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Towards Connected Living: 5G Enabled Internet of Things (IoT)

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ABSTRACT

Connected living — the true vision of the Internet of Things (IoT) – offers improvement in the quality of life while presenting new business avenues. A combined effort by researchers, industries, manufacturers, service providers, and other stakeholders is required to address distinct IoT requirements. This convergence is expected to unleash a new dimension of opportunities that cannot be fully realized with conventional solutions. At the same time, 5G wireless promises a new connected ecosystem with potential technologies, like massive Multiple-Input and Multiple-Output (MIMO), Cloud Radio Access Network (C-RAN), Heterogeneous-CRAN (H-CRAN), mmWave, software-defined networking, information (content or data)-centric communication, Multi-RAT, and novel multiplexing. Since emerging 5G network is expected to revolutionize the way of communication, its design and standardization should consider IoT as one of the major guidelines. To this regard, we present technical details of emerging 5G networks inline with pressing IoT requirements, essential for the ultimate shaping of a connected living. We also delineate limitations of legacy networks to provide for peculiarities of IoT requirements.

KEYWORDS

Battery life; Content-centric; Heterogeneous connectivity; IoT; Massive MIMO; Narrowband; 5G

1. INTRODUCTION

IoT (Internet of Things) is seen as the most promising technology to realize the vision of connected living. Pervasive connectivity is brought about by intelligent, automatic, smart, and context-aware physical objects that think and act intelligently, without explicit human involvement. In the upcoming years, it is expected to not only enhance the quality of life, but also open-up new revenue streams [1]. The economic influence of IoT is expected to be in the range of \$2.7–\$6.2 trillion by 2025 [1]. Capabilities of IoT promise to save people's and organizations money and time while at the same time contributing towards enhanced outcomes in a wide range of novel application areas [2]. We can begin to imagine the socio-economic impact of multiple services like education, health care, transportation, security, surveillance, agriculture, automotive, shipping, logistics, smart homes, smart grids, and smart cities. An example of connected environment is depicted in Figure 1. A connected ecosystem would involve many IoT-enabled devices, connected to the Internet for supporting a wide variety of applications. Figure 1 shows the applications of automated connectivity for smart cities, smart health care, smart agriculture, and smart industries. In order to realize IoT to its full potential, there is an impending need to investigate its convergence with emerging technologies and innovations. Wireless communications, one of the most successful technologies in recent years, offer to manage the complexities, like scalability, ubiquitous coverage, backhaul connectivity, and installation, associated with IoT. The ongoing revolution in wireless communications, especially Machine-to-Machine (M2M) technologies, can be considered as the first phase of IoT deployment [1]. However, legacy cellular technologies are inherently designed for an optimized Human-to-Human (H2H) communication and thus, are not efficient for M2M communications [1]. Next generation 5G communications, rapidly coming into the limelight, offer many novel and potentially disruptive elements to human-centric legacy broadband networks [3]. Recently, massive Machine-Type Communications (MTCs) gained the consensus of stakeholders, at the 3GPP RAN 5G Workshop, as a high-level use case for immediate address [4]. This would ultimately lead to embedding of an IoT landscape in the emerging 5G systems. Furthermore, with the promise of increase in capacity, reduction in end-to-end latency, better reliability, and improvement in coverage, 5G holds the potential to address even the most demanding IoT requirements [3].

Motivation: the efficient, seamless, and unified connectivity of "things" over the "Internet" requires understanding and analysis of wireless technologies for the IoT domain. 3GPP standardization of 5G has already been initiated and would potentially impact global IoT in the near future. IoT landscape requires not only new

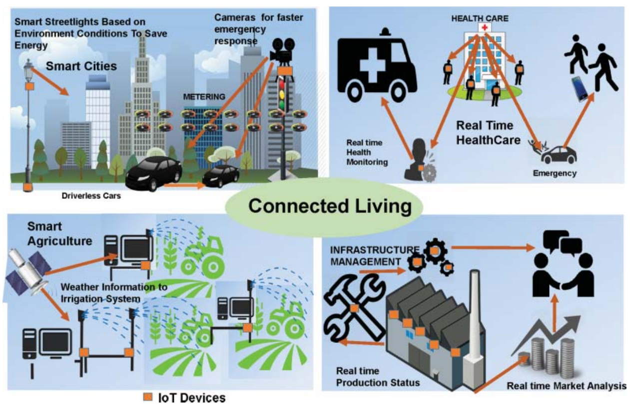


Figure 1: A vision of connected living involving different devices in smart cities, smart cars, smart health care, smart agriculture, and smart industries

protocols but also architecture standardization to meet the expected deployment of billions of entities in the near future. It is therefore important to align the research work in IoT domain with 5G standardization, lest the market fragmentation impedes IoT globalization. Many research and innovations pertaining to 5G are already gaining momentum at a global level. We believe it is critical to develop an insight into the current and advanced state of research in the wireless domain from IoT perspective. This motivates us to investigate IoT requirements from 5G wireless perspective.

Contributions: in the backdrop of recent developments in 5G communications, this paper aims to analyse the fundamental peculiarities of IoT requirements while identifying the challenges and opportunities therein in the context of 5G wireless connectivity. Though this article provides a concise review of selected literature on 5G-IoT, its main objective is not to provide a comprehensive survey of literature. Instead, this article has the following goals:

- In view of continuous developments in Long-Term Evolution (LTE) and its heavy deployment, it is important to examine the viability of LTE for various IoT requirements. We begin with a brief discussion of the major LTE shortcomings with respect to IoT requirements, in order to avoid pitfalls in 5G-IoT framework.
- We discus how the adoption and utilization of mmWaves, non orthogonality, novel multiplexing, massive MIMO, HetNets, Cloud Radio Access Network (C-RAN), Software-Defined Networking (SDN), and other blessings of 5G infrastructure would help in satisfying the massive connectivity and diversity of IoT landscape more effectively.
- We perform numerical analysis to bring about the advantages of 5G communications over legacy networks for effectual IoT landscape. We consider scalability, latency, energy efficiency, and monetary expenses to highlight the potentials of 5G technologies.
- Our evaluations incorporate data-rates, expected number of connections, Transmission Time Interval (TTI), latency, scheduling, energy efficiency (in bits per joule), Capital Expenditure (CAPEX), Operational Expenditure (OPEX), and cost estimates. The numerical analysis clearly brings about that future wireless networks will offer much more than incremental improvements of LTE.

