RADIO RESOURCE MANAGEMENT TECHNIQUES IN SMART ENVIRONMENTS

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Abstract
The introduction of the Internet of Things (IoT) and 5G technologies will result in the proliferation of a large number of communicating devices in different smart environments and for different applications. Radio spectrum management including spectrum access and energy efficiency issues are examples of challenges for these new wireless communication systems. The licensed radio spectrum is credited for its reliability, quality and control. It is however subjected to congestion as the expected number of devices and "massive data" traffic grow. Unlicensed radio spectrum becomes a necessity and has been considered for IoT connectivity to allow more devices to communicate. Proper spectrum coordination and management is therefore vital for the optimal performance of different systems and applications in smart environments. Furthermore, a large increase in energy consumption is expected as a result of the large number of interconnected devices. To ensure that application requirements are met in terms of satisfactory Quality of Experience (QoE) and Service (QoS) metrics in a scalable, heterogeneous and autonomous smart environment, new radio resource management (RRM) techniques are needed. These new RRM techniques will address challenges imposed by limited spectrum, energy consumption and QoE/QoS requirements. In this paper, we present the state of the art in the application of IoT in smart environments including examples of use cases for different systems, operational requirements and enabling wireless technologies. We also present some research issues and challenges with a focus on RRM techniques as well as directions for future work.

Key Words: Internet of Things (IoT), Smart Environments, 5G, Radio Resource Management (RRM), Quality of Experience/Service (QoE/QoS)

I. INTRODUCTION

The Internet of Things (IoT) is a new paradigm that goes beyond personal computers and smart phones. Cars, home appliances and devices in general are enabled to connect and interact via Internet. This has been made possible by the rapid advancements and innovations in sensors, radio frequency technology and emerging wireless networks. Connected devices operating in an environment are called ‘smart’ because they have the ability to autonomously learn, apply knowledge and adapt to requirements. The physical environment where smart devices interact is called a smart environment. IoT in smart environments will simplify and enhance daily lifestyle, improve productivity and transform business models. Alongside these potentials are challenges that need to be addressed in order to achieve a certain level of user satisfaction in terms of Quality of Service (QoS) and Quality of Experience (QoE). Specific requirements include security and privacy issues, interoperability, standardisation, and resource management.

Generally, smart devices are resource-constrained in terms of power, memory/storage and radio spectrum availability. Radio resource management (RRM) in particular, needs to be investigated as it is expected that a massive number of devices will be connected in smart environments. Ericsson [1] predicts there will be 28 billion connected devices by 2021, of which 15 billion will be connected Machine-Type Communication (MTC) devices and consumer electronics. This forecast shows that the exponential growth in the number of smart wireless devices will put pressure on radio spectrum resources already considered scarce. Industry experts and researchers have argued that the licensed and unlicensed spectrum can be complementary options for IoT connectivity. Efforts have been focusing on the integration, convergence and coexistence of licensed and unlicensed spectrum.

In this paper, we present the state-of-the-art in several issues related to the realisation of IoT in smart environments with an emphasis on RRM. The rest of the paper is organised as follows. In Section II, we provide examples of the application domains in smart environments and the various communication technologies used. In Section III, we discuss the operational requirements and examples of key QoS/QoE metrics for MTC. The challenges addressed in recent RRM approaches as well as distributed RRM issues are discussed in Section IV. In Section V, the current RRM techniques are presented with examples. We finally present conclusions and directions for future work in Section VI.

II. SMART ENVIRONMENTS, APPLICATIONS AND ENABLING TECHNOLOGIES

Examples of smart environments and applications using wireless communication technologies include:

1. Smart Homes
A smart home relies on home automation facilitated by IoT. In addition to smart phones and tablets, many home products and appliances such as refrigerators, ovens and televisions are embedded with sensors, tags, processors, data storage capabilities and controls. Internet connections enable users to remotely access, monitor and control these devices. Sensor technologies for sound, motion, temperature, luminance and others help in providing enhanced experience and quality of life including energy conservation and management, home security and assistance. Smart homes are also designed to accommodate the elderly and disabled and facilitate e-learning and e-health. WiFi, Zigbee and Bluetooth are some of the popular wireless protocols adopted for communication in smart homes.

