space, bandwidth, and processing power, thereby enhancing the data transmission performance of the wireless sensor network (ZigBee network). Moreover, 5G terminals can also access the IP network, enabling them to communicate sink management-related information directly without consuming ZigBee bandwidth resources. Thus, the convergence of WSN and 5G allows for the transmission of packets collected by WSN via 5G links (the Internet) [8].

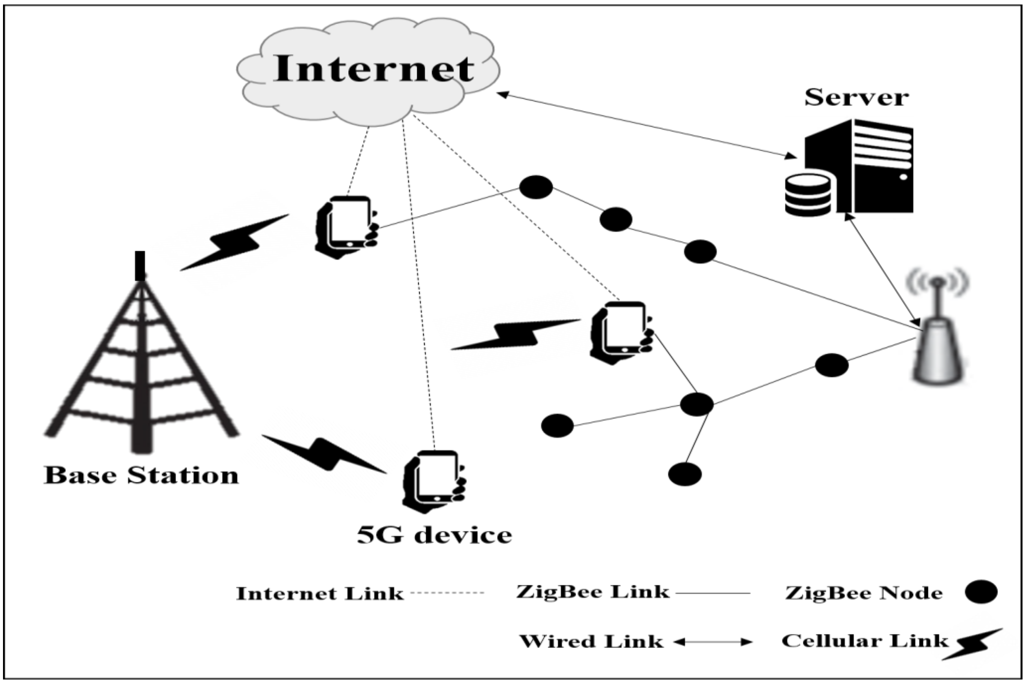

Figure 3. 13 WSN-5G convergence architecture.

3.5 Conclusion

The deployment and convergence of IoT/M2M communications and MCNs/WSNs have the potential to revolutionize the way we collect and analyze data from the physical world. By combining the power of these technologies, we can create more efficient and effective decision-making processes, leading to better outcomes in various domains. However, deploying these technologies together poses several challenges that need to be addressed. In summary, this chapter has provided an overview of the deployment strategies for IoT/M2M communications and 4G/5G mobile networks, migration strategies from 4G to 5G and beyond, and converging solutions for wireless heterogeneous networks.

CHAPTER 4

Designing, implementing and deploying IoT/M2M Smart-X applications

Contents of Chapter 4

4.1 Introduction

The fourth chapter of this thesis deals with the design, implementation, and deployment of IoT/M2M technologies in various Smart-X systems, including healthcare, homes, offices, buildings, and cities. The proposed solution presents a complete system for IoT/M2M Smart-X-based heterogeneous networks including ZigBee, Bluetooth, Ethernet, 2G, and 4G to provide security, convenience, energy-saving indoor care, outdoor care, and improvement of urban quality of life by using efficient and low-cost components such as Arduino microcontroller and NodeMCU board with various compatible sensors, actuators, and shields. The purpose of this chapter is to present a practical example of a Smart-X IoT/M2M system that provides several smart services and applications. All the proposed applications are designed and implemented to remotely control and monitor the Smart-X system, whether in the home, office, garden, or city, through our mobile application called “Raniso”, which provides users with essential daily services in a simple and accessible way, or through “Blynk App”, which is a well-known platform that acts as an intermediary between the smartphone and many hardware modules and then controls them via mobile phones.

4.2 IoT/M2M application domains

The emergence of a large number of smart IoT/M2M applications based on WSNs and MCNs have shown the robust potential that improves the quality of our life in several aspects. The most famous IoT/M2M applications shown in Figure 4.1.

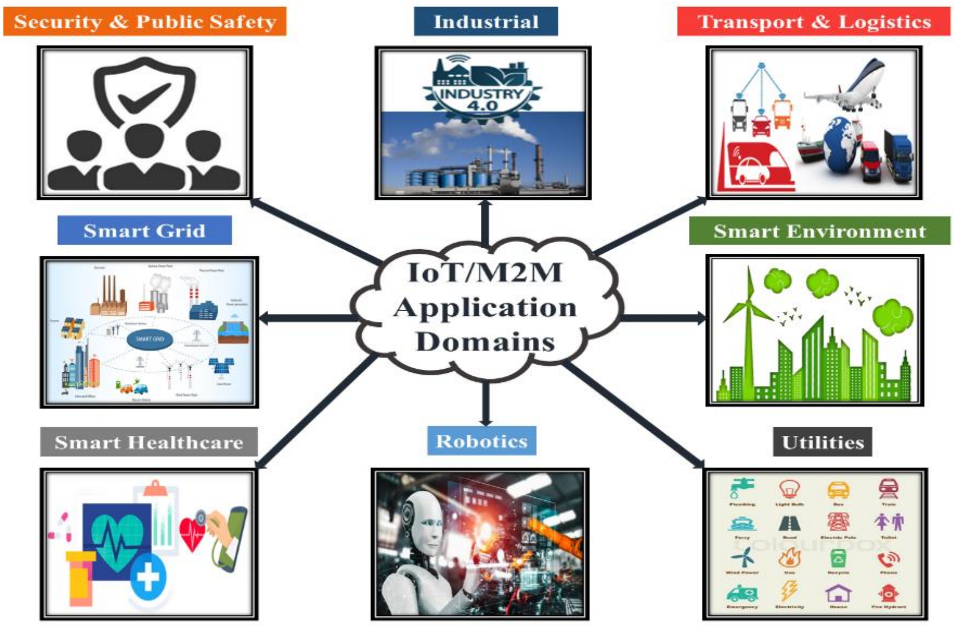

Figure 4.1 IoT/M2M application domains.

4.2.1 Security and public safety

One of the most pressing issues facing the public, private, and commercial sectors is security. Projects to develop security and safety are being worked on by a ton of researchers. The IoT/M2M paradigm is an ideal solution for the automation and simplicity of security and public safety monitoring and administration due to the high need for efficient security systems. IoT/M2M technologies enable quick, flexible, and affordable implementation for personal tracking, public infrastructure security, remote surveillance, and burglar alarms [63].

4.2.2 Industrial

The industrial sector is continuously looking for more efficient ways to improve product quality and reduce costs while minimizing the waste of energy and materials. Industrial-based IoT/M2M technologies can monitor and enhance each step of the product including production, delivery, and consumption. The IoT/M2M paradigm is an excellent candidate for monitoring the entire life of a product, gradually from raw mate provision used for its fabrication to its final assembling which can offer real-time access to information about equipment or plants, and prevent disruption of infrastructures.

4.2.3 Transport and Logistics

In transportation, the IoT/M2M paradigm incorporates a vast network of embedded sensors, actuators, and other smart devices. This network collects real-world data and transmits it to specialized software to convert it into useful information. Where the technologies enabled by the IoT/M2M paradigm and smart solutions have revolutionized the operations of the transportation sector, which has created many opportunities in the transportation and logistics sector, including various applications of transportation such as goods tracking, fleet management, assisted driving, smart vehicles, etc. Logistics services include smart parking, passenger services, journey time estimation, e-ticketing, etc.

4.2.4 Smart Grid

The smart grid is the next-generation electrical system that has been modernized with communication and connectivity technologies to support smarter resource use. The IoT/M2M paradigm is a crucial technical tool for advancing smart grid development. By utilizing IoT/M2M technologies, it is possible to more efficiently integrate the infrastructure resources in the electrical and communications power systems, raise the degree of power system information, and boost the utilization efficiency of the infrastructures in the current power system.

4.2.5 Smart Environment

The idea of having a smart environment in homes, offices, and every nook and cranny of any prospective smart city can be realized by the pervasive use of IoT/M2M communications. While this is going on, IoT/M2M data collection, management, and manipulation can lead to better decisions based on real-time information, which lowers living costs significantly, and more efficient resource utilization in smart homes, offices, shops, disaster management, weather forecasting, emergency alarm service, food monitoring/alerts, agriculture, smart metering, green environments, etc [63].

4.2.6 Smart Healthcare

Healthcare is one of the fastest-growing areas of the IoT/M2M market. Where one of the most well-known IoT applications is in medicine termed the Internet of medical things (IoMT). Smart healthcare applications include automated medical data collection and retrieval, patient and medication monitoring, inpatient identification and authentication, tracing of medication orders, remote health monitoring, sharing the data using wearables to the respective healthcare experts, and more services. Healthcare-based IoT/M2M technologies can work effectively in epidemic crisis management because of their ability to save time, enhance automation, and reduce human involvement, as well as their ability to make society more resilient to various pandemics and diseases, which has proven their ability to fight COVID-19 and save the global economy.

4.2.7 Robotics

The field of robotic systems includes everything from design, neural networks, engineering, programming, IoT/M2M technologies, artificial intelligence, and collaborative bots to assist humans in their daily activities. Intelligent bots are playing a larger role in various sectors, including healthcare during COVID-19, as the bots assisted medical workers and prevented them from coming into contact with infected cases. They examined patients and recorded their medical conditions and health data such as age, temperature, and other illnesses they were suffering from. Other bots also provide prescribed treatments and medical equipment to patients without direct contact between them and medical staff, to prevent the spread of disease. In addition, smart robotics are rapidly evolving day by day, offering tremendous potential and a variety of characteristics that are proven helpful in reducing human effort and increasing production in various domains.

4.2.8 Utilities

Smart utility meters for electricity, gas, and water are among the first set of popular applications being deployed around the world within the IoT/M2M segment. These devices typically gather end-user consumption during a period. Across their grids, smart utilities use connected sensors to deliver services more efficiently and analyze their operations. The IoT/M2M concept of connected devices is heavily used by smart utilities to streamline their operations with the latest electronic communications, software, and computing technologies.

4.3 Design of IoT/M2M Smart-X System-based Wireless Networks

4.3.1 System Hardware and Software

In the proposed IoT/M2M smart-X systems-based heterogeneous networks, we use various sensors and actuators to collect data and manage them according to services, where the Arduino microcontroller is the brain. In addition, the NodeMCU board and other modules such as Bluetooth HC-06, Sim800l, and RFID are used for wireless communication. The software used in this chapter and the following chapter are described in Table 4. 1, while the main hardware components used is defined in Table 4.2.

Table 4. 1 The main specifications of the software used.

Software	Specifications
Arduino IDE	It is open-source software written in Java and based on the Processing programming language. It allows programs to be written, modified, and converted directly to microcontrollers [11]. The version used in this work is 1.8.16.
Proteus	It is open-source software for virtual system modeling and circuit simulation. It is mainly used for electronic design automation [11]. The version used is version 8.13.
Raniso App	It is a mobile application first we created in 2019 [64]. It acts as an intermediary between the smartphone and many hardware components and it is used to control several electrical devices via various wireless networks.
Blynk App	It is an IoT platform that acts as an intermediary between the smartphone and many hardware modules and then controls them via the mobile phone. Connectivity options include Wi-Fi, Ethernet, cellular, USB, serial, Bluetooth, etc [14].
ThingSpeak	It is an IoT analytics platform service that enables aggregation, visualization, and analysis of live data streams in the cloud. ThingSpeak allows us to send data from devices, visualize live data and send alerts [1].

Table 4.2 The main specifications

Components	Type	Specifications
Arduino	**Mega**	This is an ATmega2560-based microcontroller board. There are 54 digital input/output pins, 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connector, a power connector, an ICSP header, and a reset button on this board [1].
	UNO	This is an open-source microcontroller board based on the ATmega328 processor and is produced by "Arduino.cc". The board contains 14 digital input/output pins, six analog inputs, a 16 MHz ceramic resonator, a USB connector, a power connector, an ICSP header, and a reset button [1].
NodeMCU	**V3**	It is an open-source board consisting of a physical programmable circuit board [65] created by a Chinese company called Espressif, which makes a system on chip (SoC) called the ESP8266. This board is defined as a low-cost Wi-Fi chip that uses the Lua programming language and includes a full TCP/IP stack and a microcontroller [66].
ESP32 CAM		This is a camera module equipped with Bluetooth and Wi-Fi, designed like a microcontroller. It is utilized for monitoring both inside and outside.
Modules	**Ethernet W5100**	It allows the Arduino board to connect to the Internet via a LAN cable. This shield is based on the Wiznet W5100 Ethernet chip, which provides a network (IP) stack capable of both TCP and UDP.
	RC522 RFID	The term RFID stands for Radio Frequency Identification. The RFID reader can be used to read and retrieve information from RFID cards [67].
	SIM800L	It is a miniature GSM modem that helps to make calls and send messages and can access the Internet via GPRS, and TCP/IP [64]. This module can be used in a wide range of IoT/M2M projects.
	GPS	The Global Positioning System (GPS) module uses satellite technology to continuously determine data such as longitude, latitude, speed, distance traveled, etc [68].
	Bluetooth HC-06	It is a basic Bluetooth SPP (Serial Port Protocol) module that is used to transmit data within a small area in the ISM band between 2.4 and 2.485 GHz [69].
	XBee	The XBee module is based on the IEEE 802.15.4 standards used to build a low-power, low-maintenance, self-organizing WSN. It is connected to the microcontroller via a serial link for sending and receiving signals.
	DS3231	The DS3231 Real Time Clock (RTC) is a low-power clock/calendar with 56 bytes of battery backup SRAM. The clock/calendar provides certified data for seconds, minutes, hours, days, dates, months, and years [70].
	SD Card	It enables communication with memory cards as well as the writing and reading of data on them.
Sensors	**TCRT5000**	It is a sensor that detects infrared light. It is simply a combination of a photodiode and a phototransistor [14][71].
	Ultrason HC-SR04	It is an electronic device that uses sonar to calculate the distance between physical objects. It has a wide object detection range of 2 cm to 400 cm with high accuracy [13].

	Rain	It is a rain detector that consists of two modules: a rain board that detects rain and a control module that compares analog values and converts them to digital values.
	Soil moisture	It measures the content of water and humidity in the soil. As the soil moisture increases, the sensor allows current to pass through, and the greater the moisture, the greater the proportion of the connection [69].
	DHT11	It is a digital sensor that detects the temperature and humidity of the place. It provides high levels of dependability, accuracy, and long-term stability [14].
	LM35	It is a transducer whose function is to convert the temperature scale into electrical quantities in the form of voltage [72].
	Pulse	It is a plug-and-play heart-rate sensor that can be used to easily incorporate live heart-rate data.
	SW-420 Vibration	It measures vibration levels and tilting motion continuously. This sensor is used for safety purposes.
	MQ-2	It is a gas detection sensor that detects or measures various types of gases such as LPG, alcohol, propane, H2, CO, and even methane [69].
	Flame	It is designed to find out if there is a flame as well as regular light with a detection range of up to 100 cm and a wavelength ranging from 760 to 1100 nm [73].
	PIR HC-SR501	PIR sensor refers to Passive Infrared, which is designed to detect movement based on the infrared generated by the human body and other living creatures [73].
	MQ-135	Is an air quality gas sensor that detects or measures NOx, Nh3, CO2, Benzene, Alcohol, and Smoke.
Actuators	**Servo motor**	It is an electric motor that can be used to push or rotate an object with high precision [13].
	DC motor	A DC motor is an electric motor that converts electrical energy into mechanical energy.
	Fan	Is a device used to create air movement for ventilation in hot climates to create a relaxing environment [11].
	Water pump	This submersible pump can be used as an amphibious pump and is ideal for reliable fountains.
	LCD screen	Liquid Crystal Display (LCD) is a type of character display tool in which the primary display is a liquid crystal [14].
	Keyboard	Is a contact matrix of buttons made up of rows and columns. It is used to enter numbers and letters.
	Relay	It is used to switch loads and control equipment. In our system, after receiving a specific command from the keypad, the microcontroller commands the relay to control it accordingly.
	Speaker	It emits a range of sounds and includes power amplification and voice outputs.

	Buzzer	It is an audio signaling device that produces sound. In the proposed system, the buzzer is used as a notification alarm.
	LDR	Light Dependent Resistor (LDR) is an electrical component whose resistance varies in response to the perceived light [14].
	LED	A Light Emitting Diode (LED) is a semiconductor light source that emits erratic radiation as a result of spontaneous photon emissions. It is utilized to represent light [13].

4.4 Implementation and deployment of IoT/M2M Smart-X Applications-based Wireless Networks

The main articles published in conferences and book chapters are described in the following section.

4.4.1 A Real-Time IoT/M2M-Smart Home Automation

4.4.1.1 Application of M2M Communication based on ZigBee to Control Smart home automation

A. System Description

The proposed system's concept involves utilizing wireless communication through XBee transceivers to achieve comprehensive control over two primary subsystems, namely the remote control system and the master control board [11].

- **Remote Control System:** The elderly and individuals with disabilities tend to favor a more straightforward remote control featuring laser-etched illuminated buttons, a few switches, and an LCD screen for displaying crucial notifications. This proposed particular Remote Control utilizes components such as Arduino UNO, KeyPad, LCD 20*4, and the XBee Module, as depicted in Figure 4.2. When a button on the Keypad is pressed, a command is relayed from the Arduino to the XBee Module, which in turn transfers the command to another XBee located within the Control Unit. Furthermore, when the Control Unit transmits sensor data through the XBee, the Arduino receives this information and subsequently presents it on the LCD screen.

Figure 4.2 The block diagram of the remote control system.

- **Master Control Board:** Also known as the control unit, which is managed by the remote control system. This unit utilizes an Arduino UNO microcontroller, which interfaces with an XBee transceiver module to facilitate seamless communication between the remote control and its base. Its components include relays, a fan, lamps, DC motors, MQ-2 and LM35 sensors, and a flame sensor. The Arduino UNO pins connect to the relays and sensors, allowing for on/off control of specified appliances according to sensor input conditions. The microcontroller on this control unit collects data from the sensors and transmits it through XBee to the remote control, which is then displayed on an LCD. Furthermore, when a button is pressed on the remote control unit, this command is received by the Arduino via XBee. Upon receiving the command, the Arduino UNO activates or deactivates the corresponding relay, thus turning on or off the respective appliance. The block diagram of the master control board can be seen in Figure 4.3.

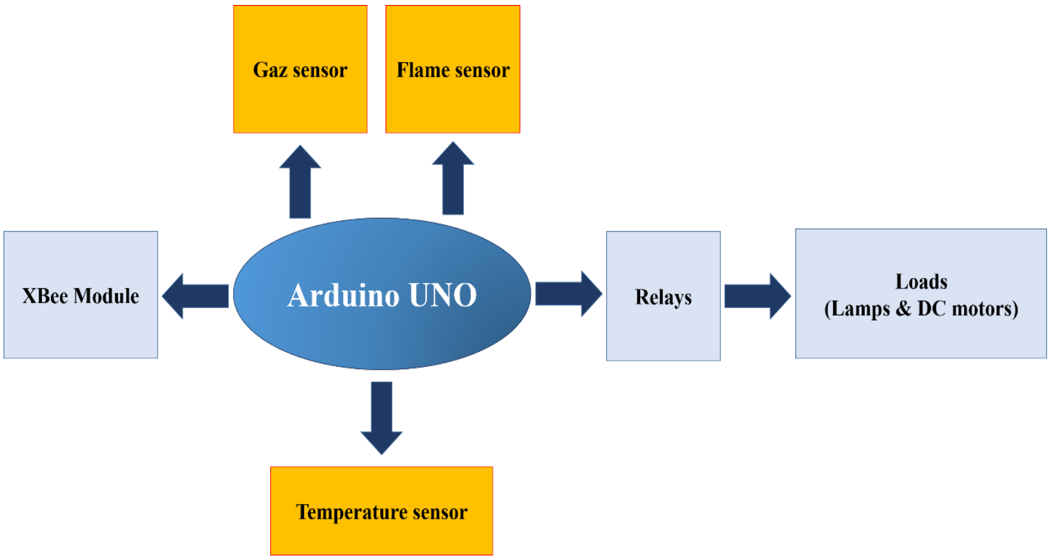

Figure 4.3 The block diagram of the master control board system.

B. View and test a smart home automation system based on ZigBee technology

In the suggested M2M smart home automation system utilizing ZigBee, the XBee module links with the Arduino UNO through Tx and Rx pins, while lamps, DC motors, and fans connect to the power source via relays. With each relay, one pin attaches to the Arduino and another to the ground. Meanwhile, the remote control's XBee module connects with the home automation system control unit's XBee using the **'VIRTUAL SERIAL PORT DRIVER'**. Virtual connections are established between COM1 and COM2 ports, as depicted in Figure 4.4.

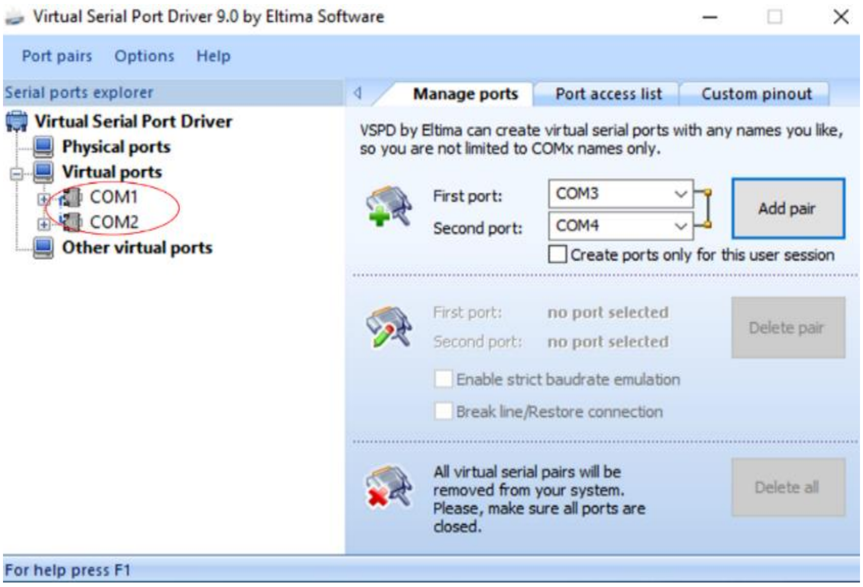

Figure 4.4 Virtual port connection.

The remote control features command buttons and is equipped with an LCD screen that displays notifications, as demonstrated in Figure 4.5. Commands are transmitted wirelessly via XBee transceivers, and the control unit subsequently receives these signals, activating the respective devices by engaging the corresponding electronic relays for ON or OFF functionality, as depicted in Figure 4.6. The system's design enables a range of home automation functions, including gas and fire detection, lighting control, temperature sensing, fan regulation, and DC motor management. This proposed system is versatile and can be employed in various settings, such as hospitals and hospices.