Though there are several research works focused on different aspects of IoT, ranging from its requirements, architecture, protocols, challenges, and potential applications [1], the novelty of our work is to explore IoT for its integration into next generation 5G networks. Hence, we have compiled, categorized, and mapped IoT requirements, keeping in view wireless communication as the key enabler. Our article aims to highlight that 5G facilities orchestration would enhance IoT deployment and provide the desired connected landscape.

2. IOT REQUIREMENTS and SHORTCOMING OF 4G WIRELESS

While the legacy network is designed with focus on H2H interface over larger distances, present communication is shifting towards a more general M2M platform. The heterogeneity of diverse specifications challenges the the cooperative event processing between several things and more generally, the information exchange and communication between things [5]. Thus, it is required to investigate the legacy wireless connectivity from IoT's perspective.

2.1 Massive Connectivity

As depicted in Figure 2(A), the very idea of IoT revolutionizes the density and diversity of connected devices. By 2020, 212 billion smart entities are expected to be deployed worldwide [1]. On the contrary, LTE wireless networks were designed for limited Radio Resource Control (RRC) connected users [6]. The industry's vision of an autonomous connectivity was traditionally facilitated by means of wires [3]. However, the enormous scalability, expected in IoT landscape, can be addressed through wireless solutions only. This gap between available technology and billions of interconnected heterogeneous objects would gradually coax a disruptive level of

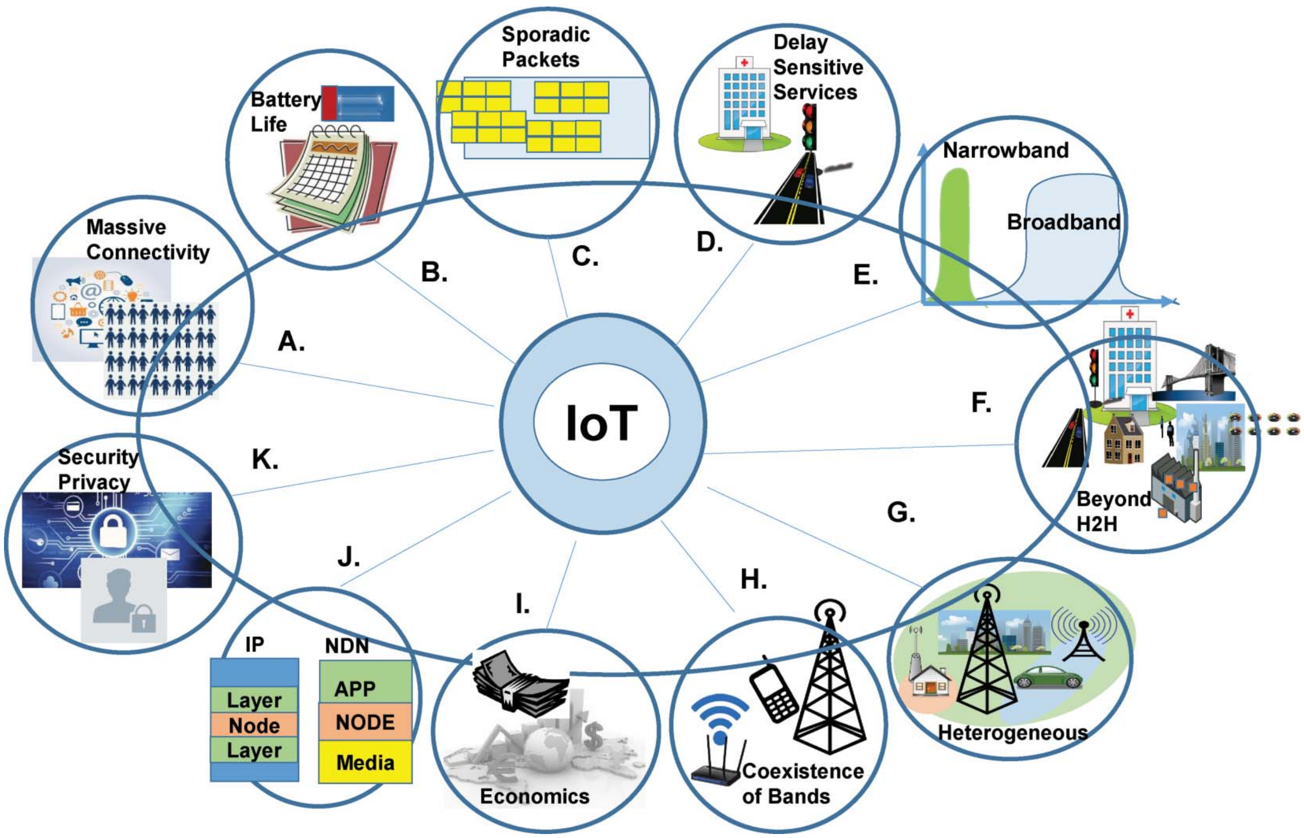


Figure 2: Different requirements for deployment of IoT

innovation into legacy networks. Moreover, the traditional mechanism of access in the wireless system would suffer from congestion and overloading, caused by umpteen requests from enormous devices. A large number of MTC devices performing simultaneous random access, would degrade the channel performance [7]. Furthermore, classical network computing techniques would fall short to extract the desired information from the massive volume, velocity, and variety of connections.

2.2 Extended Battery-Life Time

To enable wireless connectivity, majority of smart IoT devices are expected to be battery-operated. Changing or charging of batteries may not be easily or economically possible. Moreover, IoT-enabled embedded devices run on tiny batteries [3]. Thus, the need for extended battery-life time, pointed out in Figure 2(B), is an impending challenge in IoT deployment, which can not be ignored. Typical traffic patterns in M2M communications reveal that the energy requirement for transmitting messages is usually small [3]. Though 3GPP Release 12 has introduced an add-on power-saving mode for MTC communication [3], ensuring long battery life in IoT devices is still a distant reality in orthogonal frequency-division-based LTE networks.

2.3 Sporadic Traffic and Orthogonality Constraint

The bulky synchronization procedures of random access are integral to 4G-LTE networks, for addressing orthogonality constraints [8]. While synchronization ensures temporal alignment between senders, orthogonality alleviates crosstalk [8]. Establishing frequent time–frequency alignment in small data packets causes signalling overhead. In fact, in synchronous Orthogonal Frequency-Division Multiple Access (OFDMA)-based MTC approach, the amount of information data is comparable or even less than high signalling overhead [7]. Moreover, in an IoT era, everyday smart objects would become major generators and receivers of traffic [8]. Thus, future wireless traffic is expected to be of sporadic nature, as highlighted in Figure 2(C), posing a key challenge for service-based IoT architecture [8].