2. Smart Cities
In a smart city, the urban deployment of Information and Communication Technology (ICT) and IoT is used to improve services and enhance the welfare of residents. A smart city is expected to minimise and respond to challenges of urbanisation such as traffic congestion and environmental issues. This can be achieved through smart transportation, waste management, intelligent parking systems and smart street lighting among others. Continuous and reliable communication links will be required to facilitate the large amount of data acquisition and information transfer and control over long distances. LoRa is particularly suitable thanks to long range communication. Others prominent technologies include WiFi, Bluetooth Low Energy (BLE) and Zigbee.

3. Smart Industry/Manufacturing
Smart industry also known as Industry 4.0 or Industrial IoT (IIoT), is an industrial technological revolution that integrates cyber-physical systems (CPS), artificial intelligence (AI) and IoT to transform the manufacturing and production processes. Smart industry relies on massive Machine to Machine (M2M) communication. This involves interaction between sensors, machines, robots and wearable devices. The industrial wireless network deployed should have a very low end-to-end latency and high reliability with low power consumption for data acquisition and control. Device-to-Device (D2D) communication between devices in close proximity can be used to achieve low latency [2]. Commonly used communication technologies in the manufacturing domain are WiFi, Zigbee and 6LoWPAN.

4. Smart Health
Today's health care system also leverage on the benefits of IoT, virtual reality, machine learning and Big Data to improve efficiency and to enhance the quality of health services delivered. This is facilitated by sensors and wearable devices which can be attached to patients to obtain data for proactive health monitoring and diagnosis. Due to the critical nature of health care, high speed connectivity at low power is very crucial to the deployment of a smart health system and also because of the large amount of data exchange. Technologies such WiFi, Zigbee, 6LoWPAN and satellite communication can be used depending on the deployment area and the specific scenario.

5. Smart Vehicles
Autonomous vehicles, Internet of Vehicles (IoV) and Intelligent Transport Systems (ITS) also known as Vehicle-to- Everything (V2X) are typical examples. V2X technology enables a vehicle to communicate with its surroundings via IoT and can be deployed as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P) and/or Vehicle-to-Grid (V2G). An example of applications is the exchange of real time information related to traffic across a road network. This will in turn improve road safety by minimising accidents, reducing congestion and emissions and increasing energy savings. Due to the small size of safety messages during communication, smart vehicle applications will require radio resource access with low data rate but that also support high mobility and reliability with low latency. Dedicated Short Range Communication (DRSC)/IEEE 802.11p is the main communication technology for V2X systems.

6. Smart Grid/Energy
In smart grids, intelligence, communication abilities and automated controls are applied to the electrical power distribution and transmission systems for monitoring and regulation of energy flows in response to supply and demand patterns. Smart grids should also provide proactive maintenance and optimised operations. This will improve energy efficiency and reduce costs. By incorporating smart meters, consumers can control their energy

usage to reduce costs and carbon emissions. Furthermore, information on energy demand and weather forecast can help suppliers to integrate renewable energy sources and balance their networks. Smart grids typically require large volumes of data to be transferred over a long distance. Seamless connectivity that is delay-sensitive and reliable is crucial for real-time data exchange between devices and systems in a smart grid.

7. Smart Agriculture

Internet of Things (IoT), robots, global positioning systems (GPS), unmanned aerial vehicles (UAVs) and Big Data are technologies that can help to facilitate automated farming also known as smart agriculture. Data is collected via sensors and cameras. Embedded systems are used for irrigation control, environmental sensing and animal tracking.

Wireless communication technologies differ in data rates, network size and coverage, radio frequency (RF) band allocation and bandwidth as well as power consumption. The type of spectrum access for applications depends on its requirements. While cellular technologies in licensed bands offer long range connectivity and provide access to a larger number of devices, operating in licensed spectrum incurs a connection fee on users. Moreover, the scarcity and cost of licenced bands will result in higher congestion and blocking as the number of devices increase. With the diversity of applications in smart environments, it is expected that a large number of IoT devices will resort to technologies operating in unlicensed (or license-exempt) bands. Unlike the licensed spectrum, the unlicensed spectrum is free however, its uncontrolled nature results in limited QoS guarantees due to co-channel interference and congestion as the number of devices increases as well as security and privacy issues.