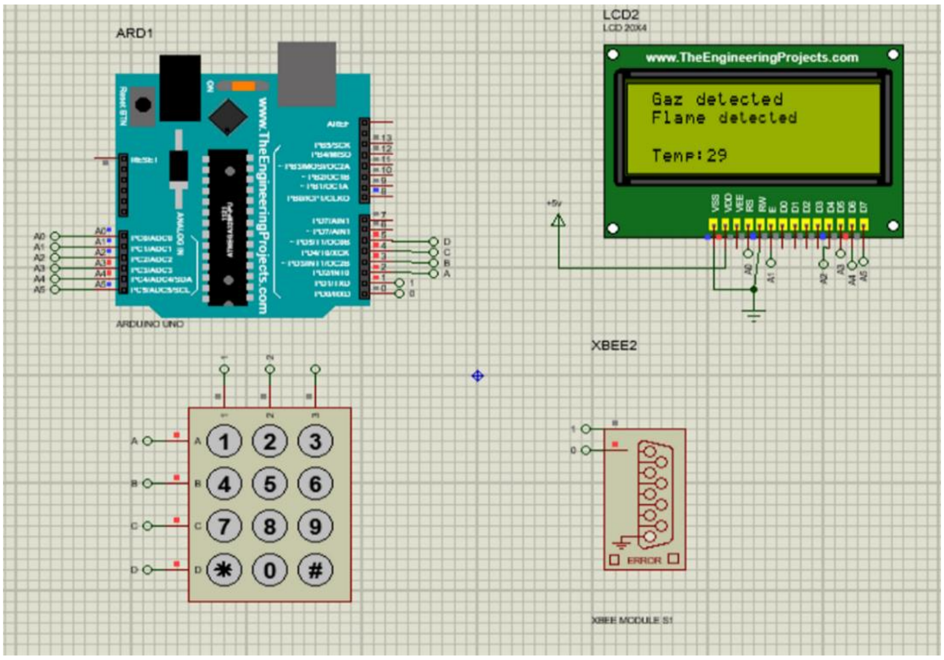

Figure 4.5 Virtual installation of the remote control system.

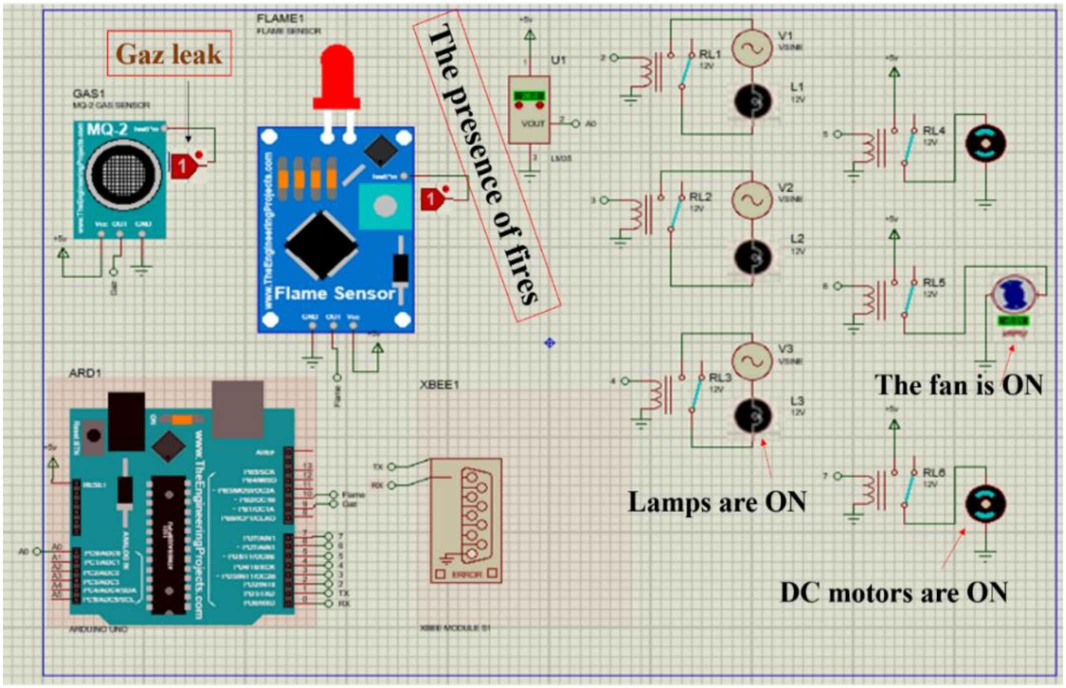

Figure 4.6 Virtual installations of the master control board.

4.4.1.2 M2M-Smart Home Automation-Based Bluetooth Using Raniso App

A. System Description

In the proposed design for an M2M-Smart home automation system utilizing Bluetooth wireless technology, various sensors, and actuators are employed to collect data and manage the services provided. The Arduino UNO microcontroller serves as the central processing unit, while the Bluetooth module (HC-06) facilitates communication between the hardware system and the Raniso App. Furthermore, well-established hardware components such as the MQ2 gas sensor, flame sensor, DHT11 sensor, LCD screen, servo motors, DC fan, relays, buzzer, and LEDs are incorporated into the system. With this proposed structure for the M2M-smart home automation system, users can monitor and modify the conditions of electronic home appliances as well as sensor operations. Examples of these appliances include lighting, heating, ventilation, and various technological equipment. The suggested method not only saves time but also offers protection against fires and gas leaks while enhancing comfort. This system is suitable for use in hotels and both industrial and domestic environments. Figure 4. 7 shows the operational flowchart of the software implementation. A block diagram illustrating the system architecture can be found in Figure 4.8, while Figure 4.9 presents the Raniso App interface used for controlling the system.

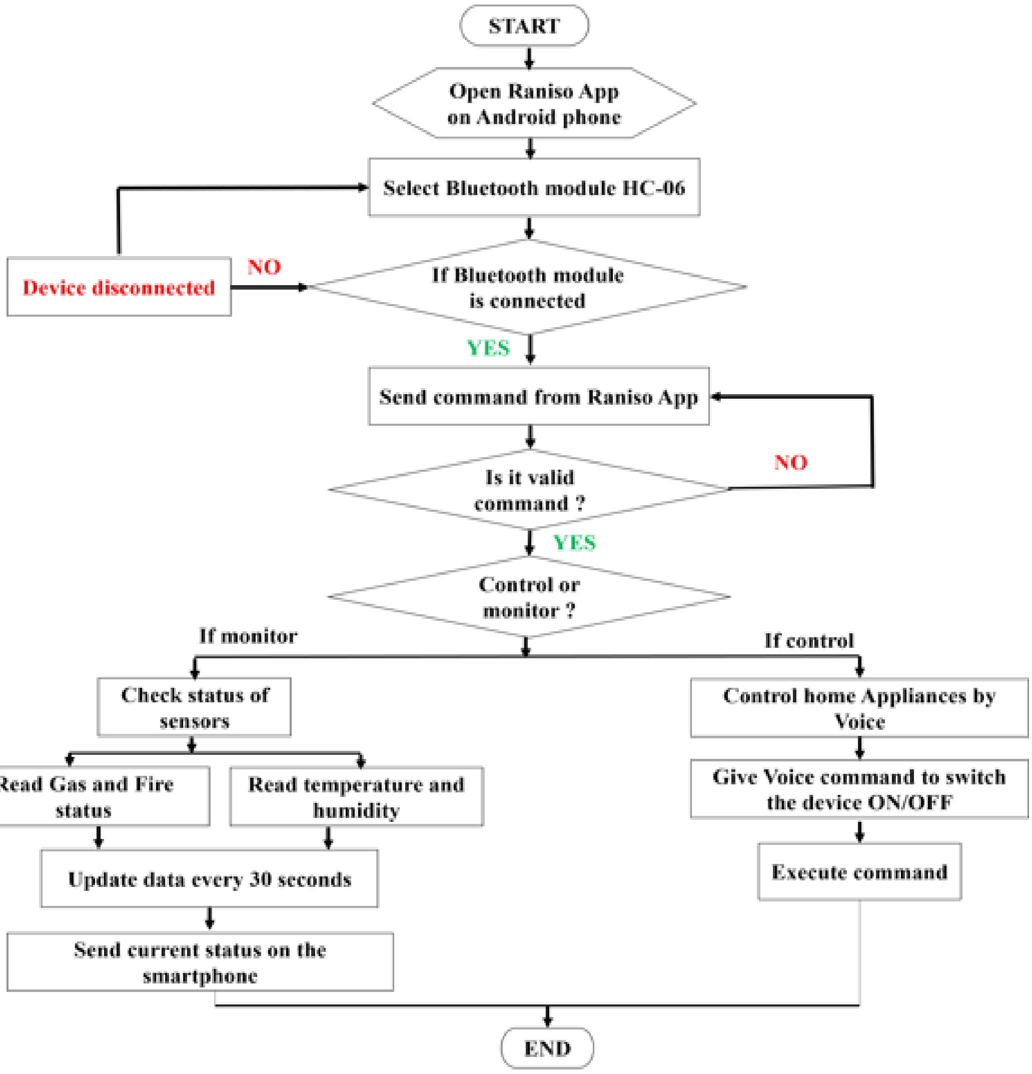

Figure 4. 7 Operational flowchart of the smart home automation system.

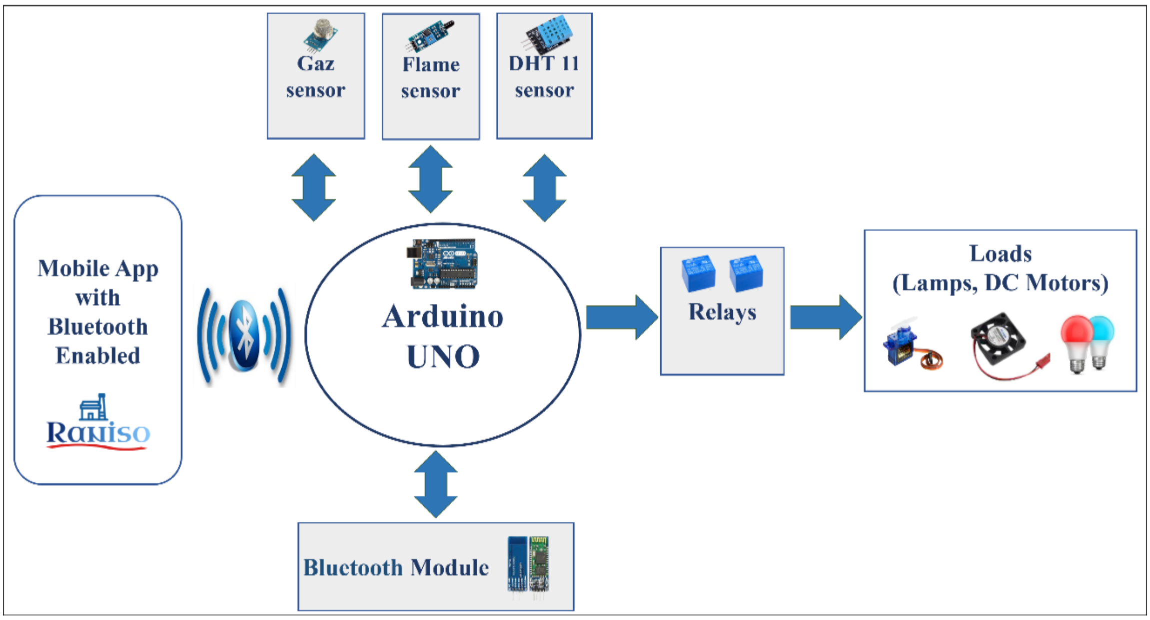

Figure 4.8 Block diagram of the system architecture.

Figure 4.9 Bluetooth-based smart home automation interface on the Raniso app.

B. Implementation of M2M smart home automation-based Bluetooth using Raniso App

This part focuses on the virtual and real implementation of the various M2M-Smart home services. Figure 4.10 shows the proposed implementation scheme for the M2M-Smart home automation system.

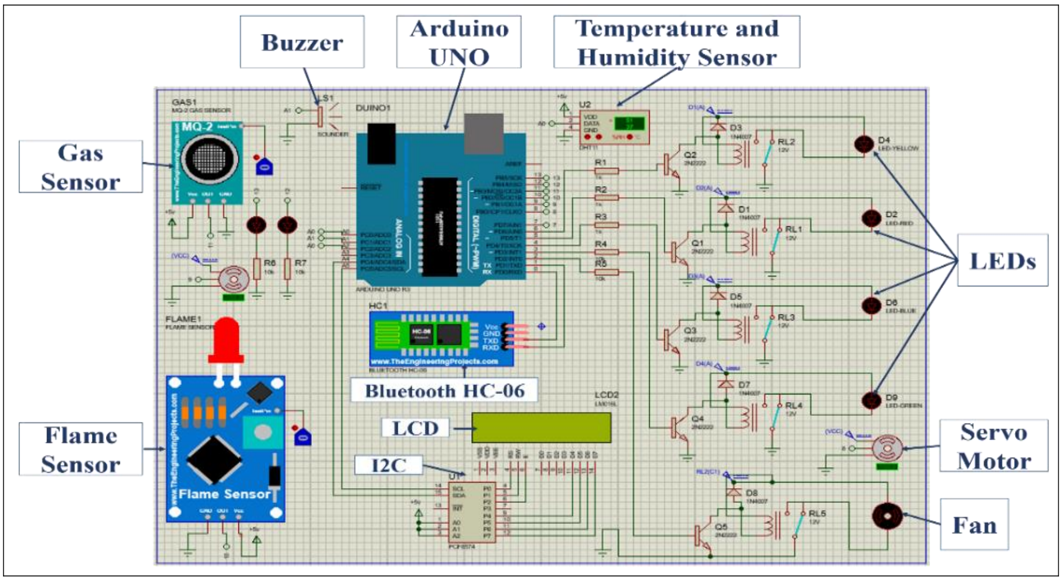

Figure 4.10 Scheme of M2M-Smart home automation.

The implemented system comprises two important services which are gas and fire detection and managing home appliances by voice (lighting, door, fan, etc) as illustrated in Figure 4.11. Our solution differs from other systems in that all implemented services can be controlled and monitored via a single interface in Raniso App using Bluetooth wireless technology. Besides, the design we offer is suitable for the elderly and disabled and also provides a versatile home automation system that can be simply integrated into an existing home. In addition, it allows control and monitoring of the house, while ensuring safety and comfort.

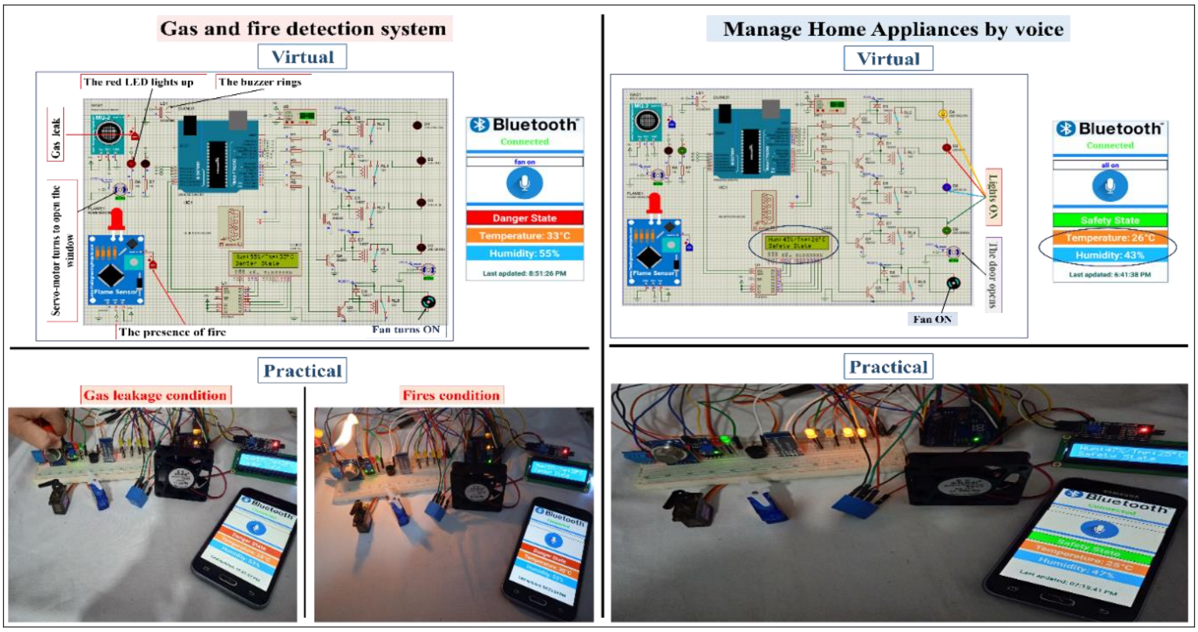

Figure 4.11 Implementation of M2M smart home automation.

4.4.2 A Smart environment management based on two IoT/M2M platforms

4.4.2.1 Architecture design of the proposed system

The proposed architectural design for an IoT/M2M smart environment system incorporates numerous smart services that users can remotely control and monitor via Blynk or Raniso applications through Wi-Fi. This infrastructure supports facility owners, operators, and managers in enhancing asset reliability and performance while reducing energy consumption. It also ensures environmental safety and comfort through the use of efficient, low-cost components. Figure 4.12 depicts the proposed architecture for the IoT/M2M smart environment system.

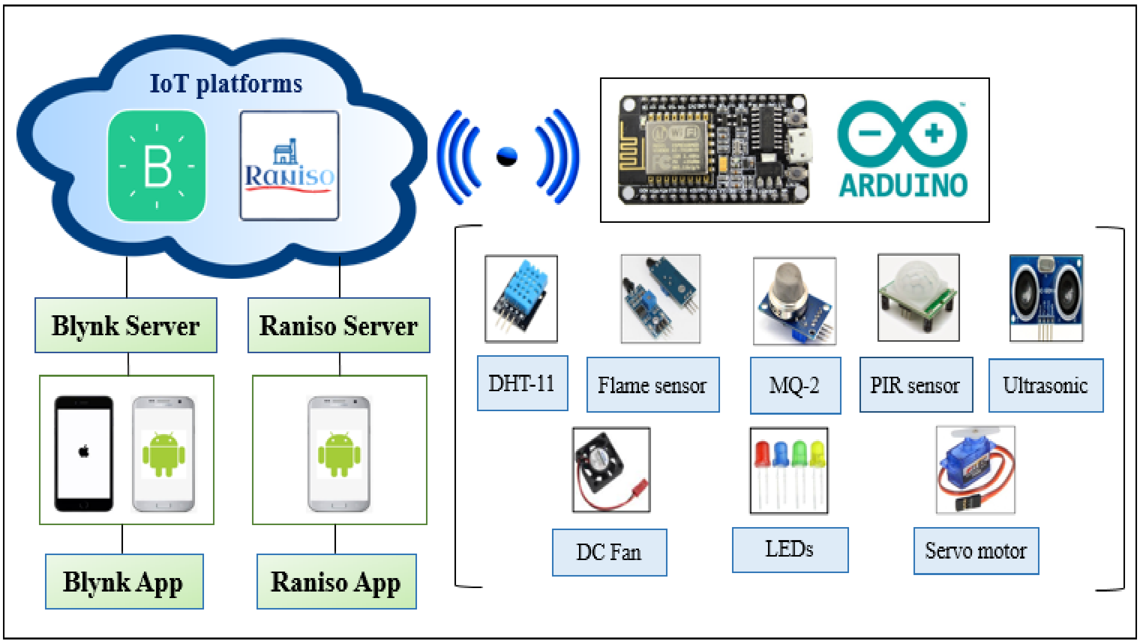

Figure 4.12 Proposed system architecture.

4.4.2.2 Implementation of Smart environment system based on two IoT/M2M platforms

The proposed IoT/M2M-based smart environment system is based on a NodeMCU board and several compatible sensors like PIR HC-SR501, MQ2, Flame, DHT11, and Ultrason HC-SR04, and actuators such as DC fan, LCD screen, servo-motor, buzzer, and LEDs. It presented carries out numerous functions such as an alarm system, detection of gas and fire, lighting management, climate control, and water tank level monitoring. This intelligent system is executed and assessed through both virtual and practical simulations using Proteus and Arduino IDE software, along with various components designed to work with the NodeMCU board, as shown in Figure 4.13 and Figure 4.14.

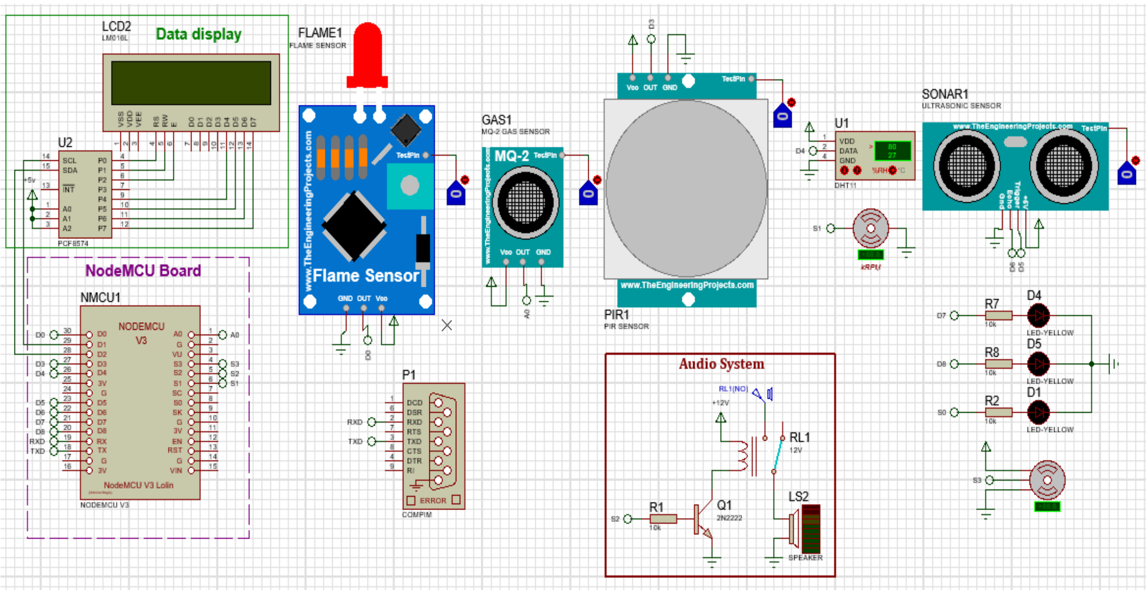

Figure 4.13 Circuit diagram of the smart environment system simulated using Proteus.

Figure 4.14 A practical proposal for the smart environment system based on two IoT/M2M platforms.

The proposed system allows users to oversee their surroundings from any location and at any moment using the Raniso or Blynk Apps, sending real-time notifications in the event of potential hazards such as intrusions, fires, or gas leaks. Furthermore, the suggested system takes specific measures like emitting a sound to serve as an alarm alerting individuals to danger, opening windows to mitigate fire damage and gas-related consequences, and more. The lighting aspect focuses on energy efficiency, convenience, and security by enabling remote control of lights through Blynk or Raniso apps. Moreover, this smart environment system allows users to track climatic conditions, such as temperature, humidity, and fan management, remotely through the internet utilizing Raniso and Blynk Apps (see Figure 4.15 and Figure 4.16). Additionally, with these two IoT/M2M platforms, online monitoring of the water tank is possible.

Figure 4.15 The user interface of the Raniso App in different conditions.

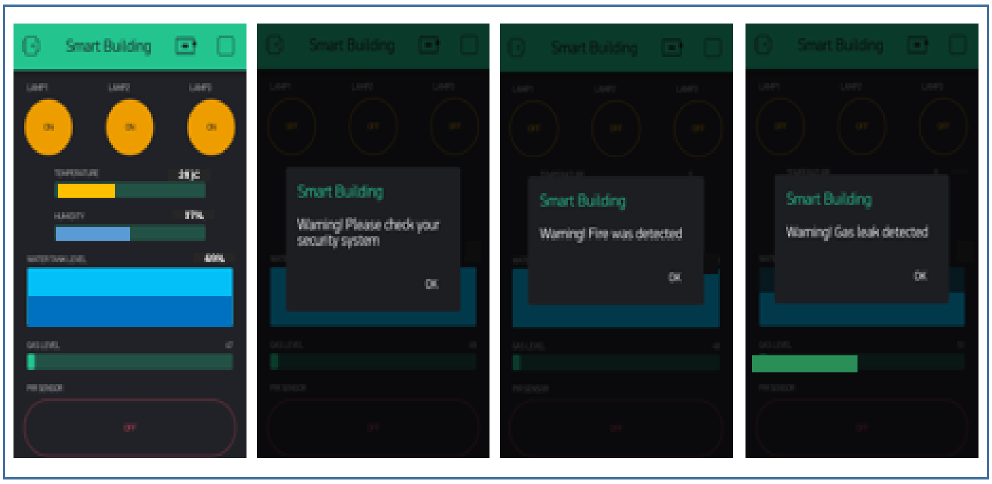

Figure 4.16 The user interface of the Blynk App in different conditions.

Figure 4.17 demonstrates the implementation of the proposed IoT/M2M-based smart environment system under various conditions.