2.4 Delay Tolerant and Delay Sensitive Services

Limited battery life and bandwidth resources encourage intermittent connectivity in IoT devices. To some extent, the delay-tolerant networking is acceptable for some applications. However, applications like health care, autonomous driving, and tracking, as shown in Figure 2 (D), are of high priority and are delay-intolerant.

Moreover, tactile internet, rapidly coming to limelight for applications at fingertips, is a big motivator for low latency internet connectivity [9]. 4G networks have around 10–15 ms round-trip time (owing to uplink schedule request) [9], which is questionable for critical communications, driverless cars, and other delay-sensitive services.

2.5 Narrowband Operation

Pressing needs for high battery life, low data-rate M2M communication, and bursty traffic are contrary to conventional broadband wireless communications. Typical LTE protocols, conceived for broadband operations, are hence overdesigned for low-rate and many-delay-tolerant services, expected in IoT landscape [7]. Recently, 3GPP has included narrowband IoT (NB-IoT) in Release 13 standards. NB-IoT technology facilitates low power and wide area connectivity in the licensed spectrum as opposed to short-range unlicensed technologies like ZigBee, Bluetooth, etc. [10]. With NB-IoT, it is possible to deploy a narrow bandwidth of about 200 kHz. Moreover, it promises improved coverage, better energy efficiency for longer battery life, and lower complexity for low-cost devices [11]. While a subcarrier spacing of 15 kHz is used in legacy LTE systems, a subcarrier spacing of 3.75 kHz is introduced in NB-IoT for the uplink design [10]. However, studies have revealed that 3.75 kHz subcarrier offers some negative effects on coexistence with the 15 kHz subcarrier spacing of LTE [10,12]. Thus, narrowband operation, depicted in Figure 2(E), is one of the key requirements that requires further investigations for low-data applications and flexible IoT deployment [3].

2.6 Beyond Human Interface

From a system-level perspective, IoT can be envisioned as a dynamic and distributed network system for interface with the physical realm. Physical phenomena are sensed through devices and IoT offers connectivity solutions integrating sensors, actuators, meters, appliances, services, and so on [11]. Thus, there is a new challenge that connects not only humans but also devices. Unlike H2H communications, the major IoT requirement lies in enabling economical connectivity of a myriad of devices wirelessly [13]. Furthermore, connectivity of physical devices require ample network capacity, prolonged battery life, and improved coverage such that the devices can reach challenging locations [13]. This quest for an inclusion of wide sensing applicability is expected to become a major obstacle to human-oriented legacy wireless communications. Things-oriented vision, shown in Figure 2(F), clearly speaks of something beyond human interaction. Moreover, as IoT becomes sophisticated, things and humans will interact more often and more harmoniously. Thus, the IoT requirement of integrating communication with the physical realm cannot be ignored.

2.7 Heterogeneous Connectivity

Legacy networks were designed for optimized communication over the macrocell deployment [3]. With IoT, the semantics of inter-connectivity are changing to allow the exchange of data not only at macro levels, but more importantly at relaying distances. In general, proximity services would be the crucial component of IoT ecosystem. Figure 2(G) highlights that the IoT connectivity landscape would involve interoperability at pico, femto, micro, and macro levels. Diversity is further magnified by an extravaganza of services, applications, devices, manufacturers, service providers, multi-vendors at different levels of abstractions. Though Heterogeneous Networks (HetNets) are rigorously researched in legacy paradigm, backhaul and interference management remain as substantial challenges. To this, addition of increased level of diversity, connectivity, analytics, and cost would further impede the performance of existing networks.

2.8 Disjoint Licensed and Unlicensed Band

Bluetooth and the IEEE802.15.4 standard have played a significant role in IoT evolution [3]. Shorter propagation ranges (between 1 and 100 m) in Bluetooth connections promise lower power consumption. ZigBee offers low-power, low-cost, fairly long-range connectivity at lower data-rates. LAN/MAN Standards Committee, in 2010, formed the Low-Power WiFi Task Group to meet the IoT requirements (large number of devices, large coverage range, and energy constraints) by extending the application area of WiFi networks [3]. At the same time, 3GPP has also been working on M2M applications. While Bluetooth, ZigBee, and Low-Power WiFi work in short-range and under unlicensed band, the LTE-based connectivity extends in kilometres within the licensed range of spectrum, as envisioned in Figure 2(H). Integration of various licensed and unlicensed bands, though inevitable in the wide landscape of connections, services, and applications of IoT, remains unanswered in legacy network.

2.9 Economic Considerations and Standardization

The success of IoT would ultimately depend on its capital benefits (Figure 2(I)). Converging various manufacturers, industries, vendors, network operators, servers, consumer applications, etc. into a single business model would require a major rework on standardization and billing procedures. A viable approach could be sharing [9]. Vendors and operators are expected to share resources, infrastructure, and services for cost-effective and fast IoT deployment [3]. The current Internet architecture follows a hierarchical design, with dedicated service providers catering specific services. A similar business model might not derive benefits in an IoT environment that needs to be harmonized across multiple industries.

2.10 Addressing

Unique addressing and representation of billions of connected objects would be a daunting task. Internet Protocols (IPs) evolved from IPv4 to IPv6, to accommodate vast connections, by expanding address space from 32 to 128 bits. Named Data Networking (NDN) is also emerging as the key contender for an interconnected ecosystem. While the energy expenditure of an IP-based network is an unanswered concern, overheads generated in NDN for data-forwarding are unsuitable for IoT. The limited bandwidth in legacy networks poses a major challenge to this wireless connection dynamics. Moreover, the viability of LTE-based addressing and information exchange in envisioned wireless IoT scenario is yet to be ascertained. The layered architecture of IPv6 in contrast to application-centric NDN is delineated in Figure 2(J).

2.11 Privacy, Security, Trust, and Reliability

The vast deployment of independently communicating objects in everyday life poses danger to the security and privacy of individuals. Sensitive data about health and habits may be at risk of exposure [3]. Thus, it is essential to address challenges related to the management of privacy and security in all the exchanged data. On the other hand, trust and reliability models are necessary to establish usefulness, authentication, accountability, and non-repudiation [3]. The volume of data, collected from millions of real-time smart objects, would be enormous [3]. Reliable ways of data-inference, efficient big-data analysis, and trustworthy data-mining techniques are crucial to avoid wrong conclusions. These functionalities may or may not be specific to various applications or services. Whatsoever be the design, a new composition would be an add-on to the already existing LTE protocols and not integral to it.