Low Power Wide Area (LPWA) technologies are key enablers for IoT applications to allow long range communication at low bit-rate with low power consumption. Proprietary technologies such as SigFox, LoRa and Weightless are LPWA networks operating in the unlicensed bands. The Third Generation Partnership Project (3GPP) introduced cellular IoT for LPWA solutions for IoT use cases to operate in the licensed bands. This includes Narrow Band Internet of Things (NB-IoT), enhanced Machine Type Communication (eMTC) and Extended Coverage for Global System for Mobile Communication for IoT (EC-GSM-IoT). Providing latencies in the order of milliseconds within a large network of thousands of nodes while guaranteeing reliability requirements expressed in very low packet error ratios (Less than 10^{-6}) is challenging. A combination of different existing and new radio access technologies will be need to be used to provide seamless connectivity with QoS/QoE guarantees depending on the application or use case .

An illustration of smart environments is shown in Figure 1. A summary of the main wireless technologies currently used in smart environments is shown in Table 1.

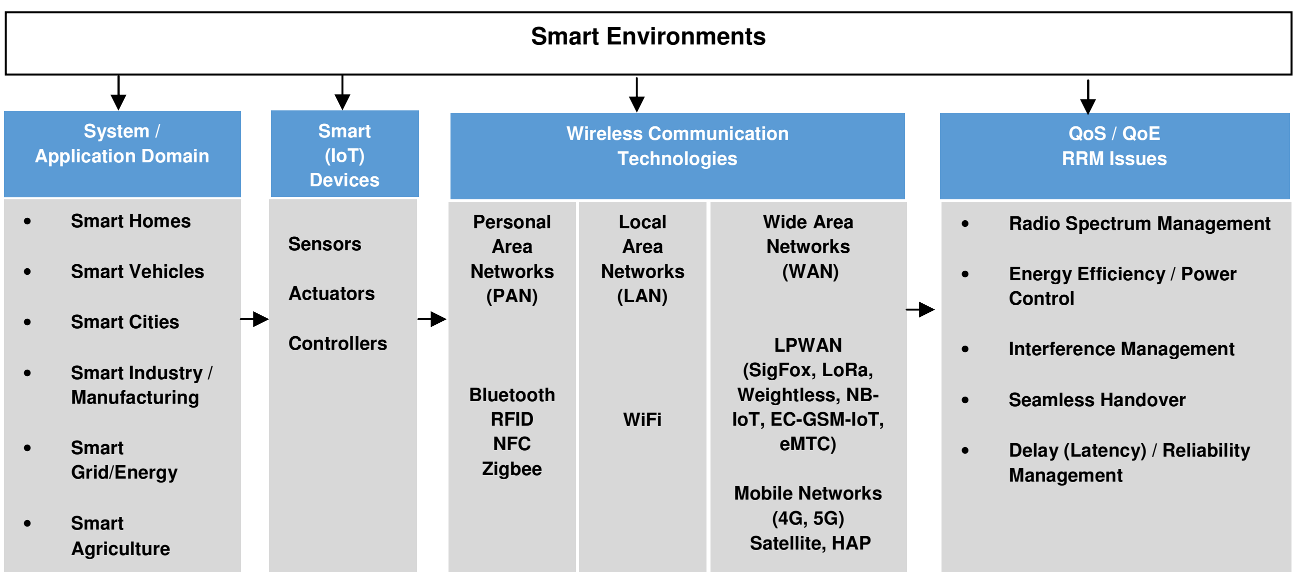

Figure 1. A Representation of Smart Environments

Table 1. Examples of Wireless Technologies used in Smart Environments

Technology	Operating Frequency/Band	Range	Peak Data Rate	Power Consumption	Application / Use Case
Zigbee	868MHz, 915MHz, 2.4GHz	Up to 100 m	250kbps	Low	Smart Homes, Smart Meters
Weightless	Sub -1GHz	5 km	100kbps	Low	Smart Meters, Smart Health
WiFi	2.4GHz, 5GHz	100-250 m	54Mbps	Medium	Smart Homes, Smart Grids, Smart Meters, Smart Industry/Manufacturing
SigFox	915 to 928MHz	Up to 20 km	100bps	Low	Smart Agriculture, Wearables, Smart Industry
Satellite	L, C, K_u K_a	>500 km	DL: ~ 64Mbps UL :~ 2Mbps	High	Autonomous Vehicles, Smart Health, Smart Cities
NB-IoT	From 450MHz to 3.5GHz Sub 2-GHz	>35 km	DL:170kbps UL:250kbps	Low	Smart Metering, Smart Vehicles, Smart Health, Wearables, Smart Grids
LoRaWAN	868MHz, 915MHz	15 km	50kbps	Low	Smart Agriculture, Smart Cities, Waste management, ITS
6LoWPAN	868MHz, 915MHz and 2.4GHz	100 m	250kbps	Low	Factory and Home Automation
High Altitude Platform (HAP)	47.2-47.5 GHz and 47.9-48.2 GHz	Up to 200 km	22-155Mbps	High	Weather and environmental monitoring, disaster management
Cellular	700, 750, 800, 850, 1800,1900 2100, 2600MHz	Up to 30 km	DL: 1Gbps UL:500Mbps	High	Smart Cities, Smart Grids
EC-GSM-IoT	850-900MHz, 1800-1900MHz	>35 km	UL :74kbps (GSMK), 240 (8PSK) DL:74kbps (GSMK), 240 (8PSK)	Low	Smart Grids, Factory Automation
e-MTC	450MHz to 3.5GHz	>100 km	UL:1Mbps DL:1Mbps	Low	Smart Cities, Smart Homes, Smart Metering