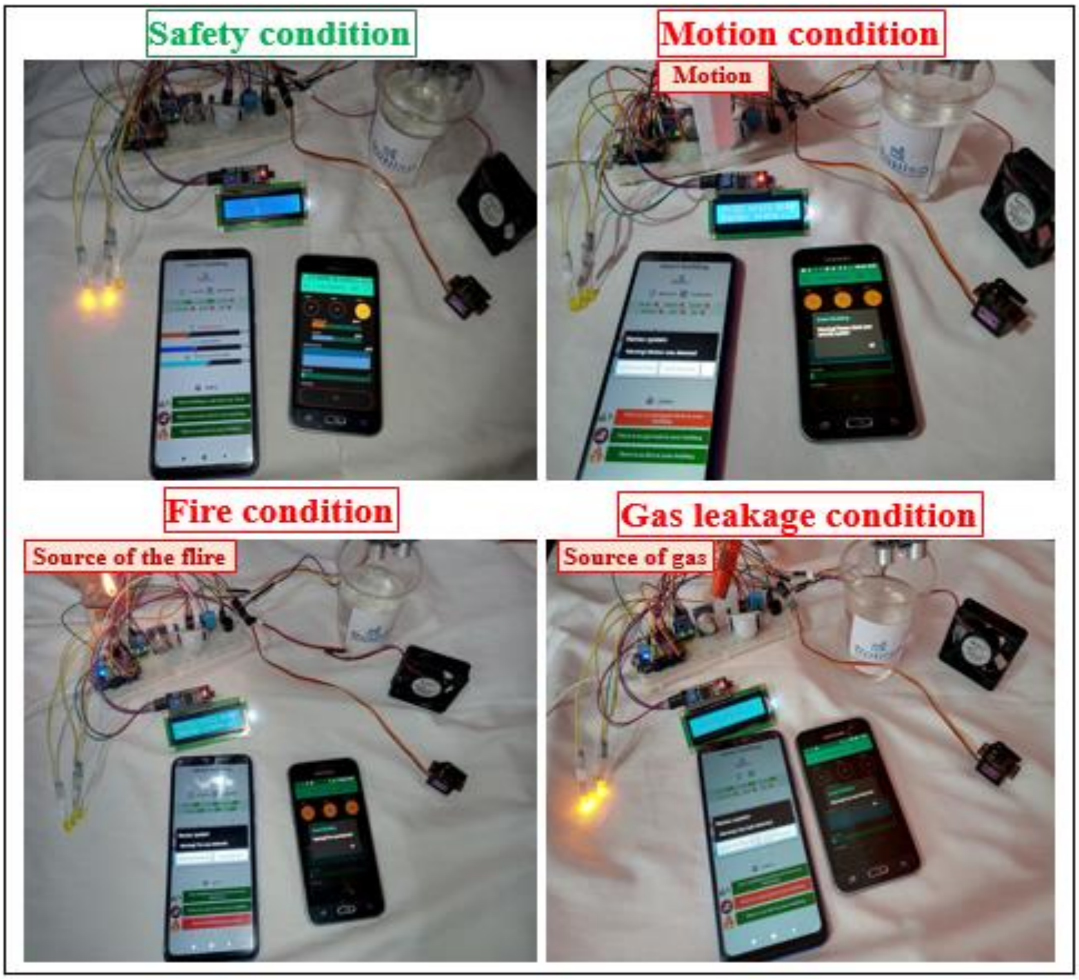

Figure 4.17 The proposed IoT/M2M smart environment system in different conditions.

4.4.3 Design, Implementation, and Deployment of IoT/M2M Smart City Applications based on MCNs

4.4.3.1 Architecture Design

The proposed architectural design for IoT/M2M smart city-based mobile cellular networks uses Raniso and Blynk apps and a variety of well-known hardware such as the Arduino microcontroller which represents the brain and the NodeMCU board as the wireless communications. The main applications proposed are smart safety; which consists of (fire and gas detection, an air quality monitoring system, and an automatic railway crossing system), smart agriculture, and smart parking; which citizens can remotely control and monitor the city through the Raniso or Blynk Apps via different mobile cellular networks like 2G, 4G/5G. This IoT/M2M smart city infrastructure prevents the loss of resources and human lives, also improves operational efficiency, and provides a better quality of government service and citizen welfare [15]. Figure 4.18 shows the proposed architectural design for the IoT/M2M smart city system.

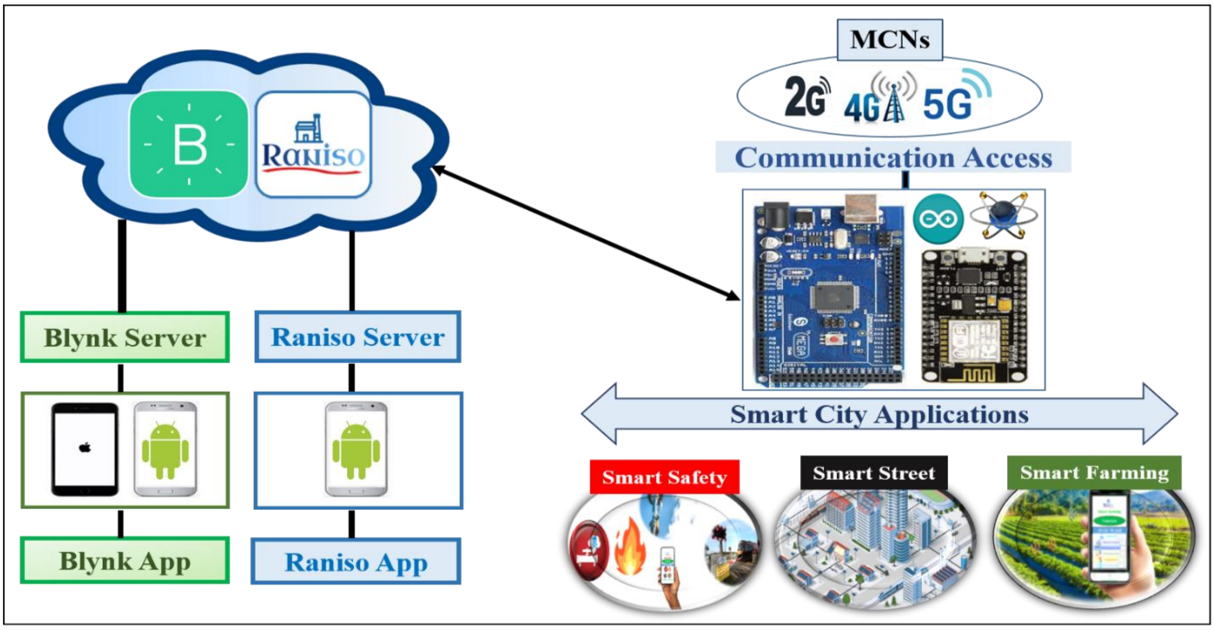

Figure 4.18 System design architecture.

Figure 4.19 shows the four interfaces of the Raniso App used for the proposed IoT/M2M Smart City.

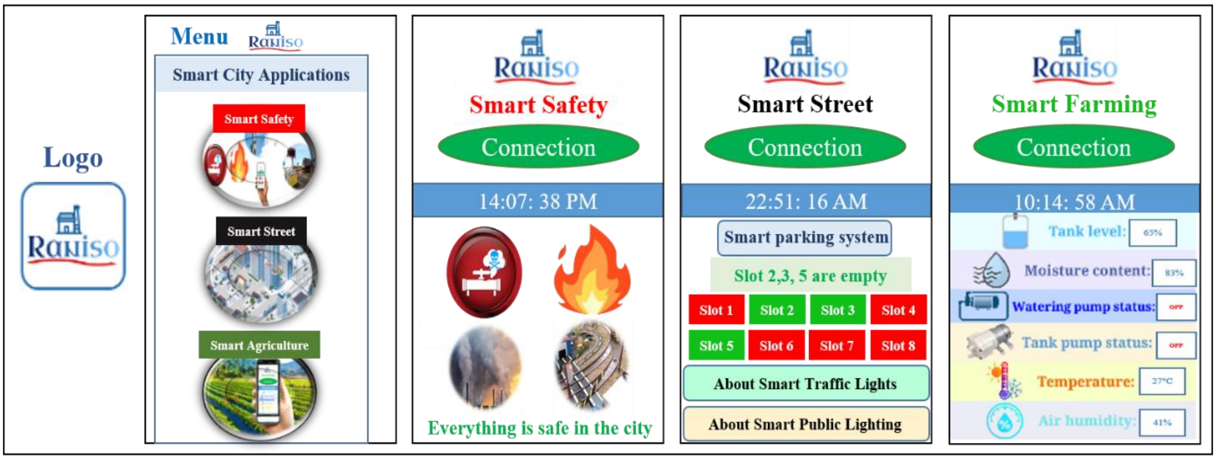

Figure 4.19 The four interfaces of the Raniso App used for the proposed IoT/M2M Smart City.

4.4.3.2 Implementation of Smart City Applications

A. Smart Safety

The proposed smart safety system incorporates flame and MQ2 sensors for fire and gas detection, an MQ135 sensor for air quality assessment, an ultrasonic sensor to determine the arrival of a train, and a DHT11 sensor to measure temperature and humidity levels. Additionally, GSM and GPS modules are included to transmit SMS/calls and incident location data to authorities like the police, fire station, or civil protection. In addition, the audio system is used to alert citizens in case of danger, and all information about the city is displayed on the

LCD screen and the interface of the Raniso app. This sophisticated safety system offers three primary services: fire and gas detection, an air quality monitoring system, and an automatic railway crossing system designed to close gates as trains approach, preventing vehicles from crossing the tracks. While, in case of fire and gas leakage, the gas and electricity meter will automatically turn OFF and the servo motor will open the water sprayer. Besides, in the case of air pollution, the air purifier will automatically turn ON. This proposed IoT/M2M smart safety system enables real-time alerts for citizens before disasters strike and allow authorities to make data-driven policy and infrastructure planning decisions. Figure 4.20 illustrates a schematic of the proposed smart safety system simulated with Proteus, while Figure 4.21 shows the implemented smart safety system.

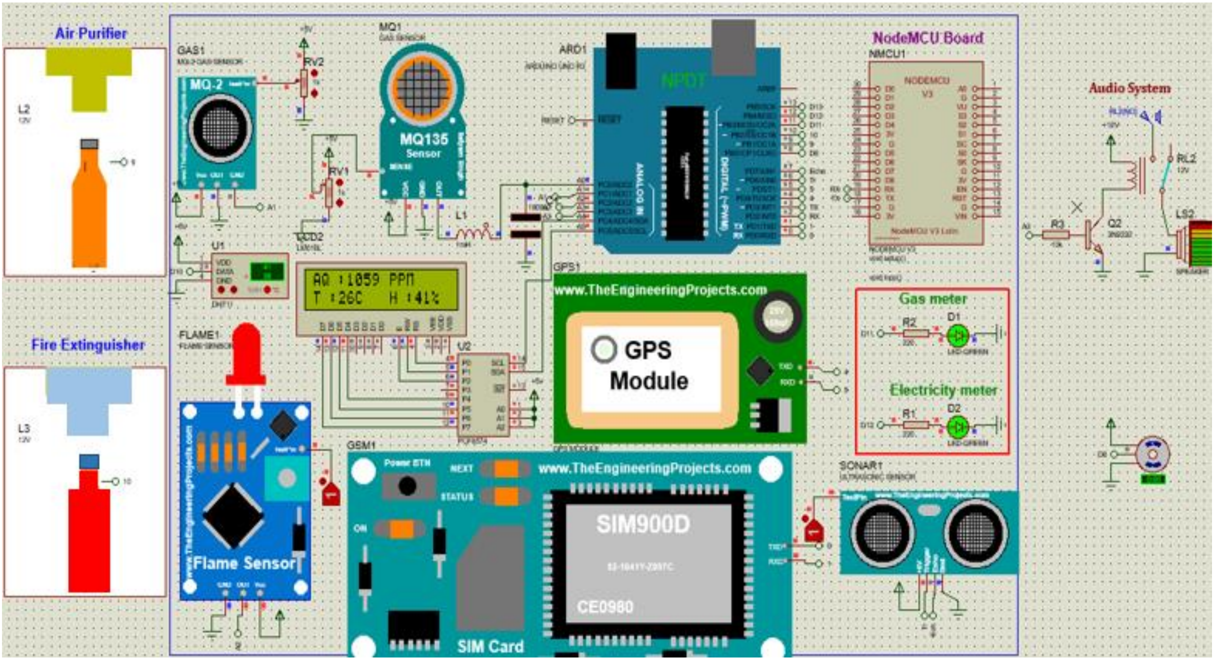

Figure 4.20 Schematic of the smart safety system simulated using Proteus.

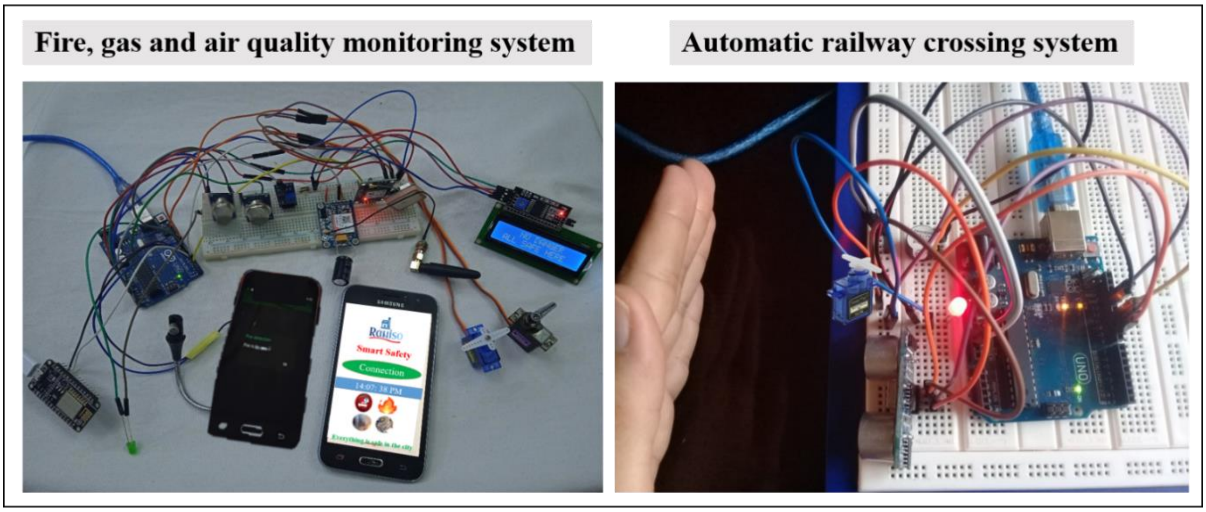

Figure 4.21 The implemented smart safety system.

B. Smart Street

The proposed smart street system consists of three main smart subsystems, namely smart parking, smart traffic light, and smart public lighting. The proposed smart parking includes an IoT/M2M-based system that provides real-time data on the availability of all parking spaces. GSM shield, vibration sensor, infrared sensors, and servo motor. IR sensors detect the presence of a vehicle and the servomotor acts as a gate to allow cars to enter and exit. A vibration sensor is used to prevent vehicle theft by detecting the vehicle's status in theft mode and sending an automatically generated SMS via a GSM shield. All information is displayed on the Raniso App interface and the Blynk App. While the proposed smart traffic light is designed to optimize traffic flow by adjusting the timing of traffic lights based on real-time traffic conditions. This intelligent system uses IR sensors for vehicle detection, Esp32-Camera to detect the presence of emergency vehicles and give them priority at intersections, and traffic lights (Red, Yellow, and Green LEDs). One of the key features of this smart traffic light is its ability to communicate with other traffic lights in the area. This allows them to coordinate with each other and create a synchronized flow of traffic that can help reduce delays and improve overall efficiency. In addition to coordinating with other traffic lights, this proposed smart traffic light can also communicate with smart vehicles to provide real-time information about traffic conditions and suggest alternate routes. Road users can also be provided with the necessary information about traffic through the Raniso App. In addition, the proposed smart public lighting is designed to be more energy-efficient, cost-effective, and environmentally friendly than traditional lighting systems. This smart system is based on LDR sensors and lamps. One of the key features of this smart public lighting is its ability to adjust its brightness based on real-time conditions, as well as, it can also be controlled remotely using the Internet. This allows operators to adjust the lighting levels or turn lights on and off as needed from a central location. This can help reduce maintenance costs and improve overall efficiency. Another important feature of smart public lighting is its ability to collect data about usage patterns and energy consumption. This data can be used to optimize the system for maximum efficiency and cost savings. Overall, Smart Street is an important part of modern urban infrastructure, helping to improve safety, reduce energy consumption, and create more sustainable cities. Figure 4.22 illustrates a schematic of the proposed smart street system simulated using Proteus, while Figure 4.23 shows the implemented smart street system.

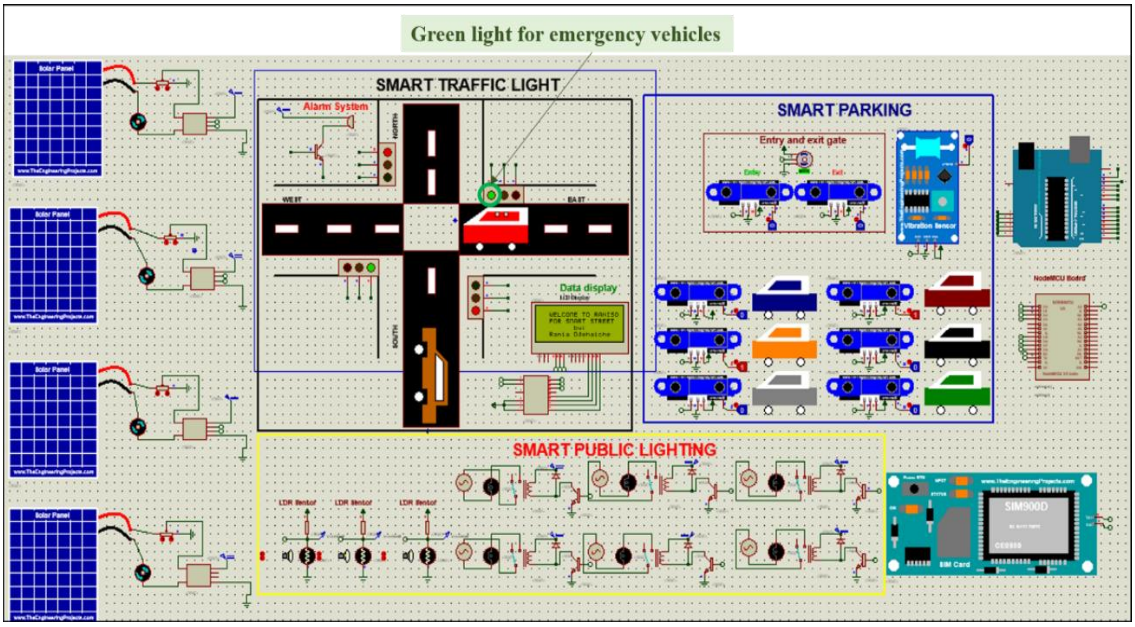

Figure 4.22 Schematic of the smart street system simulated using Proteus.

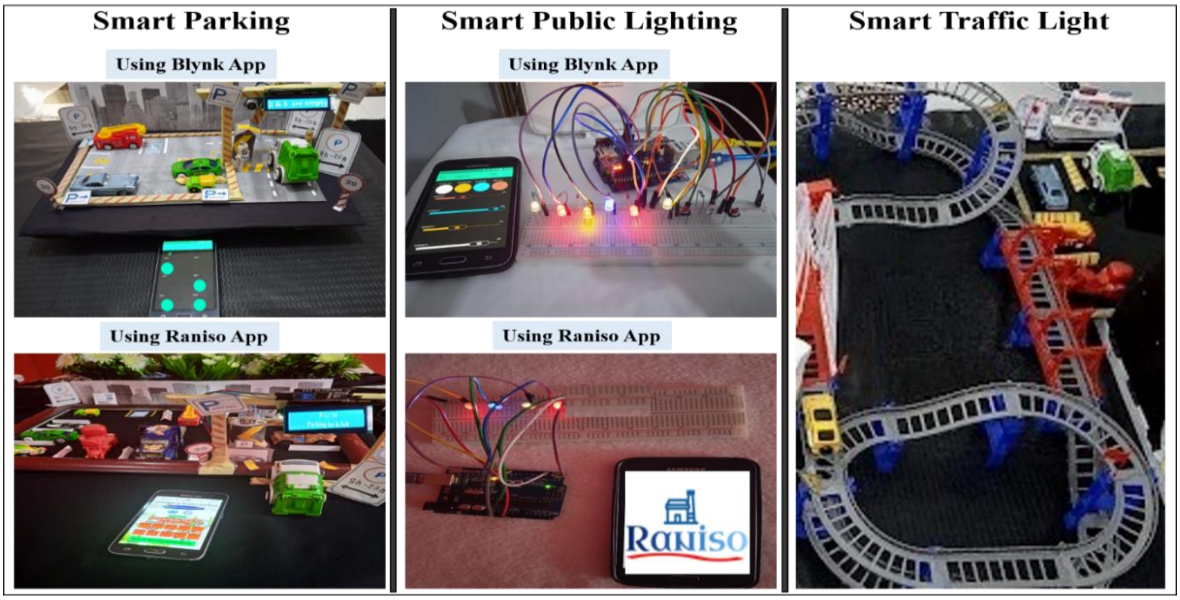

Figure 4.23 The implemented smart street system.

C. Smart Farming

The proposed smart farming system is based on a soil moisture sensor for measuring the soil moisture percentage; a DHT11 sensor for tracking temperature and humidity levels; a water level sensor for gauging the water level within the tank, a rain sensor for identifying precipitation; two pumps, one for plant watering and another for filling the tank, an LCD screen displaying water levels, moisture content, and pump statuses. The rainfall detection mechanism is employed to store rainwater in a water tank to be used in irrigation. The proposed smart farming system operates as follows: when the soil is dry, the watering pump activates to hydrate the plants and turns OFF once the soil is damp, thus conserving water. Figure 4.24 shows a schematic of the smart farming simulated using Proteus, while Figure 4.25 illustrates the implemented smart farming system. This smart farming system can also be remotely controlled and monitored anywhere via Raniso or Blynk apps, making it easy to manage irrigation systems and make necessary adjustments in real-time.

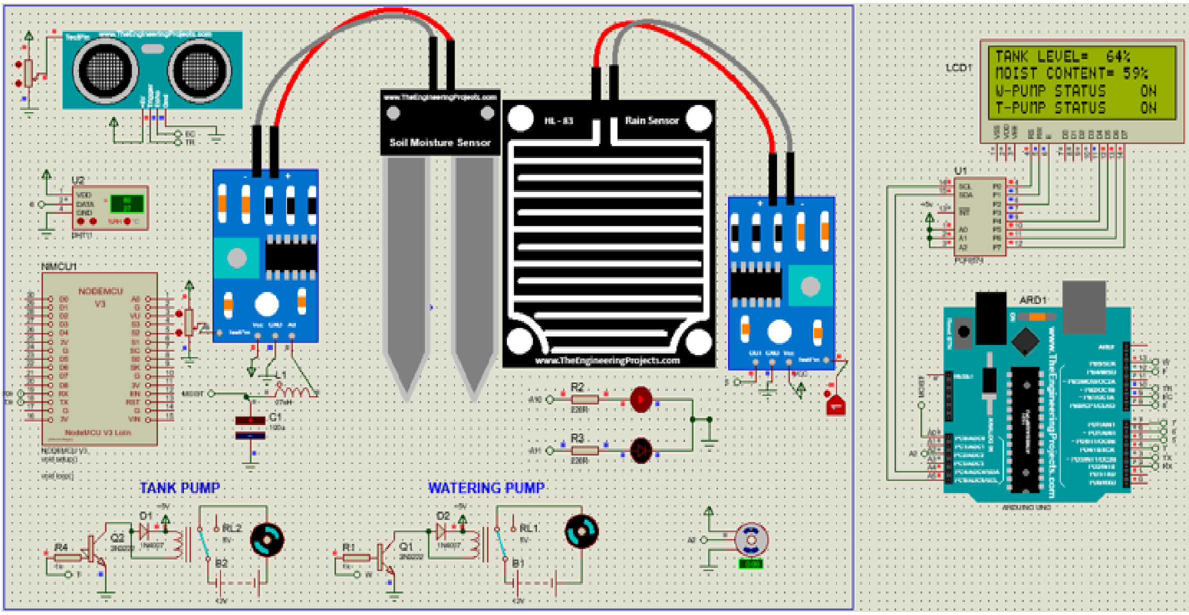

Figure 4.24 Schematic of the smart farming system simulated with Proteus.