Various IoT applications, with fundamentals embedded in density and diversity, point out at distinct

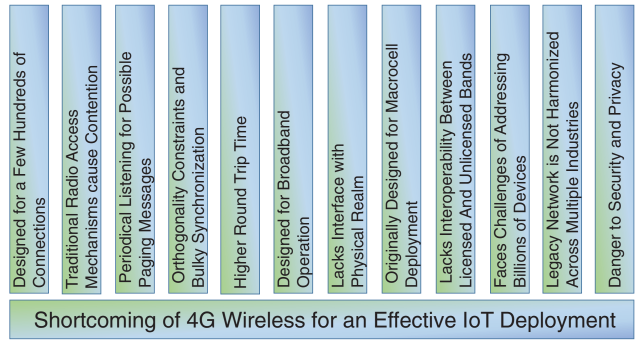


Figure 3: Major shortcomings of legacy network w.r.t IoT

requirements of high bandwidth, massive connectivity, mobility support, privacy, low latency, unique addressing, physical interface, and complex economics. Clearly, the legacy networks fall short in providing for an IoT ecosystem with various levels of abstraction in the same framework as pointed out in Figure 3.

3. BLESSING OF 5G AND IOT SUPPORT

Next generation 5G wireless communications promise to provide manifold data-rates (typically of Gbps order), low latency, and significant increase in base-station capacity compared to current 4G LTE networks [6]. Understanding of key 5G-enabling technologies would lay the strong foundation for resolving IoT challenges.

3.1 High Bandwidth

High-frequency mmWave band in Figure 4(a), ranging from 3 to 300 GHz, offers answers to spectrum limitations in wireless communications [6]. The paradigm shift to this unused mmWave spectrum is motivated by the availability of 10–100 times cheaper per Hz big chunks of bandwidth [9]. Moreover, Complementary Metal-Oxide-Semiconductor (CMOS) technology support and high-gain directive antennas further accentuate the popularity of mmWave communication [3]. This immense capacity offers support for a very large number of devices in an IoT landscape. Furthermore, mmWave-driven directional air interface enables spatial capabilities. Together with high bandwidth, spatial multiplexing would further enhance network capacity and is expected to alleviate signalling, congestion, and network overloads.

3.2 High Battery Life – Fundamental Requirement in 5G

Increase in network density enhances the share of energy consumption in an access network [9]. Research work in

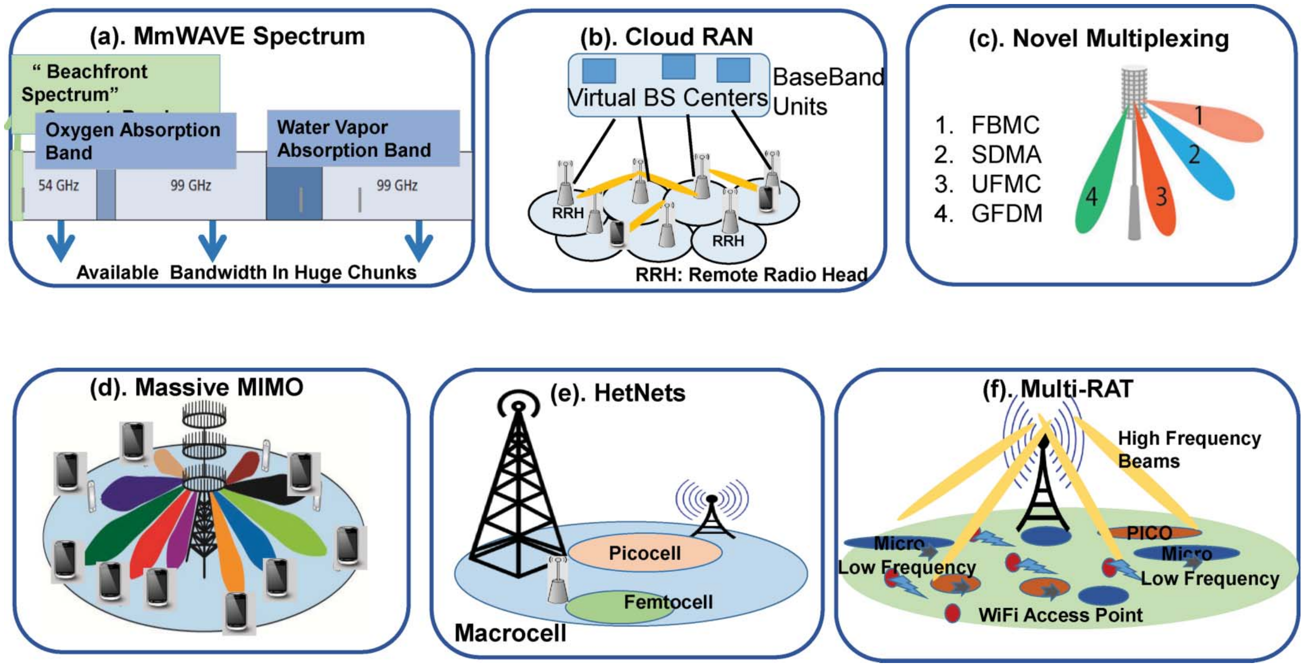


Figure 4: IoT-enabling 5G technologies

the field of resource allocation points out that significant energy savings are possible by compromising the data-rates [9]. As data-rates expected in 5G scenarios are very high [6], substantial gains are feasible even with moderate reductions in the data-rates. While legacy networks are originally designed to achieve busy-hour traffic [9], energy-efficient strategies could be prioritized in upcoming 5G networks. Moreover, two important concepts, C-RAN and small-cell deployment expected to be integral to emerging 5G networks, offer reduction in energy expenditures. The cloud-based architecture shown in Figure 4(b), shifts all processing to the centralized location, while conventional sites are simplified to energy-efficient radio heads [6]. Small-cell-based architecture brings devices nearer to the BS, thus reducing uplink energy expenses. Device-to-Device (D2D) communications, expected to be native to 5G [6], also offer to optimize uplink energy efficiency by exploiting relaying to proximity devices, rather than traversing through the far-away Base Stations (BSs).