DRSC / IEEE.802.11p	5.8GHz, 5.9GHz	1km	6Mbps	Low	Smart Vehicular Communication(V2V/V2I)
Bluetooth	2.4GHz	10m	25Mbps	Low	Smart Homes , indoor e-health care

III. OPERATIONAL REQUIREMENTS AND METRICS

There are two major categories of Machine-Type Communication (MTC): massive MTC (mMTC) and critical MTC (cMTC) [3]. Massive MTC applications can be used in smart homes or smart agriculture and typically involve large number of low cost smart devices with requirements related to extended coverage and energy efficiency. Critical MTC applications on the other hand, require real time communication between smart devices and ultra-reliable low latency communication (URLLC). Factory automation and remote surgery are typical applications of cMTC. Other applications in which sensitive information are exchanged will have strict constraints related to security and privacy (*e.g*. in e-health). Examples of QoS/QoE metrics defined depending on the application or use case are:

1. Latency

End-to-End (E2E) latency includes queuing delay, transmission and re-transmission (if allowed) delay and processing delay. mMTC often have a relaxed delay constraint whereas cMTC have hard latency requirements which varies from one URLLC application to the other. Typical values of E2E delay for cMTC are 0.5 -1ms. A shorter frame structure for LTE system with a duration of 1 ms transmission time interval (TTI) was proposed to reduce transmission delay. Using Device-to-Device (D2D) communication can also reduce transmission delay but is restricted to short distances. Interference among different links may also set back the reliability of D2D communication. Non-orthogonal multiple access (NOMA), mobile edge computing (MEC) and mobile caching have been identified as potential measures to reduce E2E delay of URLLC in cellular systems [4].

2. Reliability

Reliability can be described as the successful or guaranteed packet delivery within the latency budget. Mission-critical applications may have very low packer error ratios (orders of 1 in a million or lower) depending on the use-case. Reliability can be achieved through coding, redundancy and diversity. Diversity and beam-forming provide multiple independent paths from transmitter to the receiver and improve the received signal-to-interference plus noise ratio (SINR). Diversity gains can be achieved in frequency, time and/or space. Time diversity may not be viable for applications with strict latency requirements. Spatial diversity using multiple antennas and intelligent MIMO/beamforming techniques is more promising since frequency diversity may not be also feasible due to scarcity and limitations of spectrum resources [4]. The main drawbacks are increased processing requirements and power consumption.