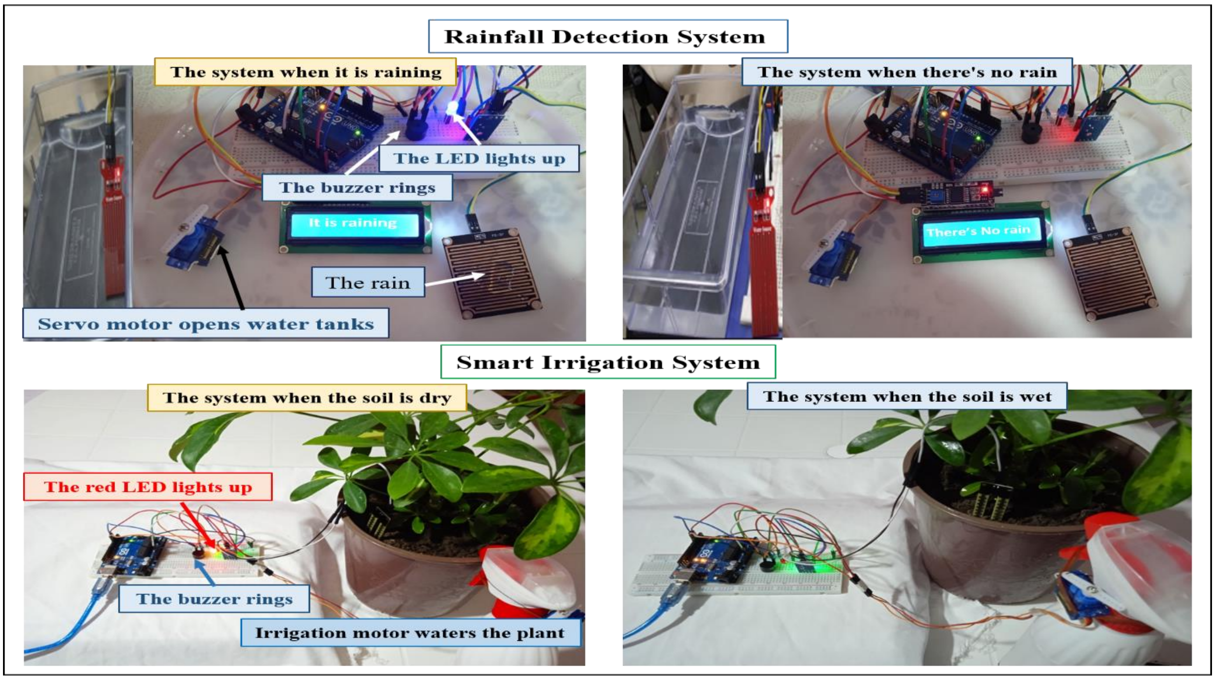

Figure 4.25 The implemented smart farming system.

4.4.3.3 Implementation of IoT/M2M applications in the final model of the smart city

This is the final stage of realizing the proposed IoT/M2M smart city, in which we have used Arduino Mega and Arduino UNO boards along with the NodeMCU to perfectly meet the requirements of the system. In this last step, we implemented all the smart applications proposed in the final prototype, and all of them work well as shown in Figure 4.26.

Figure 4.26 Smart city model.

4.4.4 IoT/M2M-based Health Monitoring System for Persons in Quarantine

The proposed IoT/M2M smart health monitoring system for persons in quarantine (see Figure 4.27 and Figure 4.28) consists of two subsystems. The first one is an automatic sanitizer dispenser which is based on an ultrasonic sensor, servo motor, water pump, and a relay. This system is a hygienic method of handwashing and helps prevent the spread of viruses, such as COVID-19. The second system is designed to monitor the user's key health markers, namely the speed of the heartbeat using a heartbeat sensor, body temperature measurement using an LM35 sensor, room temperature and humidity using a DHT11 sensor, and indoor air quality using an MQ-135 sensor. This proposed IoT/M2M smart health monitoring system is extremely versatile and can be monitored via the internet using the Raniso app, which displays all the user's key health indicators and allows direct communication between patients and caregivers anytime, anywhere (see Figure 4.29). The system also quickly alerts healthcare providers when the patient needs help by sending calls and SMS that include the patient's location. There are many locations where this IoT/M2M smart health monitoring system can be used, including healthcare facilities, hospitals, schools, or households.

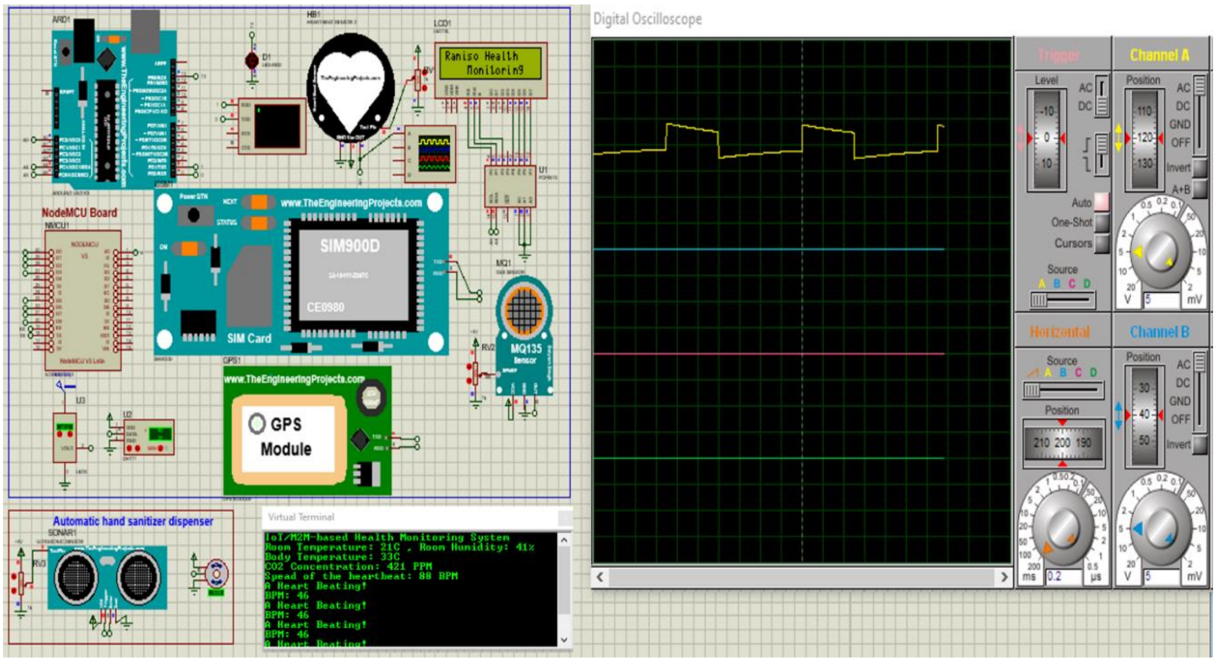

Figure 4.27 Schematic of the smart health monitoring system simulated using Proteus.

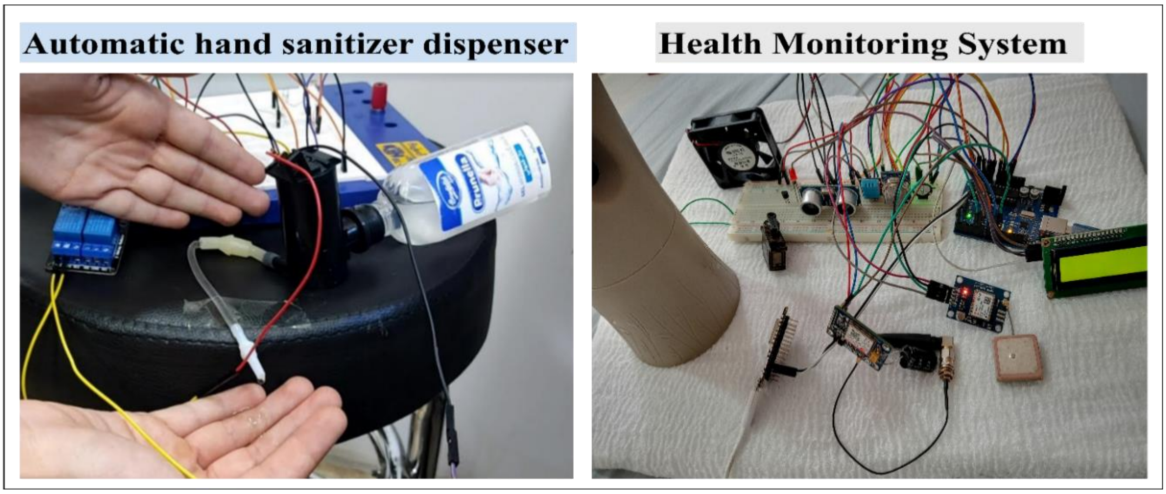

Figure 4.28 The implemented smart health monitoring system.

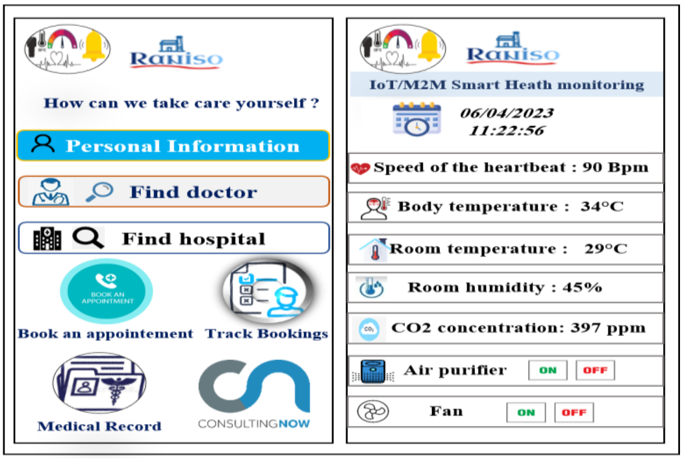

Figure 4.29 Smart health monitoring system interfaces on the Raniso App.

As shown in Figure 4.30, the system alerts healthcare providers by sending calls and SMS showing the patient's location when he is suspected of being infected with COVID-19. This is to speed up the delivery of medical care to him, thereby saving his life and preventing the spread of infection. Figure 4. 31 shows the pulse monitoring graph on the Serial Plotter tool.

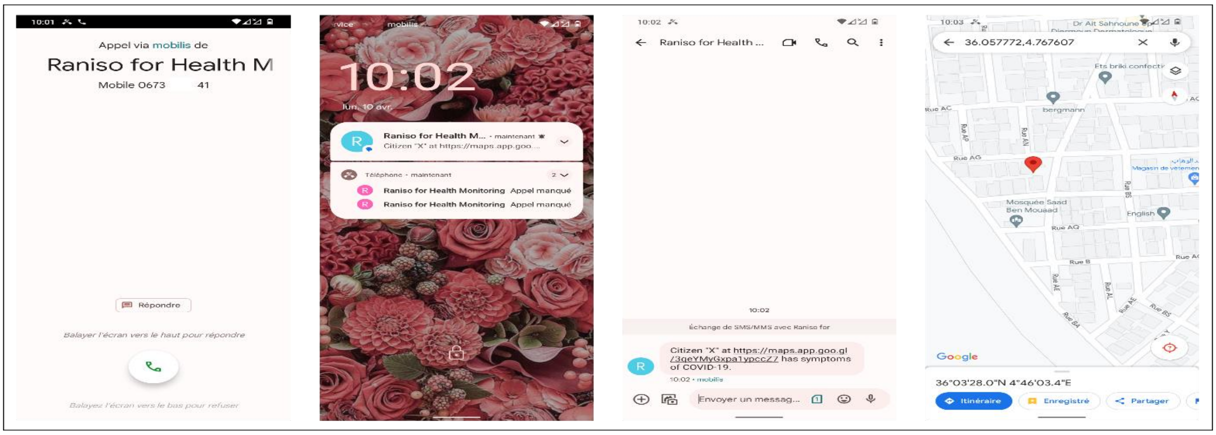

Figure 4.30 Call and SMS alerts for a suspected case of COVID-19.

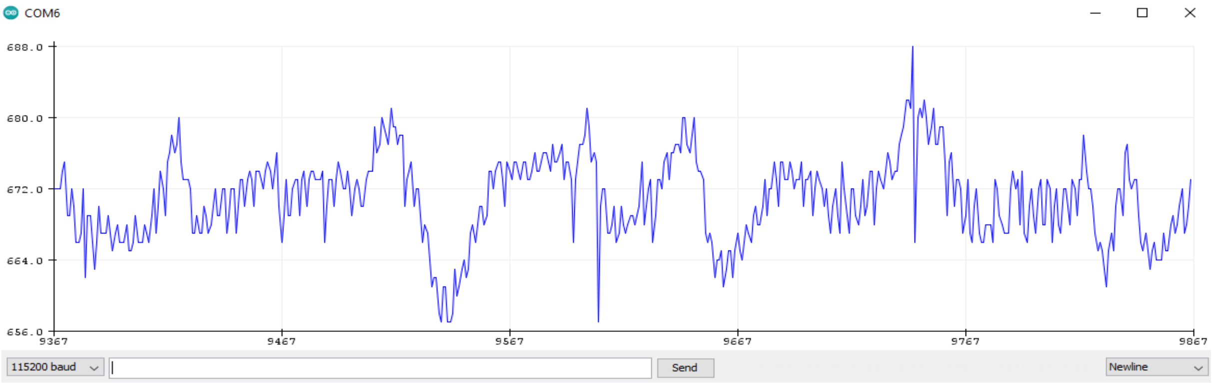

Figure 4. 31 Pulse monitoring graph on the Serial Plotter tool.

4.5 Conclusion

In conclusion, the field of IoT/M2M communications has witnessed the development of various models, frameworks, and theories for the design, implementation, and deployment of wireless networks for IoT/M2M applications in different domains. This thesis chapter has focused on the design, implementation, and deployment of IoT/M2M Smart-X systems-based wireless networks. The IoT/M2M Smart-X systems implemented in this chapter included a smart home automation system, smart environment, smart city, and smart health monitoring system. This chapter described the hardware and software used to implement each of these systems, as well as details each proposed system by explaining its architectural design and details of its deployment and implementation.

CHAPTER 5

Adaptive Control of IoT/M2M Devices in Smart Buildings using Heterogeneous Wireless Networks

Contents of Chapter 5

5.1 Introduction

With the rapid development of wireless communication technology, the IoT/M2M paradigm has become increasingly crucial for a wide range of applications. One of the most emblematic IoT/M2M applications is smart buildings. This chapter proposes a better approach of using heterogeneous wireless networks consisting of WSNs and MCNs for IoT/M2M smart building systems and compared with several related works. In this chapter we present in details the architecture design and the main results of the proposed system, which provides accurate readings to the server and very low latency, through which users can easily control and monitor remotely all the proposed services detailed in this chapter, namely smart parking, garden irrigation automation, intrusion alarm, smart door system, managing building devices, fire and gas detection, smart lighting, smart health monitoring system, indoor air quality monitoring, weather station system, smart garbage management system and smart energy. All these services are designed and implemented to control and monitor from afar the building via “Raniso”. After detailing the proposed system, we deployed and tested it, and it performed as expected; it is adaptable to the needs of users, improving safety and quality of life while reducing energy consumption. It also helps prevent the loss of resources and lives by identifying and managing risks. We end our chapter with a conclusion.

5.2 State of the art

Recently, with the rise of IoT/M2M applications based on heterogeneous wireless networks, there has been a rapid progression of smart building applications. This has increased the size of automated environments, starting from the living room and moving to the apartment, then to entire buildings, and finally to the more general scenario of smart cities. In this section, previous research on IoT/M2M smart building-based wireless technologies, including both WSNs and MCNs, are reviewed.

Researchers in [74] present the development of an Artificial Intelligence-Based Smart Building Automation Controller (AIBSBAC), which includes an intelligent user identification subsystem, an intelligent decision-making subsystem, internal and external environment monitoring subsystems, and a universal infrared communication system. The AIBSBAC system can dynamically adapt to user decisions aimed at improving energy efficiency, user comfort, and security. Heterogeneous wireless connectivity, represented by RF, Ethernet, and Bluetooth technologies, connects AIBSBAC to electrical devices. In contrast, the proposed system included only a few applications and ignored many of the other important applications (such as fire and gas detection). Reference [75] presents an intelligent building system adaptable to office environments. The proposed system is based on the ZigBee wireless sensor network coupled with Java and Android; to develop a platform for automated and manual control of devices to track real-time environmental data of smart building systems. However, using only ZigBee as the WSN in the system has disadvantages, including short range, low data transmission speed, high maintenance cost, low transmission, and low network stability.

Reference [76] focused on monitoring household appliances via IoT, using various sensors to monitor temperature, fire and gas, and an LCD screen to display the sensor values. If a gas leak or fire is detected, the system immediately sends a text message to the user's mobile phone, activates the siren, activates the spray engine, and displays a message on the LCD screen to warn the user. While the IoT is being used to improve security, the communication between sensors and transducers is done wirelessly using a single chip via Wi-Fi. However, the system has some limitations: The Wi-Fi data transfer rate decreases as the number of users increases, and GSM is expensive due to SMS charges.

A prototype home system based on heterogeneous wireless networks (Wi-Fi, Bluetooth, and RFID) for control and monitoring is proposed in [69]. The system is based on two components: the first is an automation system built using an Arduino UNO, which is responsible for reading and processing different types of sensor values. The second component is the security system and the outdoor lighting, using NodeMCU to monitor the security status of the house from anywhere through a dedicated Graphical User Interface (GUI) programmed in HTML, which allows the user to monitor the security of the house and to turn on and off the outdoor lights using a specific IP address provided by NodeMCU. However, the applications implemented are very basic and non-innovative, in addition to neglecting the user's right to choose their wireless communication preferences.

In [65], an IoT-based portable automation system called IoT@HoMe for smart homes was designed and fabricated using NodeMCU as the microcontroller and Internet gateway. In addition to using several sensors to monitor various parameters related to the building, various actuators perform control activities of home devices. The main objective of this research is to create an efficient, affordable, and portable system that can easily monitor home conditions and operate home devices over the Internet at any time and from any location. Similarly, another research [77] presented a multifunctional smart home system using a micro web server based on an Arduino Yún microcontroller with Internet connectivity via an Android-based mobile application. The system can be controlled even when no Wi-Fi connection is available, as it can be accessed via MCNs (e.g. 3G or 4G networks). However, both of these studies [65][77] remain limited in that they rely solely on the Internet for communication and do not take into account the unavailability or interruption of the Internet in some regions.

Using a Raspberry Pi 3 equipped with a camera, an obstacle sensor, and several environmental sensors to detect smart building parameters like temperature, humidity, brightness, and air quality, an IoT-based smart building system for managing indoor environmental conditions was proposed and implemented in [78]. Every 15 minutes, the Raspberry Pi was set up to gather data from the sensors and a picture shot by the camera. The Raspberry Pi additionally has a lightweight neural network that, using images from the camera, could determine the number of persons in the room. The user is unable to communicate with the server and cannot directly use the smartphone to send commands to the Raspberry Pi while he is outside the Wi-Fi AP's service region.

Researchers in [79] discuss an affordable, secure, and energy-efficient Wi-Fi-based smart home system that allows homeowners to monitor their appliances from their mobile phones at home or remotely. This system uses Raspberry Pi and Arduino Mega as microcontrollers and internet gateways for IoT automation monitoring and control. Numerous sensors and actuators are used in the system to monitor various home-related parameters via the Blynk app. Despite this, the Blynk app sometimes becomes unresponsive and displays data/output that may be incorrect in some cases. Also, in some cases, notifications from the Blynk app are delayed in being sent to the user.

In [80], a smart building fire and gas leak alarm system, namely SB112, was proposed, which combines a small-scale, multi-sensor-based system with an open-source edge computing framework and an automated next-generation (NG) 112 emergency call functionality, using ESP32 as microcontroller units and Raspberry Pi as an edge gateway. As part of an end-to-end scenario, key actors such as IoT devices, public safety answering points (PSAP), middleware for a smart city platform, and relevant operators are involved. However, only the fire and gas leak alarm system was used, ignoring other important systems that should be in the smart building, such as those related to energy consumption and comfort.

Table 5.1 summarises and reviews previous research works related to wireless network-based IoT/M2M smart building systems. The comparison of our proposed IoT/M2M smart building using heterogeneous wireless networks with existing systems also highlights its main advantages over these systems. As shown in Table 5.1, the proposed system aims to overcome the limitations of the existing systems. It is based on a simulated scenario with a real implementation for validation purposes. In addition, the main advantages of our system include the ability to connect to the Internet, cloud platforms, and different heterogeneous wireless networks, with support for multiple heterogeneous devices (sensors, actuators, and shields). Users also have the option to control IoT/M2M devices using either push buttons, WSN (Bluetooth or Wi-Fi), MCN (GSM or LTE), or voice commands via Google Assistant. In addition, the Raniso app consists of a user-friendly graphical interface that controls and monitors building system devices and alerts users in case of danger, as well as a visual display that allows users to monitor all building parameters in real time without internet, both indoors and outdoors, such as temperature, humidity, air quality, building status, whether it is safe or not, etc. Furthermore, our proposed system consists of many smart applications and services that should be part of any smart building system, such as smart parking, garden irrigation automation, intrusion detection, smart door, fire and gas detection, smart lighting, smart medication reminders, and indoor air quality monitoring. All of these proposed services contribute to improving the security, comfort, energy savings, and internal and external maintenance of the building system.

Table 5.1 Comparison of related work on.

Reference Num	[74]	[75]	[76]	[69]	[65]	[77]	[78]	[79]	[80]	Proposed system
Smart system	Building	Building	Home	Home	Home	Home	Building	Home	Building	Building
Year	2015	2018	2018	2018	2019	2019	2021	2021	2022	2022
Controller	Arduino	STM32	PC Server	Arduino/ NodeMCU	NodeMCU	Arduino	Raspberry Pi	Arduino/ Raspberry Pi	ESP32/ Raspberry pi	Arduino/ NodeMCU
Protocol	AIBSBAC	ZigBee	Wi-Fi/GSM	RFID/ W-iFi/ Bluetooth	Wi-Fi	Wi-Fi/LTE	Wi-Fi	Wi-Fi	Wi-Fi	RFID/ Wi-Fi/ Bluetooth/ GSM/LTE
WSN	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
MCN			✓			✓				✓
Outdoor Control	✓				✓	✓	✓	✓	✓	✓
Indoor Control	✓	✓		✓	✓	✓	✓	✓	✓	✓
Safety	✓		✓	✓	✓	✓	✓	✓	✓	✓
Energy Efficient	✓	✓			✓		✓	✓		✓

Comfort	✓	✓		✓	✓	✓	✓	✓		✓
Monitoring	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Smartphone	✓			✓	✓	✓	✓	✓		✓
Web-based				✓	✓	✓				✓
Google Assistant					✓					✓
User Preferences	✓									✓
Virtual Simulation of system design		✓						✓		✓
Real Implementation	✓			✓	✓	✓	✓	✓	✓	✓

5.3 Proposed IoT/M2M-based Smart Building System using Heterogeneous Networks

The proposed heterogeneous network infrastructure for the IoT/M2M smart building consists of wireless sensor networks and mobile-cellular networks. Wireless sensor networks are concerned with communication between devices in the building and include WLANs such as Wi-Fi, which support small area connectivity, and WPANs like Bluetooth and RFID, which support short-range connectivity for communication between personal devices. In contrast, mobile cellular networks are the communication network between devices in the building and devices in the outside network and include (WWANs that use mobile telecommunication cellular network technologies such as 2G, 3G, 4G, and 5G/6G. The following equation describes the proposed heterogeneous network infrastructure for the IoT/M2M smart building system.

$$\boldsymbol{HetNets = WSNs_{WLAN_{Wi-Fi}+WPANs_{Bluetooth,\ RFID}} + MCNs_{WWANs_{GSM,\ LTE}}} \qquad (5.\ 1)$$

5.3.1 System Architecture Design

The proposed architecture design for IoT/M2M smart building systems based on heterogeneous networks uses various known hardware to collect and manage data according to the functions and services of a business. The main services offered are smart parking, garden irrigation automation, intrusion alarm, smart door, managing building devices, fire and gas detection, smart lighting, smart health monitoring, indoor air quality monitoring, weather station, smart garbage management, and smart energy. All these services are designed and implemented to remotely control and monitor the building via the Raniso app using RFID/Bluetooth/Wi-Fi connectivity and cellular networks such as GSM, 4G or 5G. This IoT/M2M smart building infrastructure design helps owners, operators and facility managers to improve asset reliability and performance, and is beneficial in preventing the loss of resources and lives due to undesirable events. In addition, the proposed system is energy efficient and low cost and can be used in various buildings such as hospitals, hotels, universities, businesses, etc. Figure 5.1 shows the proposed architectural design.