3.3 Flexible and Novel Time Frequency Multiplexing

New formats of time-frequency packaging, like multi- and single-carrier transmissions, are attracting renewed interest to leverage the restrictions of synchronism and non-orthogonality. Tunable Orthogonal Frequency Division Multiplexing (OFDM) with variable subcarrier spacing, Fast Fourier Transform (FFT) block size, and cyclic prefix length offers variable delay spreads to address the low latency requirements [9]. Among many possibilities, there is a growing consensus among the research community that shorter and flexible TTI would be instrumental for MTC. Potential non-orthogonal alternatives to OFDM, are also being rigorously investigated for efficient Media Access Control (MAC) functionalities in 5G networks [6]. For instance, filter bank multi-carrier is natively non-orthogonal and promises to improve latency in sporadic traffic environment [6]. Research work on generalized frequency-division multiplexing, universal filtered multi-carrier, and spatial division multiple access, highlighted in Figure 4(c), presents new ideas of multiplexing in agile 5G networks [6]. Interestingly, non-orthogonality and variable latency would also be crucial to diverse, delay-tolerant, delay-intolerant, and sporadic IoT services. Thus, it is not far-fetched to assume that 5G multiplexing capabilities would be harmonized over IoT requirements.

3.4 Antenna Array Technology for Narrowband Operation

Massive MIMO techniques presented in Figure 4(d), are gaining momentum to achieve highly directional mmWave communications [6]. Research works focused on cost reduction and high array gains, using analog beam-forming, hybrid beam-forming and electromagnetism have been proposed for both narrowband and wide-band mmWave communications [14]. While existing transmit-beam pattern synthesis is focused on narrow-band configurations [15], recent investigations into the mmWave MIMO with lens antenna array encompass both narrowband and wideband communications [14]. Work in [14] highlights the effectiveness of lens antenna array-enabled mmWave MIMO communication system in attaining cost efficiency and large antenna gains by utilizing limited Radio Frequency (RF) chains. Such low-complexity MIMO spatial multiplexing techniques are applicable to narrowband communications as well [14]. Moreover, optimized MIMO-based waveform designs are crucial to achieve desired system performance. The benefits of waveform design are achieved such that they are coherent with each subarray while at the same time being orthogonal across the different subarrays [15]. Thus, the cross-correlation matrix is an important attribute in MIMO waveform design. However, the cross-correlation matrix problem is much more complicated in wideband signals than the narrowband case since wideband signals are dependent not only on the array sensors but also on the time-delays [15]. While mmWave MIMO plays a key role in 5G wireless, narrowband communications are important to IoT connectivity. Thus, such works lay a strong foundation for narrowband-based IoT landscape.

3.5 HetNets and Massive MIMO for IoT Architecture

Wireless networks are progressively evolving into nested small cells, including microcells, picocells, and femtocells giving rise to HetNets as depicted in Figure 4(e) [9]. The small-cell HetNets are the major building blocks of the emerging 5G architecture [6]. These low-power small BSs extend the network capacity to coverage holes. Improved coverage support is an important design item for connectivity in dense IoT landscape. For instance, European Telecommunications Standards Institute (ETSI) along with 3GPP proposed the MTC architecture, where machine-type devices can access the network either through legacy base stations or small cells [16]. Moreover, HetNets take into account architectural, operational, and economic perspectives utilizing techniques like coordinated multi-point and load-balancing. Such technical factors make HetNet design different from macro-cells only networks and provide opportunities for improved cell planning in the wake of 5G-IoT paradigm. Authors in [17] have pointed out that recent works on cell planning do not take into account IoT deployments. Fortunately, recent 3GPP study items [18] consider IoT device features (like: reduced transmit power, single receive antenna, reduced peak data-rate, etc.) that are relevant to network planning and are inline with the research work of HetNets. HetNets, being rigorously investigated for emerging 5G environment, are further supported by other 5G technologies like massive MIMO and network virtualization [6]. Massive MIMO with tens to hundreds of antenna elements is a promising technology for emerging 5G systems. The large number of antennas ensures increase in signal dimensions that results in increased aggregated data-rate, improved radiated energy efficiency, and enhanced robustness to interference [19]. Such qualities facilitate easy transition towards IoT-enabled connected living. Advances in directive massive MIMO technology offer to alleviate interference challenges in heterogeneous connectivity. The dense, diverse, and ubiquitous IoT connectivity is expected to be benefited by both HetNets and MIMO techniques.

3.6 Network Virtualization

Novel concepts of SDN and Network Function Virtualization (NFV) promise flexibility, agility, and fast implementation of new services. Various network services can quickly and adaptively re-route data-flow in SDN-enabled network nodes. At the same time, software-based implementations make network functions easy to instantiate [16]. Furthermore, C-RAN offers simplified deployment, management, operation, and round-the-clock optimization [6]. In C-RAN, many base station functionalities are migrated to the cloud [6]. Network virtualization (including SDN, NFV, and C-RAN) brings about possibilities of generic, flexible, and reconfigurable design, to establish and extract the desired information from immense number of devices [16]. On the road to dense 5G deployment, 3GPP standards' work on virtualization has already begun (since Release 12) [20]. We believe advances in network virtualization would provide scalability, adaptability, and interoperability to IoT landscape.

3.7 Self-Organizing Network (SON)

Self-healing, self-configuration, and self-optimization functionalities of Self-Organizing Network (SON) offer automation by reducing human intervention [6]. Big-data analysis, along with SON capabilities, is expected to provide intelligence about the network status, prediction of user behaviour, and dynamic association of network parameters [6]. Integration of these capabilities would ease the burden of quality, energy efficiency, and maintenance for colossal number of smart devices with variable demands. For instance, the SON functionalities could allocate extra bandwidth to IoT devices that detected some dangerous events and need quick communication at the maximum speed [3]. We believe a higher degree of virtualization and centralization in 5G wireless networks would further enhance the SON functionalities. With coexistence of multiple industries, shared physical infrastructure, and interoperability issues, the SON would be critical for automation of IoT ecosystem.

3.8 Coexistence of Multiple Radio Access

As shown in Figure 4(f), many promising radio technologies, like Zigbee, Bluetooth, WiFi, Low-Power WiFi, Low-Power Wide Area networks and several variations of cellular systems, are attractive for IoT connectivity [3]. Licensed and unlicensed radio nodes on the same bandwidth manifest as cognitive radio technique. Dynamic routing and resource allocation of cognitive radio promise support to fundamental 5G characteristics of higher traffic loads and lower delays [6]. Coexistence of multiple radios is also augmented by relaying. Relaying technologies provide scalability to high density IoT systems [9]. Interestingly, a typical 5G device is expected to support 5G standards, 3G, 4G LTE, possibly LTE-Unlicensed, various types of WiFi, and D2D-based relaying communications [9]. Though standardization, native support to D2D, and spectrum utilization in 5G are complex challenges yet to be resolved, IoT would be the primary beneficiary of such 5G developments.