3. Availability
Availability is usually defined in terms of the service coverage or outage probability. Mission-critical services have very high availability requirements in that network coverage must be available 99.999% of the time [4]. For mMTC, wide coverage and deep penetration is also essential. Multi-connectivity or Multi-radio access technology (multi RAT) which involves simultaneous connections via multiple technologies ensures ultra-high availability especially in cases of high mobility.

4. Data Rate/Throughput
With the growth of IoT devices projected to be in the order of 28 billion devices by 2021 [1], insufficient bandwidth will affect the quality of user experience. The aggregation of small data volumes from a plethora of devices will eventually result in a massive amount of data to be transferred. Proper radio resource management is therefore required for optimal performance using multi RAT technologies and over multiple frequency bands simultaneously.

5. Security
Security in smart environment covers all aspects of safety, privacy, confidentiality, authorization and authentication. The heterogeneity, mobility and massive connection of smart devices make IoT platforms vulnerable to attacks from hackers and cyber-criminals. Users exchange sensitive information via the internet, hence threats to security need to be addressed. QoS/QoE requirements involve protection of user data and intrusion detection.

6. Power Consumption
Low power consumption is a major consideration as most smart devices are expected to operate for a long period of time. Power consumption increases with range as data is transmitted from one smart device to the other. Medium Access (MAC) protocols can switch devices from idle mode to sleep mode to extend the battery life. The use of energy-efficient optimisation techniques as well as energy harvesting from renewable energy sources are necessary to mitigate power consumption issues.

IV. CHALLENGES FOR RRM IN SMART ENVIRONMENT

There are two main approaches to RRM, namely: centralised and distributed. In centralised RRM, a central authority coordinates and controls the resource allocation policies whereas distributed RRM is user terminal-centric. Owing to the large-scale nature of some smart environments such as in manufacturing, a centralised RRM solution may not be always viable due to complexity in terms of information gathering, computational/processing cost and signalling overheads [5]. A distributed implementation, on the other hand, supports autonomy and heterogeneity which is a characteristic of devices in smart environments. The main challenges that need to be addressed when developing an RRM scheme for smart environments are as follows:

1. Mobility
In some cases, an ultra-dense network of randomly deployed wireless devices will be deployed. As devices move randomly in different directions, service disruption is likely to occur. Mobility management therefore has to be considered so that users can have an always best connected service anytime and anywhere.

2. Scalability
Future expansion of the network requires that demands of new users, applications and services are met when introduced to an existing system without compromising the QoS of existing users. A scalable RRM scheme with bounded computational complexity is therefore needed for future growth.

3. Self-Organisation
Smart devices and networks are expected to be autonomous, capable of making independent decisions, managed, optimised and healed with minimal human intervention. A RRM technique with a learning capability is therefore necessary.

4. Heterogeneity
A smart environment is characterised by heterogeneity. Different device types with different service requirements in terms of energy consumption, cognitive abilities and resource demand are expected. A management framework that captures different device types and QoS requirements is necessary.

5. Energy Efficiency
Smart devices are energy constrained and mostly battery powered requiring frequent charging. Even with the use of green sources (*e.g.* solar, wind) and energy harvesting, energy demands are still challenging.

V. CURRENT RRM TECHNIQUES

RRM can use centralised or distributed approaches as describe above. Different techniques can be used to realise a RRM framework or methodology. Examples include game theory [6-7], machine learning [8-9] and general optimisation [10].

1. Game Theory

Game theory provides a framework to model characteristics and interactions between nodes in an autonomous and distributed manner. This makes it suitable for decision making among smart devices with conflicting interests in a multi-agent system such as in a smart environment. In a game theoretic approach, entities are represented as a set of players, a set of available strategies are defined for the players as well as a utility function. Nash Equilibrium is a solution concept that comes into play in a non-cooperative game when all players have chosen their best response to the actions of other players.