Figure 5.1 IoT/M2M smart building architecture.

While the proposed architecture layer design for smart buildings is composed of six layers (see Figure 5.2) which are: the physical layer, data gathering layer, communication layer, data management layer, application layer, and intelligence layer. These layers are mutually connected such that the successful implementation of each layer will lead to the success of a specific purpose. Each layer addresses the different needs of the proposed IoT/M2M intelligent building system and is presented in Table 5. 2.

Table 5. 2 Role and functional features of the IoT/M2M smart building layer system.

Physical layer	It is where the hardware, such as sensors and actuators that enable the building to operate, reside, along with the software requirements to build broad communication and sensing capabilities. This layer serves as the foundation for the system design, which is generally concerned with transmitting data wirelessly or through wires to sensors, motors, and any other microcontrollers that are attached.
Data gathering layer	It collects data from different sources and various heterogeneous devices connected to a smart building system. At this layer, pre-processing is carried out and the unnecessary information is detected and removed.
Network layer	It is responsible for the transfer of all the data from the data gathering layer to other layers. It consists of various HetNets such as GSM, 4G/5G, Wi-Fi, Bluetooth, ZigBee, etc. This layer handles all data transfer from the device to the data storage layer, as well as initial data processing and real-time decisions.
Storage layer	It is also called a Data Warehouse and can be used for storing a large amount of data, analyzing, indexing, and searching all the information. This layer provides the infrastructure for SQL and NoSQL databases. It can be used with any SQL and NoSQL database for real-time processing, like VoltDB, MongoDB, Spark, or Storm. This layer handles a large number of loads and makes sure the system runs smoothly and efficiently. Additionally, it can be used to train using different AI and ML techniques. Also, in this layer, predictions and pattern recognition take place.
Intelligence layer	It is where the decision-making functions take place, such as determining what action to take, when to notify occupants of an emergency, and how to inform them of the decision. It uses technics of artificial intelligence, machine learning, big data, and Internet of Things technologies to improve efficiency and sustainability.
Application layer	It is connected to the devices in real-time, so all the events generated are transferred to them. The end users of this last layer are the occupants of the building. This layer is the interface that announces all the information related to the building system, where reports and data in the form of graphs and dashboards are displayed so that people interact to monitor, control all the implemented services and make decisions.

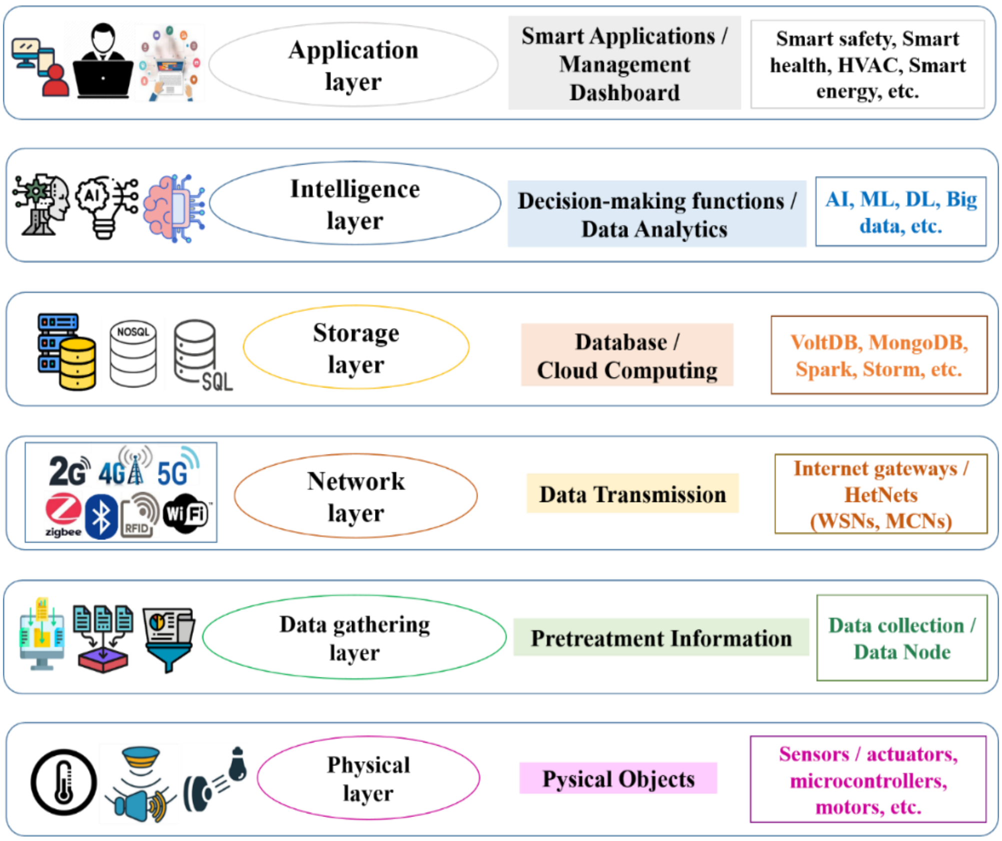

Figure 5.2 AI based IoT/M2M smart building layer system architecture.

Figure 5.3 shows the different interfaces of the Raniso application used for the proposed IoT/M2M smart building.

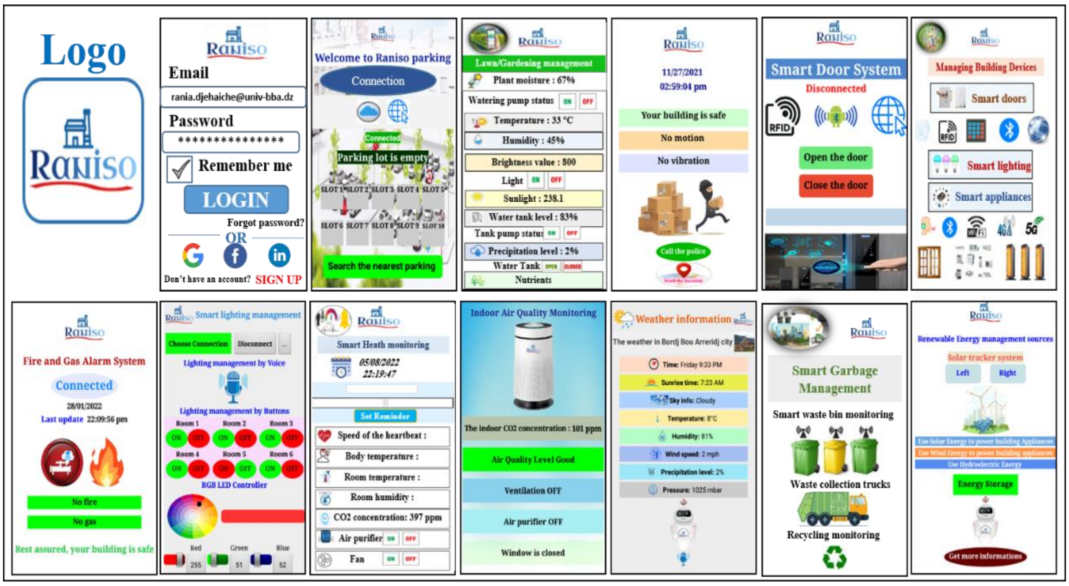

Figure 5.3 The different interfaces of the Raniso App used for the proposed IoT/M2M smart building.

5.4 Designing and implementing IoT/M2M smart building services

This section is dedicated to the simulation and practical implementation of IoT/M2M smart building services. There are two different forms of main processing units used in the implementation of all these services, namely Arduino and NodeMCU. The Arduino is used as the controller of the devices, while the NodeMCU is used as the controller of the phone devices, so that it can control the devices from a distance. In the following, we will explicitly discuss each smart application prototype.

5.4.1 Smart Parking

The smart parking involves an IoT/M2M-based system that sends data on the availability of all parking places in real-time and selects the optimal one. The system comprises an Arduino Uno microcontroller, NodeMCU board, infrared sensors (TCRT5000), servo motor, LCD, speaker, and a battery. Figure 5.4 shows the proposed system prototype for smart parking. Using infrared sensors, the system identifies whether parking spaces are occupied, then scans the number of available spaces and updates data with the cloud server every 30 seconds. The parking slot availability may be checked online from anywhere, and perform hassle-free parking through the smart parking interface of the Raniso App as shown in Figure 5.5. Also, the LCD placed in front of the gate will show which slot is free; besides, when a vehicle is detected in a specific slot, the corresponding LED in the Raniso App lights up. If all spaces are occupied by vehicles, the parking gate will not open, and the audio system will say: "sorry, this parking lot is full; you can search for another available parking lot via the Raniso app." If any spaces are available, the parking gate will open, allowing the vehicle to pass, and the audio system will welcome the user. As a result, this system solves the city parking problem and provides users with a reliable IoT/M2M-based parking management solution. With this solution, users can easily find available, nearby and cheap parking using the interface of the Raniso app equipped with GPS technology, wherever they are and whenever they want as shown on Figure 5.6.

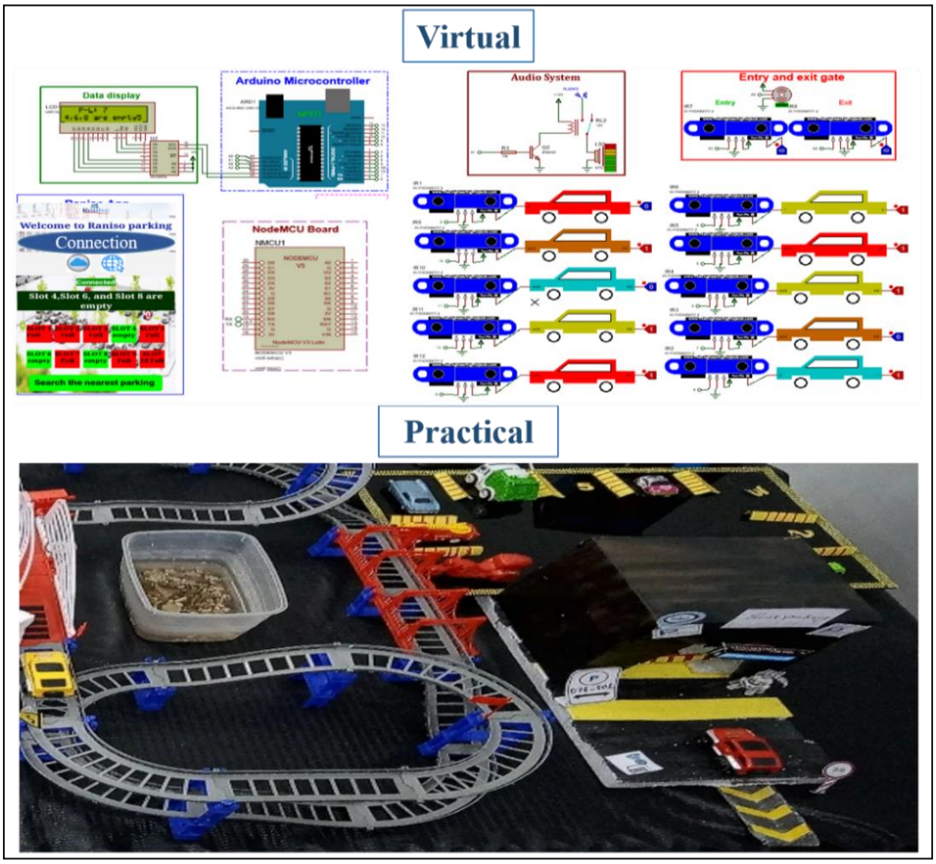

Figure 5.4 The proposed system prototype for smart parking.

Figure 5.5 Smart parking interface on the Raniso App.

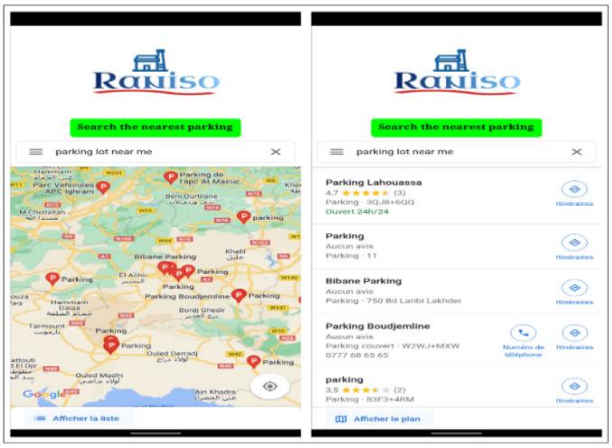

Figure 5.6 Search results for car parks near the user's location on Raniso App.

5.4.2 Garden Irrigation Automation System

The proposed irrigation automation system for gardens refers to the functionality of the system with no or minimal manual intervention, where it monitors the temperature, humidity, light levels and soil moisture of the plant (see Figure 5.7).

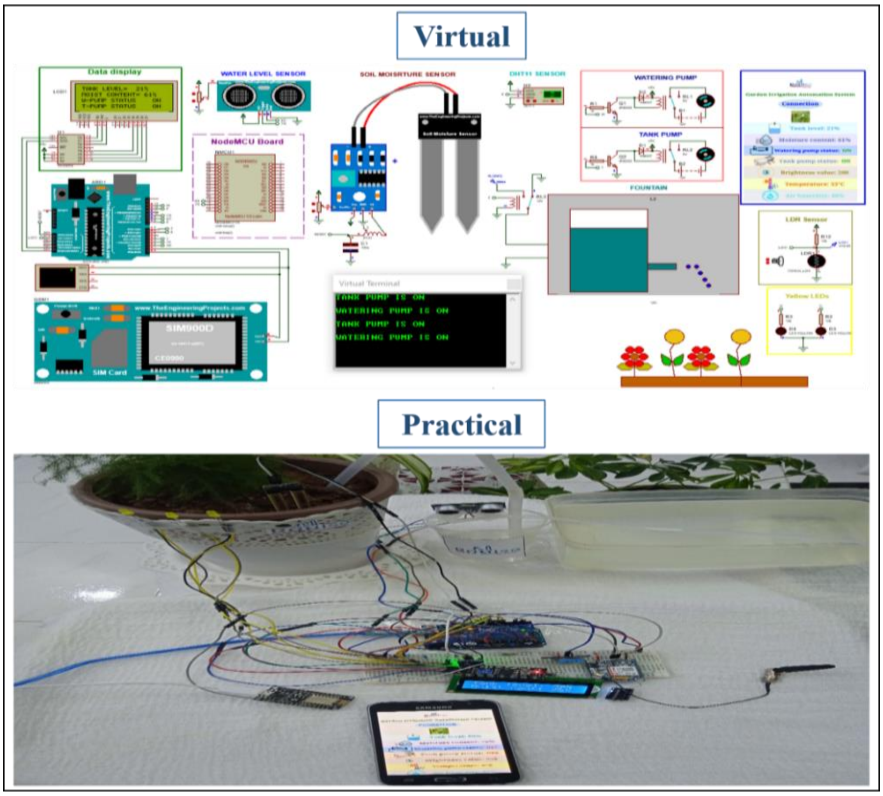

Figure 5.7 Illustration of the garden irrigation automation system.

The system includes a Soil Moisture Sensor to measure the percentage of soil moisture in order to optimise the irrigation dosage to avoid water wastage, a DHT11 sensor to monitor temperature and humidity levels, an LDR sensor to measure light intensity, two yellow LEDs to control the photosynthesis process at night to make the plant grow faster, the ultrasonic sensor

(HC-SR04) to measure the water level in the tank, the GSM module to make calls and send text messages to the farmer if the pump changes its status or if there is a watering problem, the LCD screen to display the water level and moisture content along with the pump status, and two pumps, one to water the plants and the other to supply water to the tank. When the soil is dry, the watering fountain is activated, watering the garden when needed and switching off when the soil is wet to conserve water. In addition, this solution allows remote control and monitoring of the garden irrigation system via the Raniso app (see Figure 5.8) and via our channel in ThingSpeak, which is used to remotely view data from the proposed smart garden system (see Figure 5.9), making it easier to manage the irrigation systems and make necessary adjustments in real time. This system optimises resources (water, energy and fertiliser) and irrigation scheduling through an intelligent monitoring system.

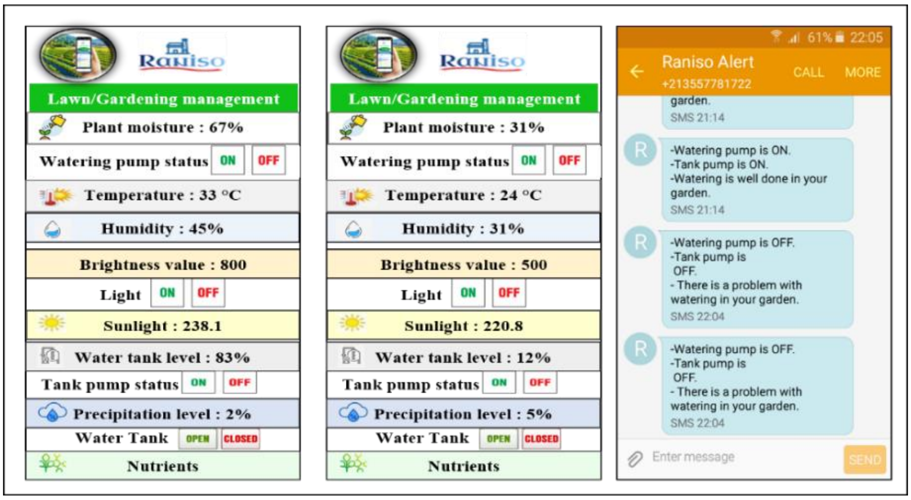

Figure 5.8 Garden irrigation automation interface on the Raniso App.

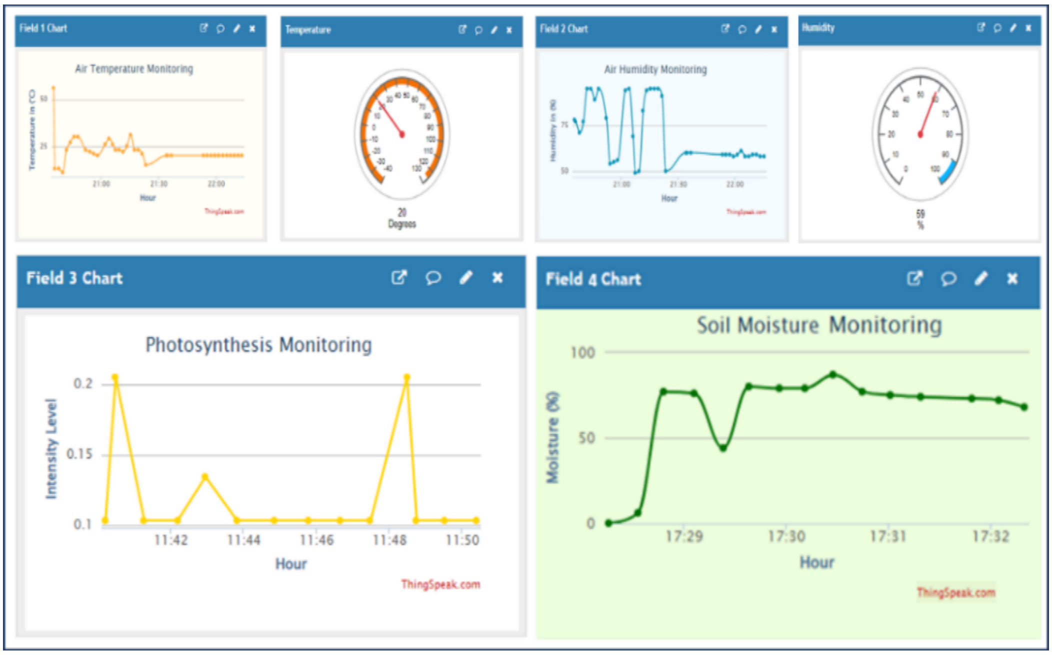

Figure 5.9 Garden Irrigation Monitoring System on ThingSpeak.

5.4.3 Intrusion Alarm System

The increased number of robberies in buildings makes people worried about losing their property. Hence, the proposed service presented in Figure 5.10 enables the protection of the building from theft or attack by using a GSM module, an ultrasonic sensor, a vibration sensor, a speaker, and a red LED. The ultrasonic sensor is used to capture the distance and the vibration sensor to measure the vibrations. When the distance is close and vibrations are detected, the GSM module sends calls and short messages to the owner of the building, the LCD screen shows an alarm state, the red LED lights up, and the speaker emits a sound indicating that there is a theft, where the resulting sound is obtained from a micro SD memory card in MP3 format, which allows users to use the sound of screams, a guard dog, or a siren to scare away the thief. In addition, users can monitor their building from anywhere at any time via the intrusion alarm interface in the Raniso app that sends real-time alerts in the case of any danger, as shown in Figure 5.11 and via our channel in the ThingSpeak platform, as illustrated in Figure 5.12.

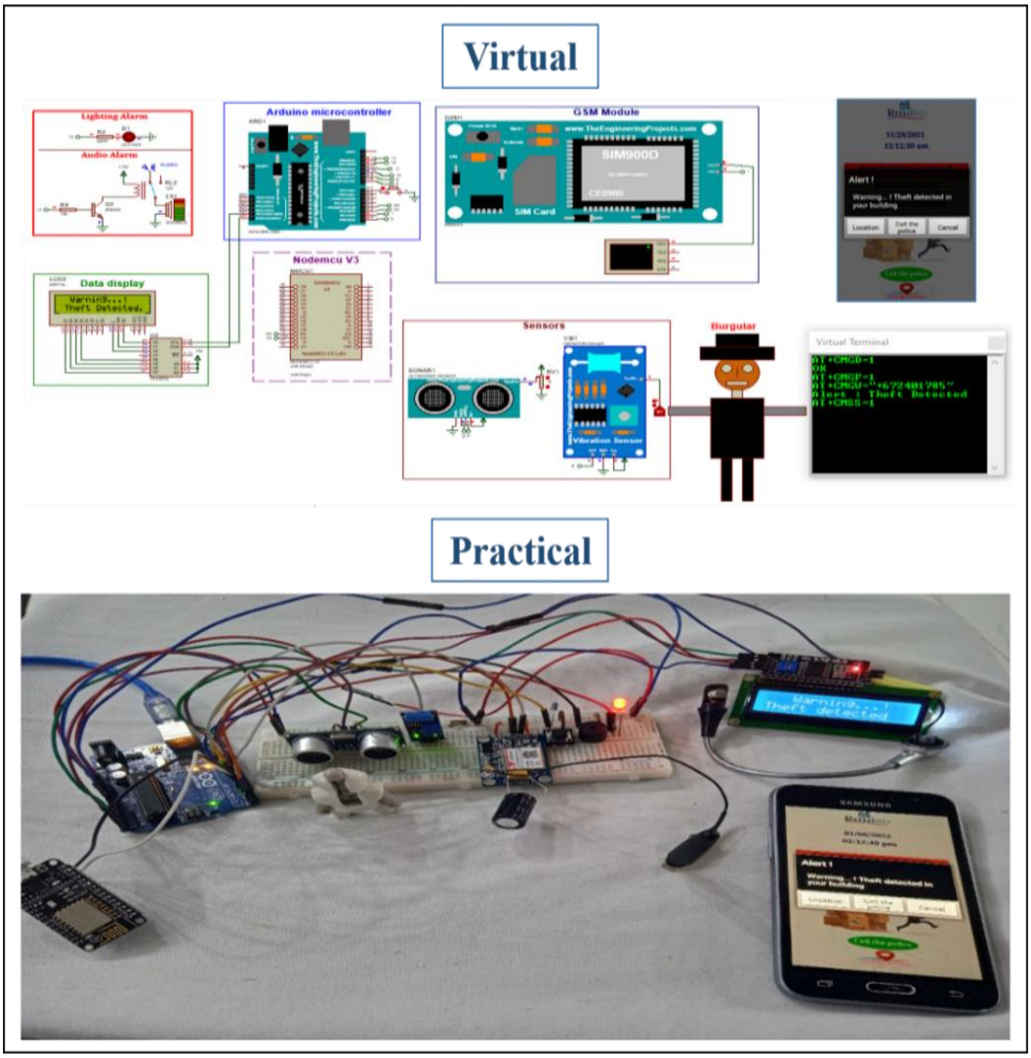

Figure 5.10 Intrusion alarm system.