3.9 Content-Centric Architecture

Unlike existing host-centric network, the vision IoT is focused on data-centric services irrespective of content location [21]. The new paradigm of Information (content or data) Centric Communication (ICN) is well suited to content dissemination and sharing [21]. With the aim of high performance support to new modes of service delivery over wireless networks, research work is changing gears from connection-centric to content-centric networks [22]. The framework of a content-centric design offers to combine wireless access with computer hardware from within the networks [22]. Moreover, group resources and multi-cast technologies in the field of IoT provide decimation of same content to a group of M2M resources [3]. Such novel concepts of addressing and delivery, in emerging paradigm, hold the promise of an efficient communication to IoT devices.

3.10 Business Models and Multi-Tenancy

Traffic characteristics in densely connected machine-type environment are dominated by small and infrequent data-bursts, constituting high volume on uplink [7]. This sporadic IoT traffic encourages operators to share both spectrum and infrastructure resources [9]. Current market and wireless standards are not flexible enough for dynamic market-sharing. However, in future, a dynamic spectrum market is expected to emerge, which would allow assets to be bought, sold, and leased, on time-scales of hours, minutes, and even milliseconds [9]. Such propositions would require an adaptable and agile environment [9]. Moreover, novel business models are needed to address billing issues in the dynamic environment [3]. 5G enablers, like radio access network as a service, network virtualization, self-healing, self-configuration, self-protection, and self-optimization, offer flexibility to management platforms for new regulations [3].

We believe that novel 5G technologies and not legacy network add-ons, hold the potential for fulfilling the distinct IoT requirements as summarized in Table 1.

4. 5G – THE ROAD TOWARDS CONNECTED LIVING

Novel IoT services and applications are not only satisfying users' requirements, but are also opening-up new business opportunities. With 5G over the horizon, its time to assess its capabilities for diverse IoT requirements.

4.1 Numerical Analysis

We emphasize our claims, about the effectiveness of 5G communication for a connected environment, by an elaborate numerical analysis. To ascertain scalability, we consider $M_{\min}$ as the minimum required throughput of every mobile user and $D_{\min}$ as that of every IoT device. If p is the percentage of IoT devices and R is the maximum available data-rate, then we evaluate the number of IoT devices supported by system (Γ) as

$$\Gamma = \frac{(P/100) \times (R)}{D_{\min}} \tag{1}$$

For the evaluation of round-trip latency, we consider the average uplink and downlink delays along with Hybrid Automatic Repeat Request (HARQ) re-transmission delay. The total round-trip latency L_{RRT} can be calculated as

$$L_{\mathrm{RRT}} = \mathrm{UL}_{\mathrm{delay}} + \mathrm{DL}_{\mathrm{delay}} \tag{2}$$

$$\mathrm{UL}_{\mathrm{delay}} = \frac{\mathrm{TUL} + \mathrm{Loss} \times \mathrm{HARQ}_u}{N+1} \tag{3}$$

$$\mathrm{DL}_{\mathrm{delay}} = \frac{\mathrm{TDL} + \mathrm{Loss} \times \mathrm{HARQ}_d}{N+1} \tag{4}$$

$$\mathrm{HARQ}_u = \mathrm{Loss} \times \mathrm{TUL} + \mathrm{Loss} \times \mathrm{TUL}^2 \cdots + \mathrm{Loss} \times \mathrm{TUL}^N \tag{5}$$

Table 1: Key differentiators between legacy networks and 5G wireless to address IoT requirements

Requirement	Limitations of legacy network	What 5G offers?
Massive connections	• Were designed for limited RRC users. • Congestion and overloading.	• mmWaves offer vast spectrum. • Directional interface for spatial capabilities. • Reduce congestion.
Long battery life	• Periodical listening for possible paging. • Power-saving modes are add-on and native.	• C-RAN offers energy management. • D2D, native to 5G, optimizes uplink energy.
Sporadic traffic	• Orthogonality constraints. • Bulky synchronization procedures. • Time-frequency alignment in small packet. • Signalling overhead and battery drains.	• New formats of time-frequency packaging. • Leverage synchronism and non-orthogonality. • Potential alternatives to OFDM. • Efficient MAC functionalities in 5G networks.
Delay-sensitive	• Some applications are delay-sensitive. • 4G networks have ~15 ms round-trip time. • Not suitable for critical communications.	• Multiplexing for variable delay spreads. • Addressing of low-latency requirements. • Expected to have 1 ms round-trip latency.
Narrowbands	• Narrowband for low-data applications. • Flexible deployment. • Optimized for broadband communications.	• MIMO and electromagnetic lens for narrowband. • Coexistence of narrowband and broadband.
Beyond H2H	• IoT envisions interface with the physical realm. • LTE networks designed for H2H communication.	• M2M has native support in 5G wireless. • Automation through SON.
Heterogeneity	• Interoperability needed at small and macro levels. • Legacy networks designed for macro-cells.	• HetNets are being rigorously investigated. • Massive MIMO and C-RAN support. • Virtualization for flexibility and agility.
Coexistence	• Bluetooth, Zigbee, etc. work in unlicensed bands. • LTE connectivity extends over licensed range.	• Device to support 5G standards, LTE, 3G. • Unlicensed, types of WiFi, and D2D. • Cognitive radio techniques.
Economics	• Business model needs be harmonized. • Multiple cross-provider information sharing. • Current architecture follows hierarchical design. • Dedicated service providers.	• Multi-tenancy. • Decoupling of infrastructure and services.
Addressing	• Energy expenditure of an IP-based network. • Overheads generated in NDN for data-forwarding.	• Information-centric communication. • For content dissemination and sharing.
Privacy and security	• Management of the privacy and security. • Trust and security are not integral.	• Expected to increase privacy and security.

$$\mathrm{HARQ}_d = \mathrm{Loss} \times \mathrm{TDL} + \mathrm{Loss} \times \mathrm{TDL}^2 \cdots + \mathrm{Loss} \times \mathrm{TDL}^N \tag{6}$$

where TUL and TDL respectively are the average uplink and downlink delays without any loss (the values depend on TTI), the value of loss is in percentage, and N is the total number of re-transmissions allowed.