Different game models can be used to represent a smart environment where smart devices (sensors, actuators and controllers) adapt their transmission parameters as strategies such as power or frequency channels to maximise their utility such as data rate, energy efficiency or low latency. In [6], a non-cooperative game theoretic approach was used for power and channel allocation to maximise energy efficiency in an Industrial IoT system. In [7], the authors proposed a proximity-aware resource allocation for Vehicle-to-Vehicle (V2V) communication with the objective of satisfying the reliability requirements while reducing interference to other cellular pairs using a many-to-one matching game.

2. Machine Learning

The vast number of intercommunicating devices deployed in some smart environments may make a centralised RRM approach impractical. A distributed solution is better suited to support learning. By learning, smart devices can adapt to the environment, manage their limited resources and satisfy strict QoS requirements [5]. Machine learning was originally designed and developed for computers to learn and make decisions that will yield better performance for a given task. There are three main categories: i)Supervised, ii)Unsupervised and iii)Reinforcement Learning. The range of applications include modelling cognitive radio networks, massive MIMO systems, heterogeneous networks and IoT. For smart environment applications, A Hidden Markov Model (HMM) was used for throughput maximisation in a cognitive smart grid network by predicting the idle time of channels and matching channels to users based on data priority [8]. In [9], a cooperative spectrum resource allocation (CSRA) was proposed to achieve fairness through partially observable Markov Decision in smart home systems.

3. Mathematical Optimisation

Mathematical optimisation involves techniques used for minimisation or maximisation of a utility function with a given set of constraints. Examples include latency and reliability optimisation for V2V communication in [10].
Examples of RRM techniques used in different smart environments are presented in Table 2.

Table 2. Examples of Radio Resources Management Techniques

RRM Technique	QoS Metric Optimised	Achieved Performance	Smart Environment Domain
1) Game Theory			
Non-Cooperative Game [6]	Energy efficiency	Higher energy efficiency performance compared to the Greedy algorithm	Smart Industry
Matching Game [7]	Reliability	Higher percentage of V2V satisfying up to 50% QoS requirement and target SINR gain compared with baseline approach	Vehicle-to-Vehicle (V2V) Communication
2) Machine Learning			
Hidden Markov Model [8]	System throughput	Higher system throughput and channel performance compared with random matching	Smart Grid
Partially Observable Markov Decision Process [9]	Fair spectrum allocation	Overall maximization of spectrum resources	Smart Home
3) Mathematical Optimisation			
Heuristic Method [10]	Latency and reliability	Achieved QoS requirement under a power efficiency of >24dBm	Vehicle-to-Vehicle (V2V) Communication

VI. CONCLUSIONS

In this paper, we highlighted some issues related to the application of IoT in smart environments with a focus on radio resource management (RRM). We presented examples of applications and use-cases, the main wireless communication technologies used, operational requirements and key QoS/QoE metrics. We discussed the main RRM challenges and showed that a distributed RRM approach is likely to be more suitable for a smart environment. Some game theoretic based methodologies can be used for a distributed RRM solution. There are however some limitations that make a game theory solution inadequate for large-scale network deployment such as in a smart factory. These limitations include the complexity associated with modelling utilities, slow convergence to equilibrium and high overheads. General mathematical optimisation techniques often adopt a centralised approach which may not be efficient in an ultra-dense network of devices with strict latency requirements. It is concluded that no single wireless protocol or technology can currently satisfy all the requirements in some smart environments. Our future work will focus on exploring possible machine learning techniques to help solve some of these challenges. Examples of the proposed techniques that will be investigated include:

1. Reinforcement learning for power management with the coexistence of multiple technologies where the agents choose power policies that will result in an energy efficiency reward.
2. Multi-armed bandits learning to model resource allocation under a fixed reliability or delay constraint for different processes and with different performance requirements (*e.g.* a smart manufacturing scenario with different use-cases such as production automation, robotic control and/or monitoring of machines' condition)
3. Q-Learning for mobility handover and load balancing in a D2D-based network.

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