Figure 5.11 Intrusion alarm interface on the Raniso App.

Figure 5.12 Intrusion alarm system monitoring on ThingSpeak.

5.4.4 Smart Door System

The proposed smart door system is an automatic identification and authentication system deployed at the doors of various buildings, including banks, corporate offices, financial institutions, jewelry stores, government organizations, and so on. It is designed to prevent unauthorized access and violation by using a Bluetooth module, an RFID module, a servo motor, a keypad, an LCD screen, a speaker, a buzzer, and LEDs. Figure 5.13 shows the prototype of the proposed smart door system.

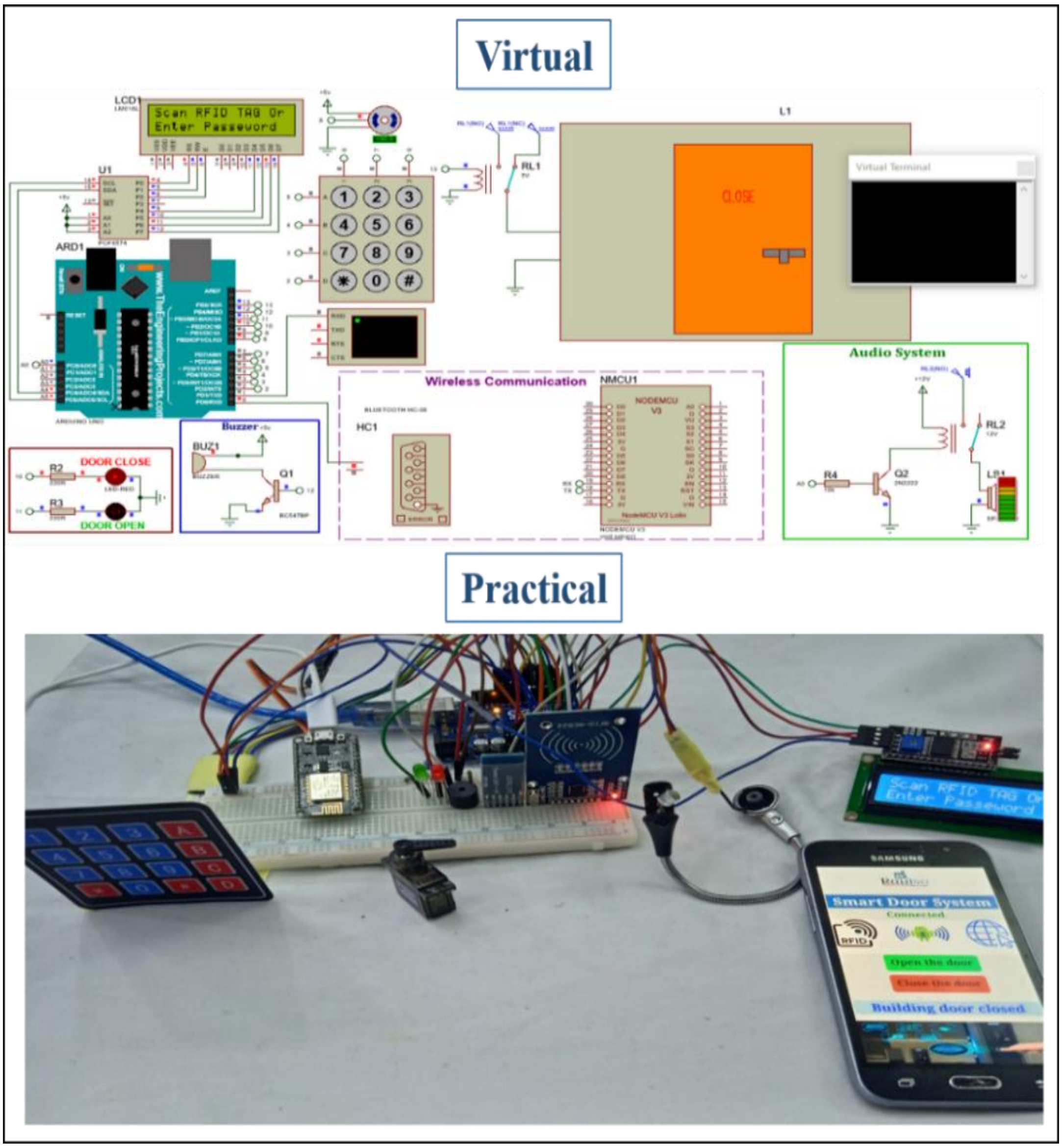

Figure 5.13 Prototype of a smart door system.

As soon as the user approaches the door, the sound system reminds him to disinfect his hands and take all precautions against COVID-19. The LCD screen also displays all the options by which the user can control the keyless door, either by RFID card, password, or remotely via the smart door system interface of the Raniso app using the Bluetooth connection or the Internet via Wi-Fi and 4G/5G (see Figure 5.14), or by face recognition (see Figure 5.15). The system will give access using the Raniso app, or on scanning the right tag or entering the correct password, and on scanning the wrong tag or entering the wrong password; the system will deny; a red LED will light up; and the buzzer will make a beep sound. This solution is intended to control doors in the building with a relatively low-cost design, user-friendly interface, and ease of installation. It also provides a protection system and building security.

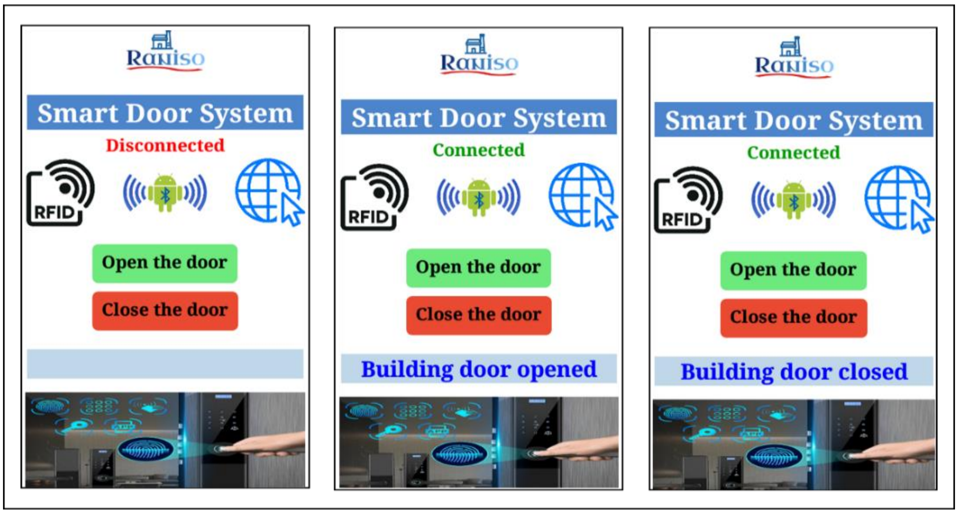

Figure 5.14 Smart door interface on the Raniso App.

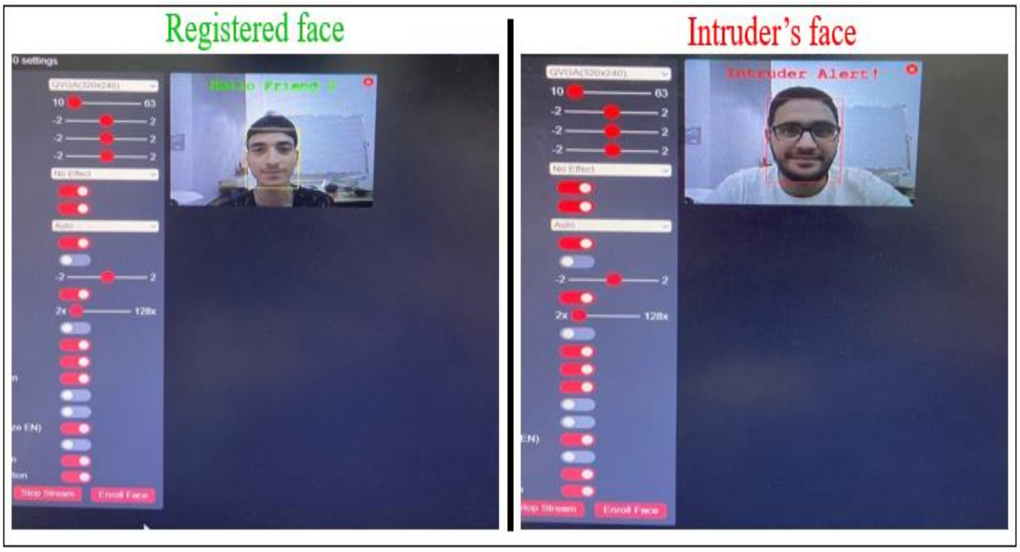

Figure 5.15 Control the door system by facial recognition.

5.4.5 Managing building devices

The proposed building devices management system enables real-time monitoring and control of various appliances to ensure energy efficiency, convenience, and safety (see Figure 5.16). The developed system consists of a smart sensing unit, wireless sensors and actuators, and the Raniso App for remote control. The Raniso App provides users with a consistent and holistic view and control of devices, whether via different heterogeneous networks such as Bluetooth, Wi-Fi, Ethernet, and 2G, 4G/5G networks, or via the use of AI by activating Google Assistant voice commands embedded in the Raniso platform as shown in Figure 5.17. In addition to all this, the system also suggests to the user the best way to control the devices in real-time. For example, in places where the Internet is weak, the system suggests the user activate Bluetooth in the control devices instead of using the Internet. Among the devices we controlled and monitored in this service are doors, windows, fans, heaters, motors, etc.

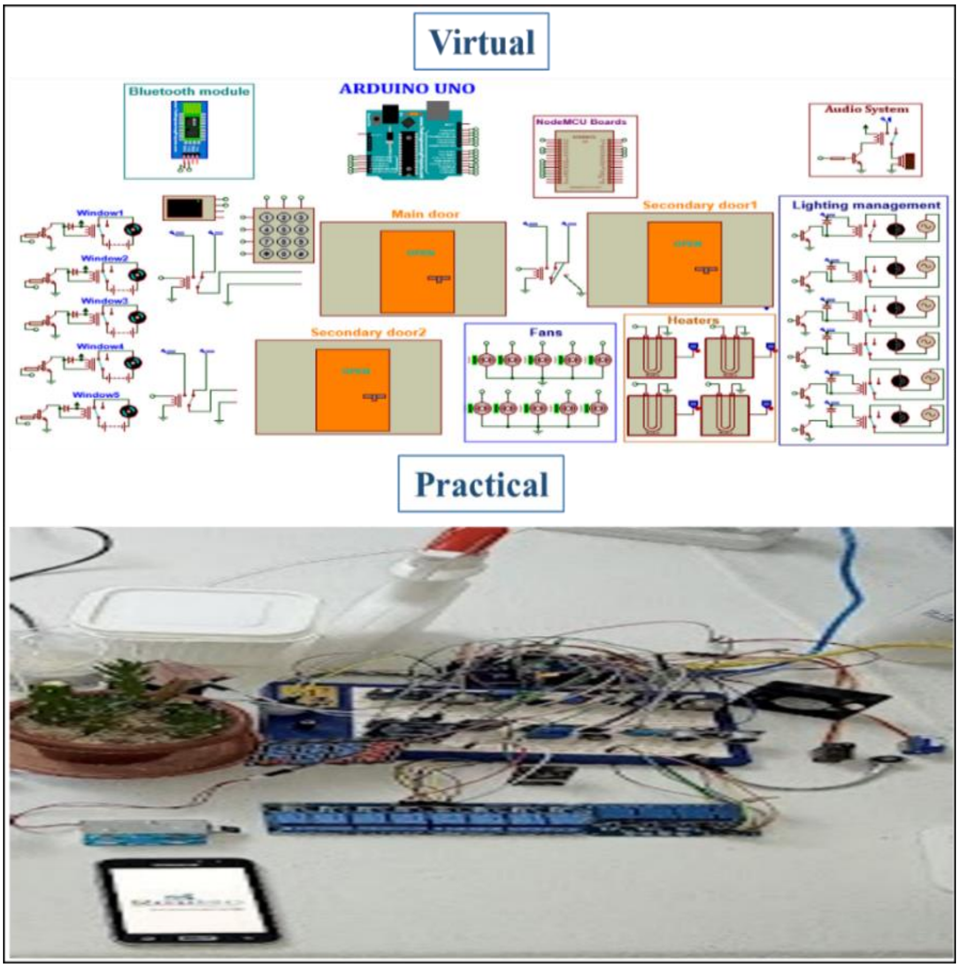

Figure 5.16 Managing building devices.

Figure 5.17 Managing building devices interface on the Raniso App.

5.4.6 Fire and Gas Alarm System

This proposed system for extinguishing fires and detecting gas leaks is implemented to protect lives and property from gas and fire hazards that lead to serious accidents, human injuries, and material losses (see Figure 5.18). This service is based on a GSM module, a GPS shield, servo motors, a flame sensor, a gas leakage sensor, an LCD screen, a speaker, and LEDs. Sensors are used to sense fire and gas in the building. Whenever the fire or the gas is detected, the alarm rings, the LCD screen displays "There is Danger, Not safe here," a red LED lights up, one servo motor opens the water sprayer, and the other one opens the window. In addition, the system not only sends calls and SMS alerts to the owner but also sends an SMS along with the location of the incident to the fire station and civil protection. The system also guides the building owner to a safe, fire-free route through an audio system and a green light. Besides, users can monitor data of gas and fire detection of their buildings from anywhere at any time via the Raniso app's fire and gas alarm interface, which sends real-time alerts in the case of fire and gas leaks, as illustrated in Figure 5.19, and via our channel in the ThingSpeak platform, as shown in Figure 5.20.

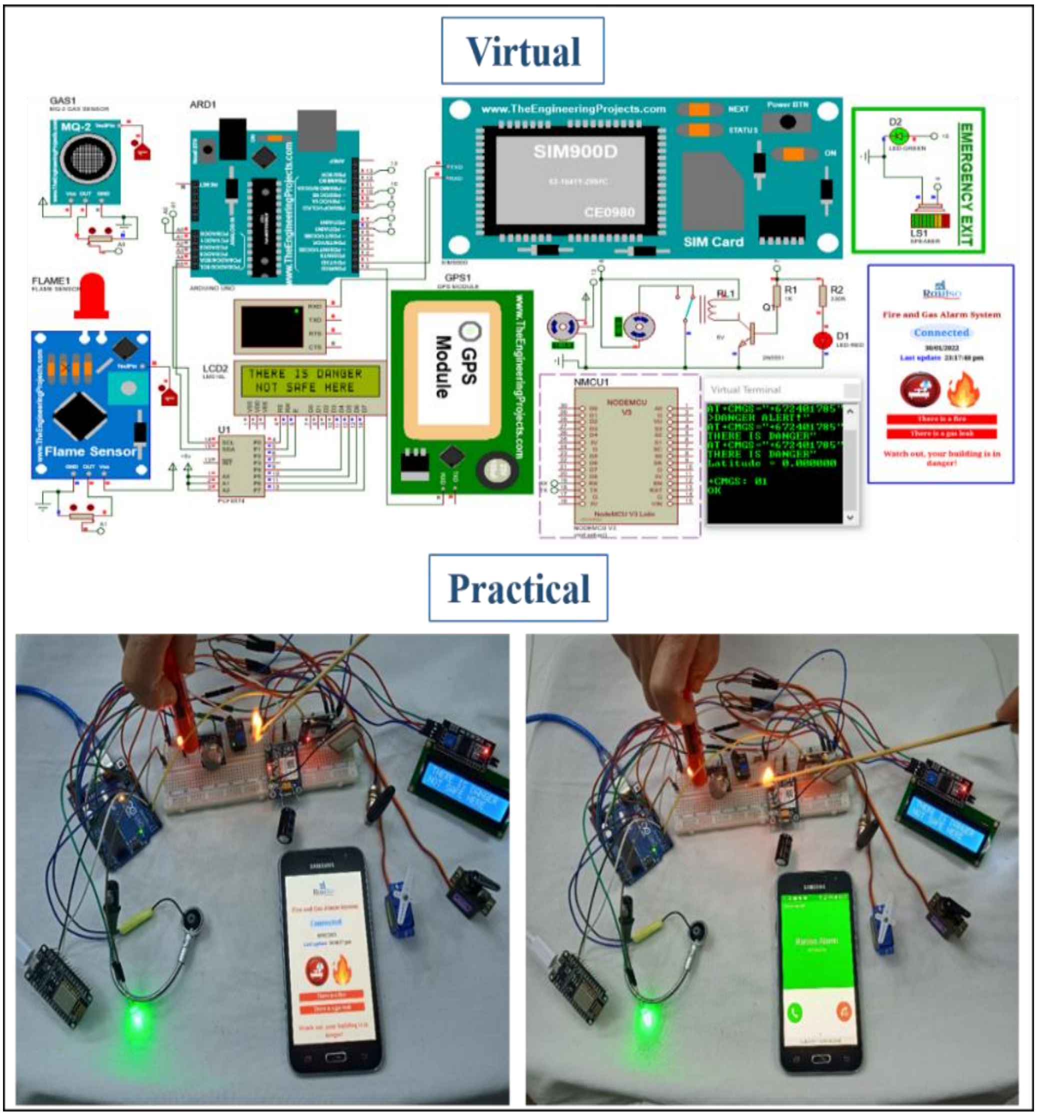

Figure 5.18 Fire and gas alarm system.

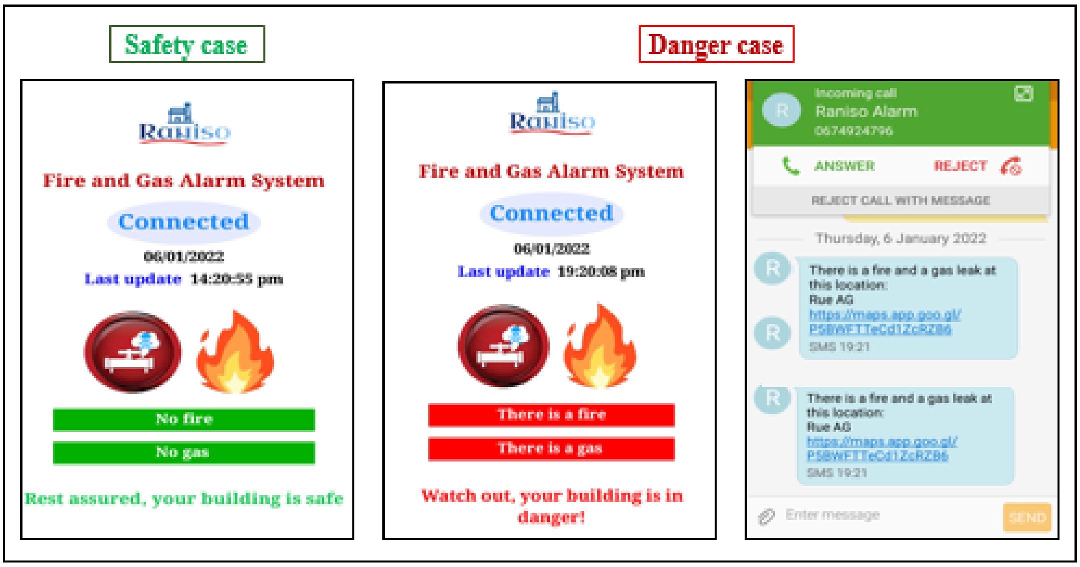

Figure 5.19 Fire and gas detection interface on the Raniso App.

Figure 5.20 Fire and gas detection monitoring on ThingSpeak.

5.4.7 Smart Lighting Management

The proposed system is an advanced smart lighting management system based on IoT/M2M technologies and includes two important services, namely remote control of lights, shown in Figure 5.21, and automatic lights, shown in Figure 5.22. The proposed system was built using a Bluetooth module, a PIR sensor, LEDs, RGB LEDs, LDR sensors, and push buttons. This system is built to be energy-efficient, convenient, and safe. It gives users the freedom to choose how to control the lights, whether controlling the lights via pushbuttons, Bluetooth, Wi-Fi, 4G/5G networks, or via the use of artificial intelligence by enabling Google Assistant voice commands integrated into the Raniso App. It also suggests to the user the best way to control the lights in real time. Also, we can generate any color with an RGB LED by adjusting the brightness of the individual red, green, and blue LEDs through the interface of smart lighting in the Raniso App, as shown in Figure 5.23. Besides, in places such as garages, stairs, and bathrooms, where there is no need for continuous light, we have implemented automatic lights, where lights are automatically turned on when a human is present and when it is dark. In addition, the user can monitor in real-time LDR sensor data, motion detection, and light intensity via our channel in ThingSpeak, as shown in Figure 5.24. This service was proposed to save the max of energy and provide a level of comfort and convenience. The following figure represents the proposed smart lighting management by remote (voice/Internet/Bluetooth) or push button switches.

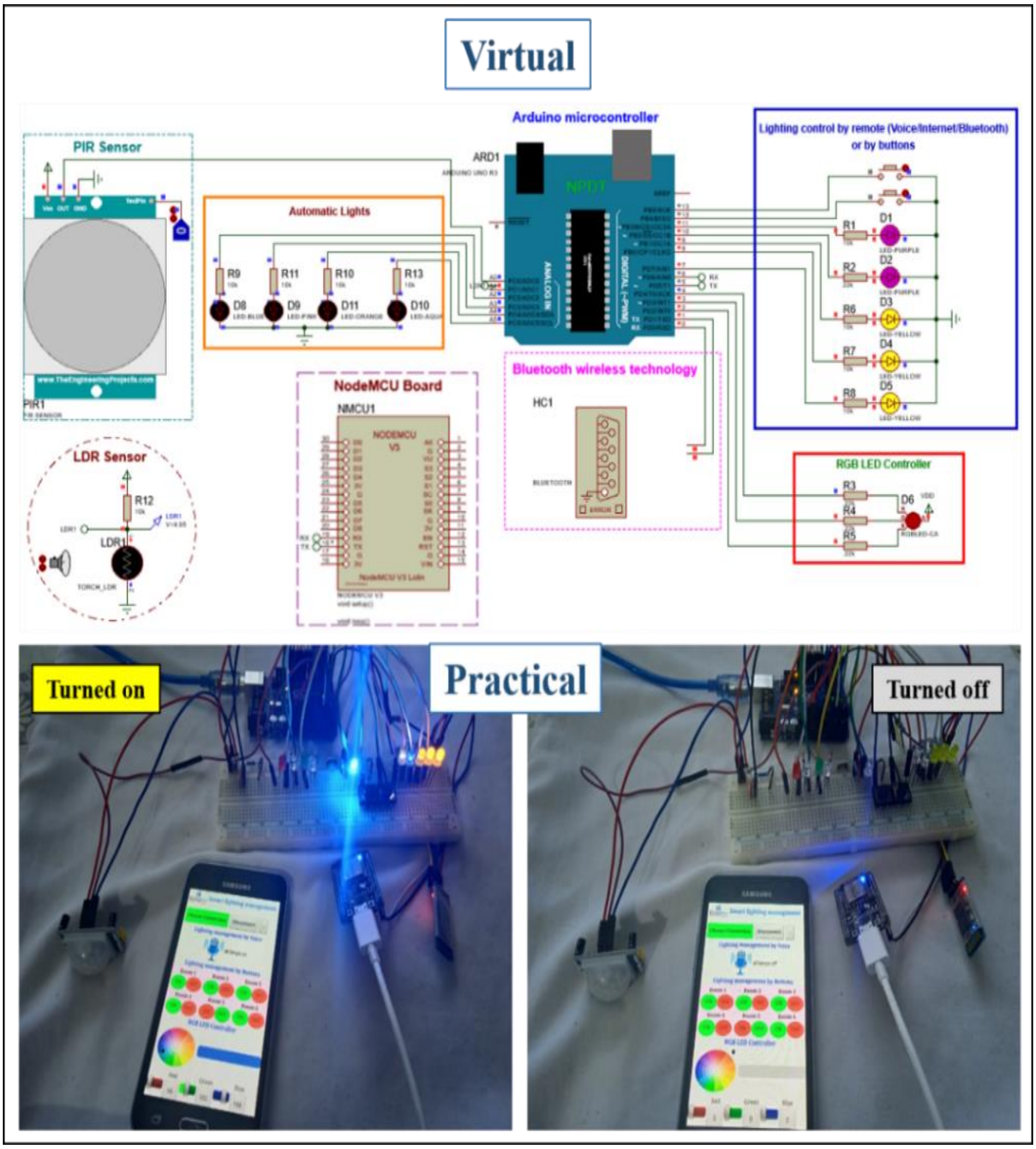

Figure 5.21 Smart lighting management by Remote (Voice/Internet/Bluetooth) or by Push Button Switches.