Let M_b be the traffic and P_{total} be the power expenditure such that $P_{\text{total}} = \frac{1}{\alpha} \times P_{\text{trans}} + \mu \times P_{\text{RF}} + C$, then we can evaluate the energy efficiency in bits/joule (EE) as

$$\mathrm{EE} = \frac{M_b}{\frac{1}{\alpha} \times P_{\text{trans}} + \mu \times P_{\text{RF}} + C} \tag{7}$$

where α is defined as the efficiency of the power amplifier, P_{trans} is the transmit power, P_{RF} is the power that is consumed by the RF chain, and C is the power consumed at the BS for site cooling and processing [23].

Finally, we can calculate the cost per bit as

$$\mathrm{EE} = \frac{\mathrm{Capex} + \mathrm{Opex}}{\mathrm{BW} \times N_S \times N_C \times S_E} \tag{8}$$

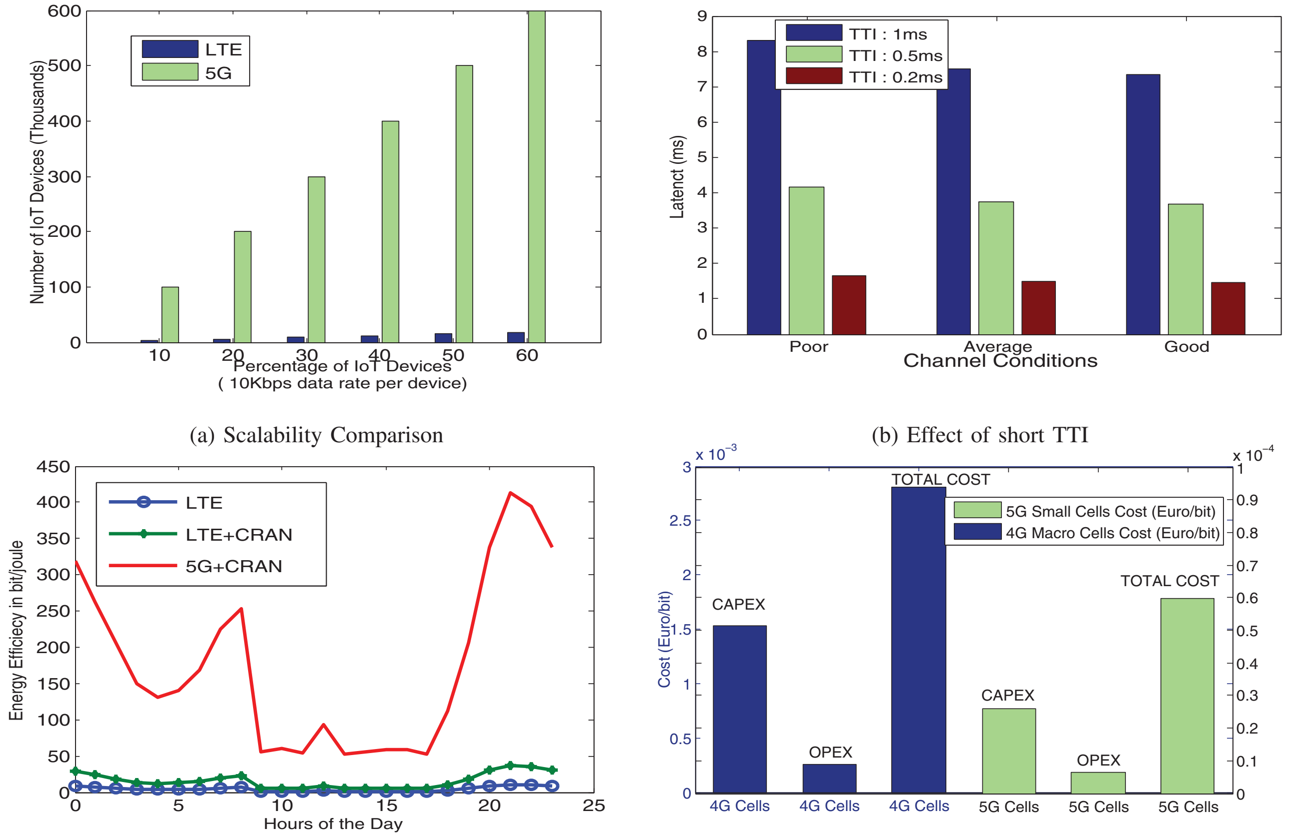
where BW is the system bandwidth and S_E is the average spectral efficiency in bits/Hz/cell. N_S and N_C are the total number of BS sites and the total number of cells, respectively.

4.2 Performance Evaluation

Emerging 5G communications offer to improve scalability, without wires, across a myriad of IoT connections. The evaluation parameters are given in Table 2. While the maximum possible data-rate in 20 MHz, 4 transmitter, 4 receiver LTE is around 300 Mbps, 5G promises a data-rate as high as 10 Gbps [24]. According to ETSI [25], the observed size of various instances of machine-type data-exchanges are in the order of 1K octets. Thus, we consider the data-rate for each IoT device to be around 10 Kbps and show the comparison of the number of IoT devices that can be supported by LTE and 5G networks (from Equation (1)) in Figure 5(a). In 2013, 2.8% of global mobile connections (195 million) were machine-type [26]. This indicates that the sector is still

Table 2: Evaluation parameters.

Parameter	Value
Data-rate	1Gbps (5G), 300 Mbps (LTE)
Sub-frame length (TTI)	1, 0.5, 0.2 ms
Data-rate per IoT device	10 Kbps
Number of re-transmissions	4
Transmitted power	46 dBM (macro-cell)
Transmitted power	20 dBM (small cell)
Power amplifier efficiency, α	0.38



(a) Scalability Comparison

(b) Effect of short TTI

(c) Energy Efficiency

(d) Cost per Bit (CAPEX, OPEX and Total Cost)for same coverage

Figure 5: Scalability, latency, energy efficiency, and cost per bit comparison between LTE and 5G wireless networks

in the early stage of its development and numbers are expected to increase over the years. Hence, in Figure 5(a), we also consider the varying percentages of IoT devices in coexistence with H2H communication. The results clearly show the suitability of 5G for unprecedented device proliferation in IoT. As pointed out in Section 2.1, this addresses one of the very first requirements of IoT, that is, massive connectivity. Moreover, the figure brings about the possibility to address heterogeneity and coexistence of H2H and M2M communications (discussed in Sections 2.6 and 2.7) by allocating the percentage of resources for the different services.

Figure 5(b) shows the comparison of latency for legacy standards to the proposed shorter TTIs. 3GPP standards define a TTI of 1 ms for LTE networks [27] and the communication system has been designed with the same reference. However, recent 3GPP research efforts are focusing on the feasibility of shorter TTIs (TTIs ranging from 0.5 ms and 1 OFDM symbol) to meet the low-latency requirements of 5G networks. We evaluate latency, based on the time required for scheduling at evolved Node B (eNB), scheduling request, average delay to next scheduling opportunity, data processing for downlink, transmission, etc. We also considered different losses to account for good (1% loss), poor (30% loss), and average (10% loss) channel conditions. HARQ retransmission with a maximum of four downlink retransmissions is considered. The shorter TTI of 0.2 ms achieves around 81% reduction in delay compared to 1 ms of TTI in legacy networks. Thus, smaller TTIs in 5G are far more conducive for delay-sensitive IoT services (pointed out in Section 2.4), compared to LTE networks.

Figure 5(c) delineates the comparison of energy efficiency (in bits per joule) based on a day's residential traffic patterns for legacy and 5G networks with/without C-RAN. C-RAN has been gaining research interest due to its power-saving capabilities. We consider the power consumed at the base station as the function of transmit power, processing power, and cooling overheads. As presented in [28], we consider the transmit power for macro BS as 46 dBm and for small BSs as 20 dBm. Considering that the LTE macro-cells these days cover distances in metres [9], we assume a cell size of 250 m. For C-RAN and 5G evaluations, five small cells are assumed to cover the same area. For the evaluation of total power consumption, the power amplifier efficiency, the number of RF chains and the power consumed at every RF chain (which includes mixers, converters, filters, phase-shifters, etc.) are incorporated [23]. We also consider the power consumed for baseband processing, site cooling, and synchronization. Cooling overheads and processing power at the datacentre are considered for C-RAN. We also take into account the daily average data-rates [29]. The results show that the energy efficiency in 5G is almost 20 times more than in C-RAN-enabled LTE networks. Higher energy efficiency is expected to alleviate the battery-life constraint highlighted in Section 2.2. Moreover, since C-RAN enables operational ease at the datacentre, it is expected to address issues like maintaining orthogonality, coexistence of broadband and narrowband operations, and facilitating both H2H and IoT traffic simultaneously (discussed in Sections 2.3, 2.5, and 2.6).

It appears that an increase in the number of cells, for the same coverage, might lead to a rise in capital and operational costs. Therefore, we evaluate and compare the cost per bit for legacy and 5G networks in Figure 5(d). We consider the CAPEX, OPEX, and resulting discounted cost estimates per BS class for greenfield deployment (all amounts in kEuro) as suggested in [28]. The total cost for LTE macro-cell is almost 30 times higher than the corresponding 5G small cells for the same coverage (for one macro-cell, five small cells are considered). The numerical analysis clearly brings out the staggering difference between what 5G offers and what LTE increments can achieve. Thus, it is not hard to imagine that 5G holds the potential to address the economic considerations pointed out in Section 2.9.

Finally, in Figure 6, we consolidate and compare the advantages of 5G with respect to legacy network in terms of various characteristics, like data-rate, coverage,

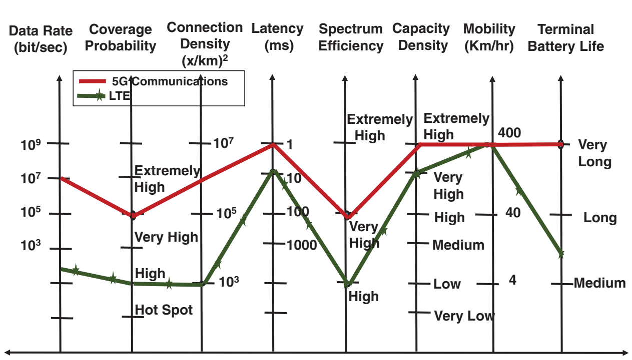


Figure 6: Comparison between 5G promises and LTE offerings

latency, spectral efficiency, battery life, etc., as pointed out by the ITU reports [30]. It can be clearly inferred from the figure that several 5G features are more inline with IoT requirements than legacy LTE networks.

4.3 Open Issues and Discussions

Our analysis reveals that emerging 5G technologies have a huge potential to provide solutions for diverse IoT requirements. However, a dedicated research effort is needed by academia and industries to exploit the plethora of new technologies, with the aim of a connected ecosystem. We categorize the future 5G-IoT research broadly into the following directions:

(1) Though mmWave spectrum offers enormous increase in network capacity, we believe the distinct IoT traffic characteristics would substantially influence the spectrum utilization. Research work focused on mapping of IoT applications and distributions to site and spectrum-specific beam-formed 5G communication would boost the effectiveness of 5G-IoT ecosystem.
(2) The major challenge, in the massively connected environment, is to simplify the management complexity. We believe progress in 5G wireless, especially C-RAN and SDN, should be researched for maintenance of billions of connected devices.
(3) Signalling overheads of legacy network impede device batteries of their precious energy. Such overheads are menacing in time-critical and delay-intolerant services. Investigations of wireless access for energy-efficient and time-critical IoT services require a dedicated effort.
(4) Low latency is very crucial for delay-sensitive applications. Round-trip latency of 1 ms [10] is identified as an important 5G requirement. However, achieving this stringent requirement in diverse IoT landscape is a major challenge to be resolved.
(5) While the expected impact of the IoT is considerable, effective virtualization would be instrumental in efficient capital and operational expenditures. Virtualization initiatives, which lead to optimization of the two, require in-depth investigation of distinct IoT requirements, technical as well as commercial.
(6) Most of the research work in the field of wireless communication is focused on broadband communication. However, for efficient IoT deployment, researchers may be implored to investigate from the narrowband perspective.

5. CONCLUSIONS

As a part of 3GPP standardization, 5G wireless is undergoing major evolution. Cellular standards are now adding techniques to improve network capacity as well as quality. While the legacy network falls short of fulfilling IoT requirements, ongoing discussions around C-RAN, HetNets, Massive MIMO, mmWaves, and non-orthogonality strengthen the viability of an IoT era. 5G offers a paradigm shift in interoperability of devices, applications, and services, compared to the quick-fixes in legacy networks. In this article, we point out distinct IoT requirements and how 5G offers to address them. An organized research effort to overcome the challenges of IoT in 5G era would lay a strong foundation for a connected living.

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