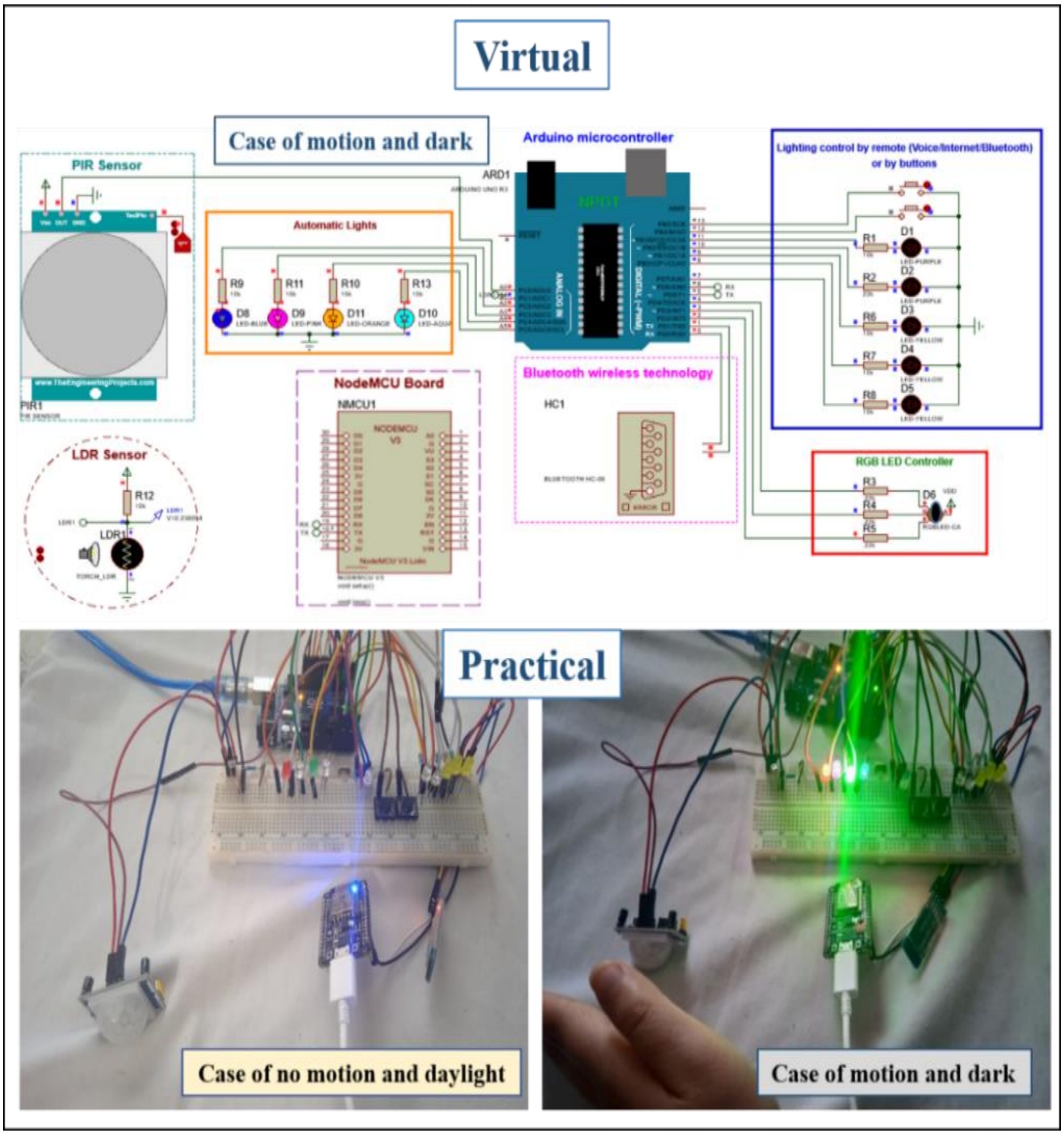

Figure 5.22 Automatic lights.

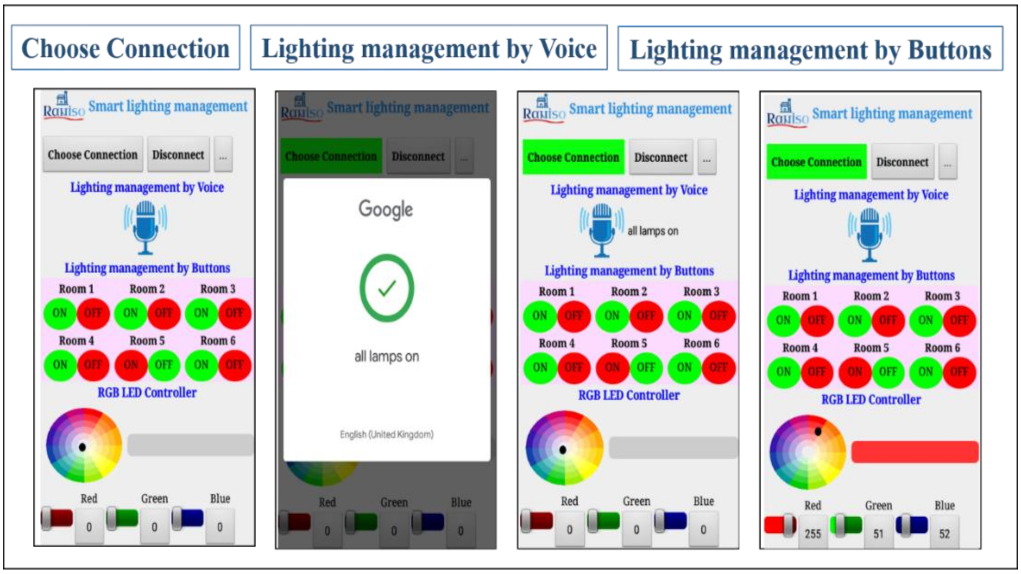

Figure 5.23 Smart lighting interface on the Raniso App.

Figure 5.24 Smart lighting monitoring on ThingSpeak.

5.4.8 Smart health monitoring system

The proposed IoT/M2M Smart health monitoring system includes two main tasks, namely Smart Medicine Reminder (SMR) that solves such problems by reminding and alerting patients to take the right dose at the right time (see Figure 5.25). The proposed SMR system includes a GSM module, DS3231 real-time clock module, LCD screen, push buttons, speaker and LEDs. The speaker and LEDs are used to alert and remind the patient that it's time to take their medication. The LCD screen is set to cycle through three screens. The first screen displays the message "Please take care of your health". The second screen is a help screen that instructs you to press the select button to choose a one-time time slot for the reminder (once/twice/three times a day). The time slot is changeable in the program and can be configured accordingly. Four push buttons are used, each with a different selection function. The first button is used for once daily reminders, the second for twice daily reminders and the third for three daily reminders. The fourth button stops the reminders when the user has taken their medication. If the patient is half an hour late, the GSM module sends calls and text messages to remind them to hurry up and take their medication. In addition, the user can use the Raniso app's intelligent medication reminder interface, shown in Figure 5.26, which helps them take their medication on time according to their treatment plan, and allows them to remotely manage and control medication/pill schedules and usage data. The second task is to monitor the user's key health markers, namely speed of the heartbeat using a heartbeat sensor, body temperature measurement using an LM35 sensor, room temperature, and humidity using a DHT11 sensor. On top of all this, the proposed smart health monitoring system is extremely versatile, with the Raniso platform enabling direct communication anytime, anywhere between patients and caregivers, as it quickly alerts the caregiver if the patient needs any help. There are many locations where this system can be used, including at home, hospitals, and other medical facilities.

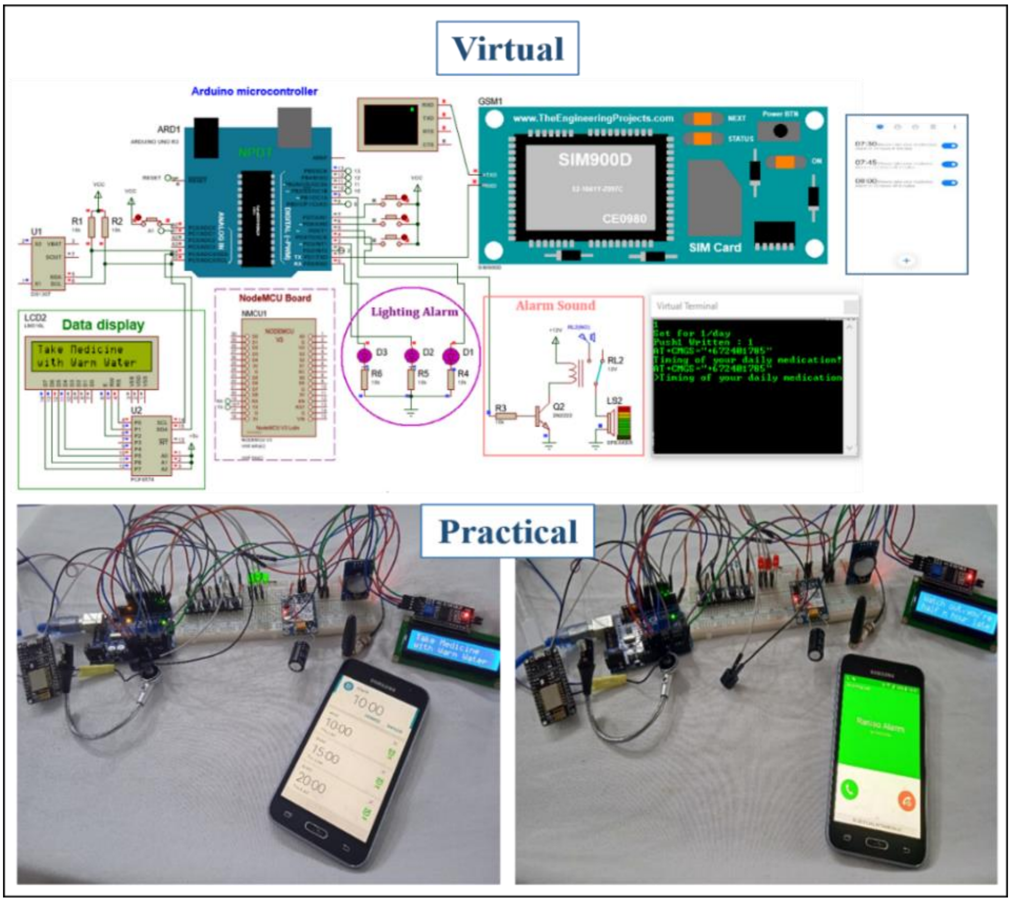

Figure 5.25 Smart health monitoring system.

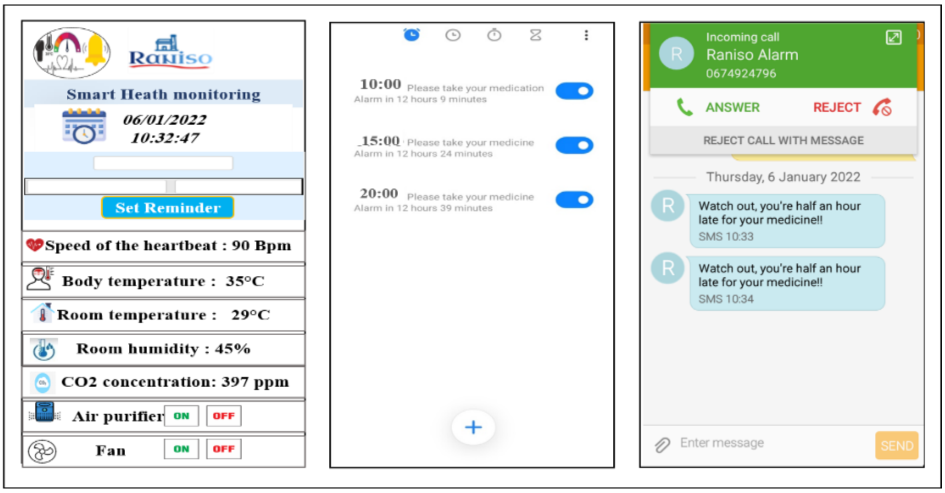

Figure 5.26 Smart health monitoring interface on the Raniso.

5.4.9 Indoor Air Quality Monitoring System

Indoor air pollution has become a real problem and a common phenomenon in buildings. With the spread of COVID-19, people spend most of their time indoors and poor indoor air quality (IAQ) is a significant public health risk that can increase short-term health problems such as fatigue and nausea, as well as chronic respiratory disease, heart disease, and lung cancer. It is now necessary to monitor air quality in real time in most buildings. The air quality monitoring system developed in this thesis is based on the MQ135 sensor, DHT11, servo motor, DC fan, air purifier, speaker, buzzer, LCD screen, and LEDs (see Figure 5.27). IAQ is measured in parts per million (PPM), where a lower PPM value indicates good air quality and a higher value indicates polluted air containing toxic gases. If the value is less than 130 PPM, the LCD and the Raniso App will display "Air Quality Level Good". The fan turns on when the reading is between 130 PPM and 250 PPM. The LCD and Raniso App will display "Air Quality Level Medium. " when the reading rises to 250 PPM. The buzzer will sound, the red LED will light, the fan and purifier will turn on, and the LCD and Raniso App will display "Air Quality Level Danger". This service is connected to the Internet, so anyone can view the air quality index remotely from anywhere via the air quality monitoring interface in the Raniso App (see Figure 5.28). This system aims to provide real-time monitoring of IAQ parameters through our channel in the ThingSpeak platform (see Figure 5.29) and generate alerts to building occupants via the Raniso App to avoid dangerous conditions.

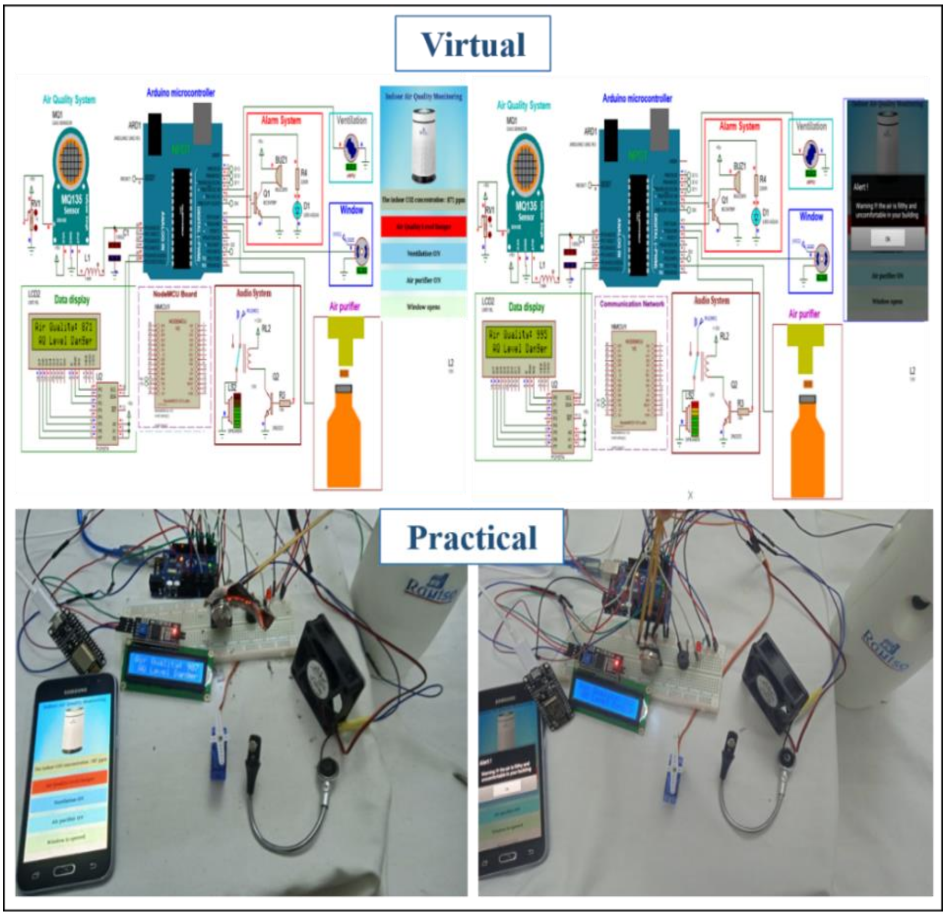

Figure 5.27 Indoor air quality monitoring system.

Figure 5.28 Indoor air quality monitoring interface on the Raniso.

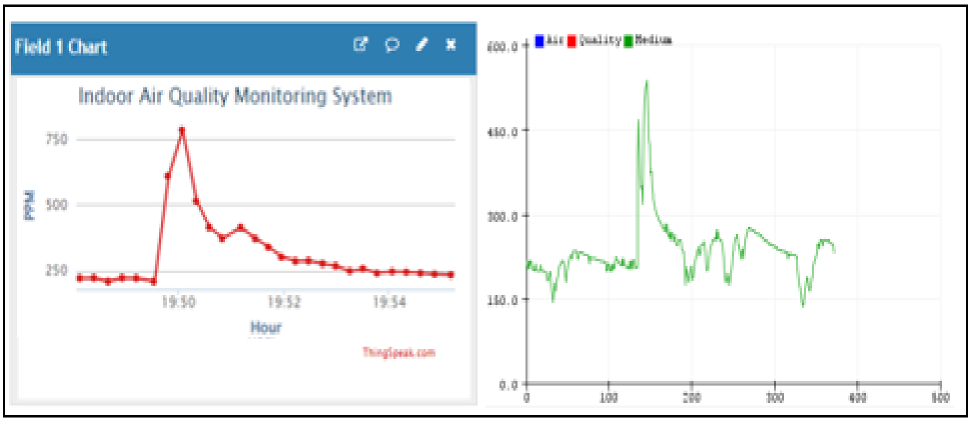

Figure 5.29 Indoor Air Quality monitoring graph on ThingSpeak and the Serial Plotter tool.

5.4.10 Weather Station System

The proposed IoT/M2M weather station system collects weather and environmental data and accurately informs us about indoor and outdoor weather information in real time by measuring atmospheric conditions, such as temperature, relative humidity, barometric pressure, altitude, precipitation, wind speed, and direction, sunrise, sky information, and current date and time (see Figure 5.30). The system includes a DHT11 sensor, BMP180 sensor, anemometer, rain sensor, DS3231 real-time clock module, DC fan, heater, and LCD screen. The DHT11 sensor detects temperature and humidity, while the BMP180 sensor calculates pressure, the anemometer measures wind speed and direction, and the rain sensor detects rainfall. The system turns on the fan when the indoor temperature is high and turns on the heater when the temperature is very low. In addition, when it rains, the water tank automatically opens to store rainwater and uses it to water the plants. In addition, all weather information is displayed on the LCD screen and the weather station interface of the Raniso App which allows too to monitor weather conditions from anywhere and share the results with other weather enthusiasts. It is also possible to query from the AI-based Raniso robot about current indoor or outdoor conditions and receive a weather report locally or for any city in the world. This weather station system can be installed on the roof or anywhere in the building. Figure 5.31 shows the weather station information interface on the Raniso App for six cities in the world which are Bordj-Bou-Arreridj, Algiers, London, Washington, Canberra, and Beijing.

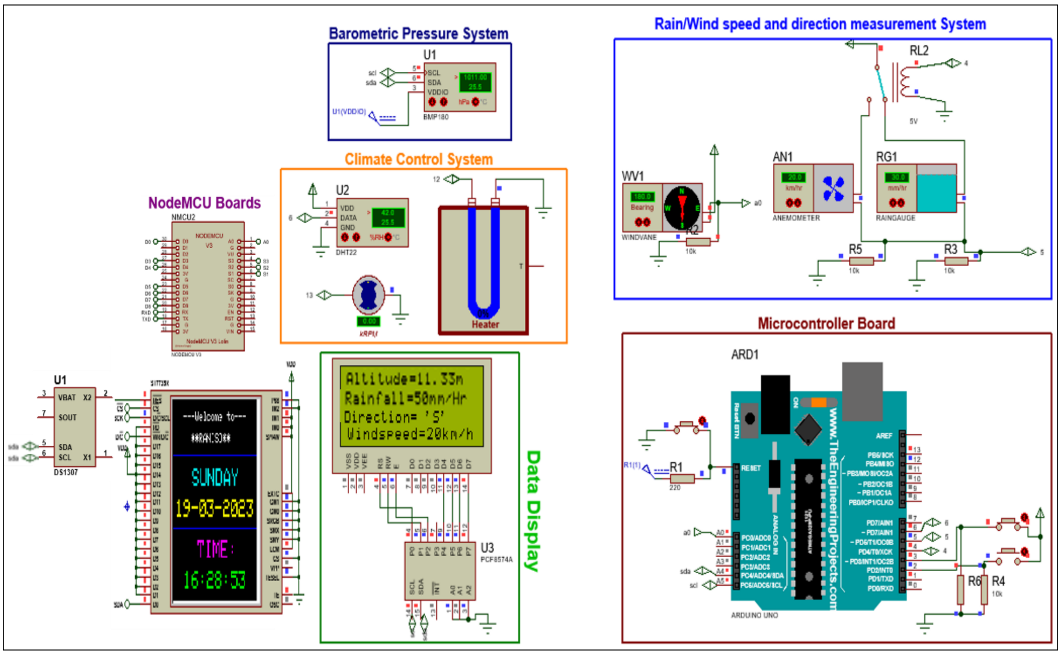

Figure 5.30 Weather station information interface on the Raniso App.

Figure 5.31 Weather station information interface on the Raniso App.

5.4.11 Smart Garbage Management System

The proposed smart garbage management system (see Figure 5.32) consists of a smart circuitry that transmits all information over the Raniso App (see Figure 5.33) to signal the main garbage collector of the facility to empty the particular garbage bin which contributes to making the building clean and attractive and it. The system consists of two ultrasonic sensors, one of which detects distance so that when a person approaches the bin, the lid automatically opens to allow waste to be dumped and closes again after a set time. While the other sensor continuously measures the level of waste in the dustbin and automatically detects if it is about to fill up. If the garbage can is full, the system notifies the building owner and collectors that the garbage bin is full via the Raniso App, the lid of the garbage can does not open automatically, and an audio system indicates that 'this dustbin is full, please dispose of your waste in another trash can', and a red LED lights up. The proposed smart dustbin also has a self-sealing feature that will seal the trash bag when it's full and automatically scented immediately after being emptied. Thus we get a fully automated smart dustbin that allows for automated garbage cleaning which can be utilized in different buildings like houses, offices, and even in public places for garbage management.

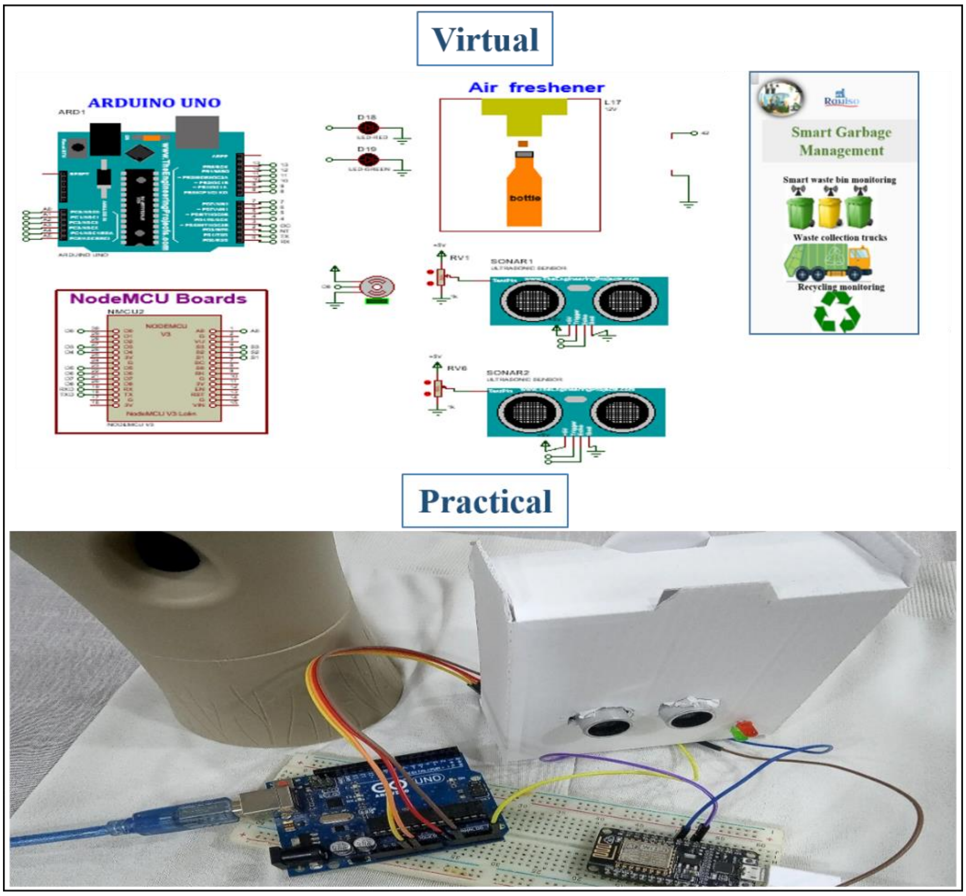

Figure 5.32 Smart garbage management system.

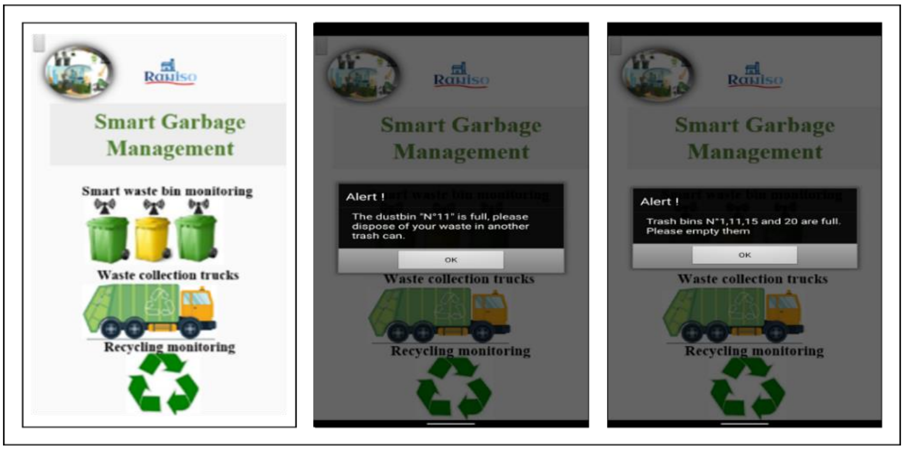

Figure 5.33 Smart garbage management interface on the Raniso App.

5.4.12 Smart Energy

The forms of renewable energy sources (RES) used in the proposed system are solar, wind and hydro. In addition, a simple and low-cost IoT/M2M solution is provided to monitor and control a smart axis solar tracker system for performance evaluation. The proposed system includes a solar panel, anemometer, servo motor and LDR sensors. A solar tracker system is an axis solar tracker that can rotate automatically to track the position of the sun using LDR sensors, or manually by the user using the Smart Energy interface of the Raniso app shown in Figure 5.34. All solar tracker data and renewable energy information is displayed in real time on the LCD screen and on the Raniso platform, which is also programmed to send alerts in the event of system failure. This provides the user with the necessary data related to the environment and the performance of the RES. The user can therefore control the system to find the best environmental conditions and extract the maximum energy from different RES. In addition, the system allows energy to be stored and used to power the smart building. Figure 5.35 shows the proposed smart energy system.

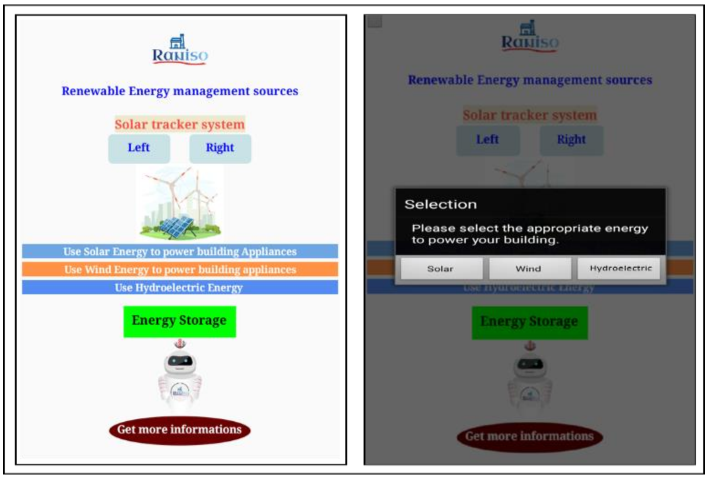

Figure 5.34 Smart energy interface on the Raniso App.

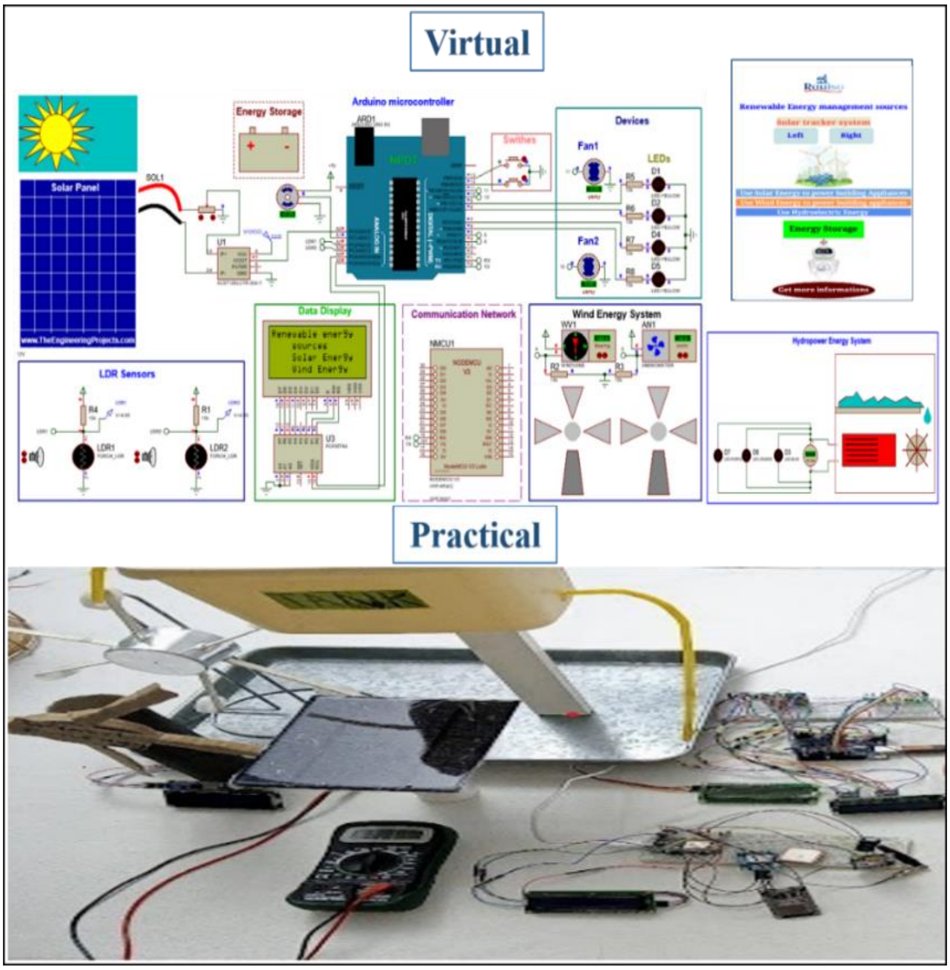

Figure 5.35 Smart energy system.

5.5 Results and Discussion

This section presents the results of the functional testing of the prototype of the proposed IoT / M2M smart building system, which consists of several innovative services and functions, such as smart parking, garden irrigation automation, intrusion alarm, smart door system, managing building devices, fire and gas detection, smart lighting, smart health monitoring system, indoor air quality monitoring, weather station system, smart garbage management system and smart energy. In the previous section, we tested these services individually, while in this section, the effectiveness of the designed system is confirmed by testing all its services and functionalities on the final IoT / M2M smart building model, which was created to elaborate the performance and functionality of the proposed approach. The large number of sensors, actuators and shields used resulted in a low power supply and a limited number of ports. As a result, we added the Arduino Mega board along with the Arduino UNO and NodeMCU for perfect operation and to meet the requirements of the IoT/M2M smart building. Our aim was to design and implement an IoT/M2M smart building based on the convergence of two heterogeneous networks: wireless sensor networks based on RFID, Bluetooth, Wi-Fi and mobile cellular networks such as GSM, 4G or 5G. All data collected by the proposed system is stored in the cloud database, sent to the ThingSpeak server, and visualized in four channels. The channels receive data from the building sensors every 10 seconds and are visualized as line graphs on the ThingSpeak website and the Raniso app in real-time. Figure 5. 36 shows the graphs obtained from our channels in the ThingSpeak platform. In addition to demonstrating the ability to monitor building data in real time from anywhere via the Internet, these graphs also show the good performance and fast response of the proposed approach. For example, garden irrigation automation graphs show how quickly the system responds in seconds when a plant needs to be watered, photosynthesized, a water tank replenished, etc. The same applies to other services, as the indoor air quality, fire and gas detection graphs also show how quickly the system reduces the risk of fire and gas leaks. This is in addition to the automatic lighting service, whose graphs show brightness, lux, and movement values in real time. The results we have obtained are very satisfactory as we have achieved the desired objective of providing accurate readings to the server. In addition, the latency is very low, so users can easily control and monitor the smart building remotely at any time and from anywhere using mobile phones via the Raniso app. In addition, one of the achievements of this study is the use of artificial intelligence to control devices by allowing voice commands through Google Assistant. The proposed smart building presented in Figure 5.37 is customizable according to the user's preferences. For example, the user can control the lights through push buttons, Bluetooth, Wi-Fi, 4G/5G networks, a voice through Google Assistant, or automatically based on the feedback from the PIR sensor. The same goes for the proposed smart door, where the user can control the keyless door either with an RFID card or a password or remotely through the Raniso app using the Bluetooth connection or the Internet via Wi-Fi, 4G/5G. The same applies to the other proposed applications (smart parking, smart garden, etc.). Furthermore, in order to verify the performance metric of the error rate of the proposed system, based on the data collected in Table 5.3, including temperature, humidity, and indoor air quality for 15 days, we were able to calculate the error rate of the proposed system, which was less than 1%.

Figure 5. 36 Quantitative sensing results for all the proposed applications.

Figure 5.37 Top view of the validated IoT/M2M smart building prototype.

Table 5.3 presents the data collected, including the Temperature observed by the proposed system (T_{ps}), Temperature observed from Official Data (T_{od}), Humidity observed by the proposed system (H_{ps}), Humidity Data observed from Official Data (H_{od}), IAQ Data observed by the proposed system (IAQ_{ps}), and IAQ Data observed from Official Data (IAQ_{od}). The data collected was taken over 15 days, which represents the number of observations (N).

Table 5.3 Collected data over 15 days.

Date	T_{ps}	T_{od}	H_{ps}	H_{od}	IAQ_{ps}	IAQ_{od}
01/11/2022	24°C	25°C	90%	89%	240	239
02/11/2022	27°C	26°C	76%	78%	225	228
03/11/2022	26°C	25°C	84%	83%	279	275
04/11/2022	23°C	24°C	77%	78%	459	470
05/11/2022	17°C	19°C	75%	77%	760	757
06/11/2022	18°C	18°C	77%	76%	500	499
07/11/2022	22°C	23°C	49%	51%	447	450
08/11/2022	23°C	24°C	50%	53%	330	333
09/11/2022	26°C	25°C	54%	55%	109	112
10/11/2022	24°C	24°C	56%	56%	83	85
11/11/2022	24°C	25°C	47%	46%	100	96
12/11/2022	19°C	20°C	61%	59%	69	71
13/11/2022	21°C	20°C	78%	78%	168	163
14/11/2022	20°C	19°C	80%	82%	251	249
15/11/2022	19°C	19°C	99%	98%	270	266

For the temperature, the mean of T_{ps} is given by equation (5. 2), the mean of T_{od} is given by equation (5. 3), and the temperature error rate (e_T) is expressed by (5. 4).

$$MT_{ps} = \frac{\sum_{i=1}^{N=15} T_{ps}}{N} \quad (5.\ 2)$$

$$MT_{od} = \frac{\sum_{i=1}^{N=15} T_{od}}{N} \quad (5.\ 3)$$

$$e_T = \frac{MT_{od} - MT_{ps}}{MT_{od}} * 100 \quad (5.\ 4)$$

For humidity, the mean of H_{ps} is given by equation (5. 5), the mean of H_{od} is given by equation (5. 6), and the humidity error rate e_H is expressed by (5. 7).

$$MH_{ps} = \frac{\sum_{i=1}^{N=15} H_{ps}}{N} \quad (5.\ 5)$$

$$MH_{od} = \frac{\sum_{i=1}^{N=15} H_{od}}{N} \qquad (5.\ 6)$$

$$e_H = \frac{MH_{od} - MH_{ps}}{MH_{od}} * 100 \qquad (5.\ 7)$$

For indoor air quality, the mean of IAQ_{ps} is given by equation (5. 8), the mean of IAQ_{od} is given by equation (5. 9) and the error percentage e_{IAQ} is expressed by (5. 10).

$$MIAQ_{ps} = \frac{\sum_{i=1}^{N=15} IAQ_{ps}}{N} \qquad (5.\ 8)$$

$$MIAQ_{od} = \frac{\sum_{i=1}^{N=15} IAQ_{od}}{N} \qquad (5.\ 9)$$

$$e_{IAQ} = \frac{MIAQ_{od} - MIAQ_{ps}}{MIAQ_{od}} * 100 \qquad (5.\ 10)$$

Based on the data collected in Table IV and the mathematical equations in (4) through (12), we were able to calculate the estimated error rate for temperature as 0.89%, humidity as 0.56%, and indoor air quality as 0.06%. These error rates are very low, indicating the good performance and efficiency of the proposed system.

In addition, through Raniso's user preferences interface (see Figure 5.38) the users can enter their preferences such as living temperature, humidity, illumination level, illumination color, scent type, and music type, and all these entered preferences are stored in SQL database as shown in Figure 5.39. These results allow us to derive multiple optimal configurations for future work based on user interaction behavior.

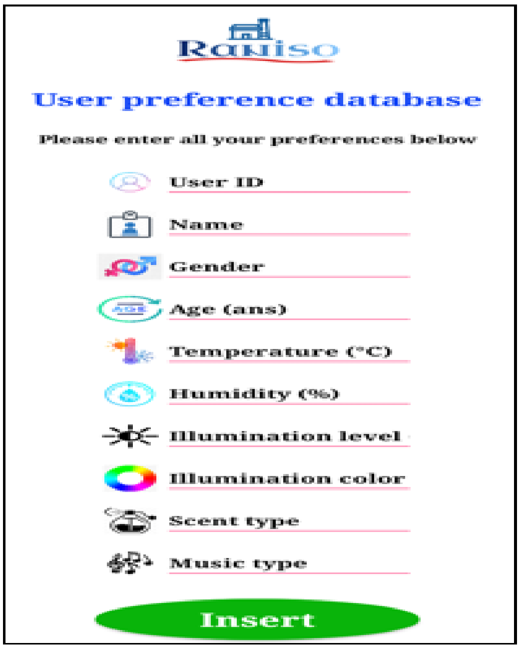

Figure 5.38 User preferences interface

User_ID	Name	Gender	Age (ans)	Temperature (°C)	Humidity (%)	Illumination level (Lux)	Illumination_color	Scent_type	Music_type
User 1	Rania	Female	26	25	40	500	Blue	Jasmine	Classical
User 2	Hocine	Male	59	28	50	800	Yellow	Floral	Classical
User 3	Djamila	Female	52	22	30	600	White	Lavender	Soul
User 4	Nadjib	Male	36	27	30	200	White	Jasmine	Soul
User 5	Mounia	Female	34	24	35	350	Red	Lavender	Jazz
User 6	Mohamed	Male	31	23	50	150	White	Lemon	Tango
User 7	Nihad	Female	27	26	45	400	Purple	Floral	Folk
User 8	Assia	Female	27	25	55	200	Green	Lemon	Jazz
User 9	Morad	Male	40	25	30	500	White	Lavender	Classical
User 10	Ammar	Male	75	27	50	700	Green	Jasmine	Classical
User 11	Khoula	Female	27	23	40	250	Red	Jasmine	Folk
User 12	Oussama	Male	30	24	40	300	White	Floral	Salsa
User 13	Abdou	Male	25	22	55	250	Yellow	Lavender	Soul
User 14	Ghania	Female	38	25	40	500	Blue	Lemon	Jazz
User 15	Karima	Female	39	23	30	700	White	Floral	Soul
User 16	Amina	Female	28	22	40	400	Green	Jasmine	Jazz
User 17	Samir	Male	31	27	40	350	Blue	Lavender	Folk
User 18	Youcef	Male	46	24	50	800	White	Jasmine	Tango
User 19	Omar	Male	43	23	35	600	Purple	Floral	Salsa
User 20	Hadjer	Female	22	26	50	600	Blue	Floral	Tango

Figure 5.39 User preference database.

The proposed approach can be deployed and extended for various smart IoT/M2M systems, including smart grids, smart retail, smart cities (see Figure 5.40), etc.

Figure 5.40 Top view of the extended IoT/M2M smart building to smart city prototype.

5.6 Conclusion

This chapter focused on the development of an IoT/M2M smart building system based on the convergence of wireless sensor networks and cellular networks. In this chapter, the proposed system has been compared to many related works, as well as has been detailed by explaining its architectural design. Based on our findings in this chapter, we prove that our proposed solution offers a novel architectural design for a low-cost and flexible system that can be deployed for various smart IoT/M2M systems, including smart grids, smart retail, smart cities, etc. As an example, the architectural design was provided in more detail for the case of a smart building, where we suggested several main services and functionalities like smart parking, garden irrigation automation, intrusion alarm, smart door, managing building devices, fire and gas detection, smart lighting, smart health monitoring, indoor air quality monitoring, weather station, smart garbage management, and smart energy. All these services can be controlled and monitored remotely via our channels in the ThingSpeak platform and through our multiple-platform mobile application named ‘Raniso’, a local server that allows remote building control via RFID/Bluetooth/Wi-Fi connectivity and cellular networks like GSM, 4G, or 5G. The proposed IoT/M2M smart building was designed, implemented, deployed, and tested and yielded the expected results.

General Conclusion

The convergence of IoT/M2M technologies with 4G/5G networks has the ability to enable efficient and reliable communication, resulting in improved productivity, cost savings, and enhanced user experiences. In order to achieve seamless communication between devices and machines, the convergence of IoT/M2M networks and 4G/5G mobile networks necessitates not only the deployment of network infrastructure but also the integration of different wireless technologies and protocols. The ambient backscatter technology has emerged as one of the most popular wireless communication technologies for large-scale IoT/M2M applications because it allows data to be transmitted without the use of electricity. In addition, heterogeneous networks based on different wireless communication technologies offer a wide range of applications in different industries. However, the deployment and convergence of IoT/M2M technologies and 4G/5G mobile networks also pose several challenges such as cost, privacy, security, scalability, and managing the massive influx of data. Furthermore, emerging newer cellular networks such as 5G/6G aim to address these challenges by prioritizing features like human-centric design, security, and intelligent services, supporting various IoT/M2M requirements, including massive device connections and different service types.

In this thesis, we have studied IoT/M2M technologies and 4G/5G mobile networks, analyzing different aspects such as their architecture, protocols, and applications. We have also analyzed the benefits, challenges, and solutions associated with the deployment and convergence of these networks. As well as we have assessed existing methods for convergence and presented case studies of successful implementations and converged networks. In addition, we have compared our proposed work in this thesis with existing systems that have the following disadvantages: do not integrate IoT and M2M technologies together, rely on one or at most two wireless communication technologies, limited wireless transmission range, inconvenient interface, and excessive cost. The research contribution of this thesis is summarized as a design for adaptive control of IoT/M2M devices in smart-x systems using two well-known IoT platforms (ThingSpeak and Blynk), along with our multi-platform mobile application called "Raniso", over heterogeneous wireless networks. This thesis focused on the development of an IoT/M2M smart-x paradigm based on the convergence of WSNs and MCNs, using open hardware and open source software. Based on our findings in this thesis, we prove that the proposed mechanism provides a novel architectural design for a low-cost and flexible system that can be used for various smart IoT/M2M systems, including smart grids, smart retail, smart cities, etc. As an example, the architectural design has been provided in more detail for five smart applications, namely smart home automation, smart environment, smart city, smart healthcare, and smart building. All these innovative applications can be remotely controlled and monitored via ThingSpeak, Blynk, and Raniso which is a local server that allows remote control of smart-x systems via different HetNets, such as RFID/Bluetooth/Wi-Fi connectivity and cellular networks, such as GSM, 4G or 5G. The proposed IoT/M2M smart-x system was designed, implemented, deployed, tested, and yielded the expected results. Furthermore, the proposed mechanism presented a hybrid (local and remote) and low-cost IoT/M2M-based smart-x system that allows for the efficient, secure, and cost-effective connection of all IoT/M2M smart devices. It also enables the reception of data from smart-x systems, data storage in the cloud database, and the display and remote monitoring of this data through the ThingSpeak webpage as well as the Raniso and Blynk apps. This deployment and convergence of M2M networks and 4G/5G mobile networks enhances the overall functionality and accessibility of the system.

Perspectives

Many interesting areas and prospects can be further investigated for future works based on this thesis:

First, we can directly study new perspectives for integrating machine learning techniques to enhance the robustness and advancement of the proposed approach. Where machine learning algorithms have the ability to analyze large amounts of data, identify patterns, and make accurate predictions or decisions based on the learned patterns. By incorporating these techniques into the proposed approach, we can improve its performance and adaptability.

Second, in addition to the sectors addressed in this thesis, we can implement the application of the mechanism proposed for example in the integration of smart transportation systems, which can alleviate traffic congestion, reduce carbon emissions, and improve overall mobility. Autonomous vehicles and intelligent traffic management systems can revolutionize commuting experiences while ensuring safety and sustainability.

Third, considering the user experience perspective is crucial when examining the deployment and convergence of these networks. This includes evaluating factors such as usability, accessibility, and user satisfaction. Understanding how users interact with M2M/IoT devices and the newer mobile networks they rely on can inform the design and implementation of user-centric solutions.

Fourth, another perspective to consider is the regulatory frameworks surrounding M2M networks and 4G/5G mobile networks. As these technologies advance, there may be a need for updated policies and regulations to address issues such as spectrum allocation, interoperability standards, data governance, and privacy protection. Examining the regulatory landscape can provide insights into the legal and policy considerations associated with their deployment and convergence.

Fifth, the convergence of M2M networks with 4G/5G mobile networks raises concerns about privacy and security. With an increasing number of connected devices, there is a need to ensure data integrity, confidentiality, and protection against cyber threats. Exploring the challenges and potential solutions in securing these networks by addressing ethical considerations such as data privacy, algorithmic bias, and cybersecurity in deploying and converging such networks can be an important perspective for the thesis.

Finally, another perspective to consider is the economic impact of deploying and converging M2M networks with 4G/5G mobile networks. This includes examining the potential for new business models, revenue streams, and cost savings. For example, M2M networks can enable predictive maintenance in industries, reducing downtime and optimizing resource allocation. Understanding the economic implications can help organizations make informed decisions about investments in these technologies.

We hope that this thesis will inspire further research in this area and contribute to the development of innovative solutions that leverage the power of these technologies in our country.

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