Next Generation 5G Wireless Networks: A Comprehensive Survey

Mamta Agiwal, Abhishek Roy, and Navrati Saxena

***Abstract*—The vision of next generation 5G wireless communications lies in providing very high data rates (typically of Gbps order), extremely low latency, manifold increase in base station capacity, and significant improvement in users' perceived quality of service (QoS), compared to current 4G LTE networks. Ever increasing proliferation of smart devices, introduction of new emerging multimedia applications, together with an exponential rise in wireless data (multimedia) demand and usage is already creating a significant burden on existing cellular networks. 5G wireless systems, with improved data rates, capacity, latency, and QoS are expected to be the panacea of most of the current cellular networks' problems. In this survey, we make an exhaustive review of wireless evolution toward 5G networks. We first discuss the new architectural changes associated with the radio access network (RAN) design, including air interfaces, smart antennas, cloud and heterogeneous RAN. Subsequently, we make an in-depth survey of underlying novel mm-wave physical layer technologies, encompassing new channel model estimation, directional antenna design, beamforming algorithms, and massive MIMO technologies. Next, the details of MAC layer protocols and multiplexing schemes needed to efficiently support this new physical layer are discussed. We also look into the killer applications, considered as the major driving force behind 5G. In order to understand the improved user experience, we provide highlights of new QoS, QoE, and SON features associated with the 5G evolution. For alleviating the increased network energy consumption and operating expenditure, we make a detail review on energy awareness and cost efficiency. As understanding the current status of 5G implementation is important for its eventual commercialization, we also discuss relevant field trials, drive tests, and simulation experiments. Finally, we point out major existing research issues and identify possible future research directions.**

***Index Terms*—5G, mm-wave, beamforming, channel model, C-RAN, SDN, HetNets, massive MIMO, SDMA, IDMA, D2D, M2M, IoT, QoE, SON, sustainability, field trials.**

I. Introduction

IT HAS BEEN more than a few decades since mobile wireless communications were initiated with the first generation, voice-only systems. Over the last couple of decades the world has witnessed gradual, yet steady evolution of mobile wireless communications towards second, third and fourth generation wireless networks. Introduction of digital modulations, effective frequency reuse, penetration of packet-based Internet and rapid advancement in physical layer technologies, like WCDMA, OFDMA, MIMO, HARQ etc. have significantly contributed towards this gradual evolution. Besides this, with the ever increasing popularity of smart devices, currently all-IP based fourth generation LTE networks have become a part of everyday life. As a result, a set of new, user-oriented mobile multimedia applications, like mobile video conferencing, streaming video, e-healthcare and online gaming are coming up. These new applications are not only satisfying users' requirements, but also opening up new business horizons for wireless operators to increase their revenue.

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A. *Existing Cellular Networks—Issues and Challenges*

A quick look into recent wireless network statistics reveal that global mobile traffic experienced around 70% growth [1] in 2014. Only 26% smartphones (of the total global mobile devices) are responsible for 88% of total mobile data traffic [1]. Cisco's Visual Networking Index (VNI) forecasts that mobile networks will have more than half of connected devices as smart devices by 2019. Increasing smartphone usage is resulting in an exponential growth in mobile video (multimedia) traffic. In fact, since 2012 video traffic is more than half of the global mobile traffic [1]. An average mobile user is expected to download around 1 terabyte of data annually by 2020 [2]. Moreover, researchers are exploring new applications in directions of augmented reality, Internet of Things (IoT), Internet of vehicles (IoV), Device to Device (D2D) communications, e-healthcare, Machine to Machine (M2M) communications and Financial Technology (FinTech). Supporting this enormous and rapid increase in data usage and connectivity is an extremely daunting task in present 4G LTE cellular systems. For example, with a theoretical 150 Mbps maximum downlink data rate, traditional LTE systems, with 2×2 MIMO can support only up to $\lfloor (150/4) \rfloor$ simultaneous full HD (@ 4 Mbps rate) video streaming. Furthermore, while standard LTE networks were originally designed to support up to 600 RCC-connected users per cell [3], [4], M2M communications and IoT requires supporting of tens of thousands of connected devices in a single cell. LTE cellular network is exploring avenues of different research and development, like, MIMO, small cells, Coordinated Multi-Point (CoMP) transmission, HetNets and multiple antennas to enhance capacity and data rates. However, it is unlikely to sustain this ongoing traffic explosion in the long run [2]. Hence, the primary concern is to satisfy the exponential rise in user and traffic capacity in mobile broadband communications.

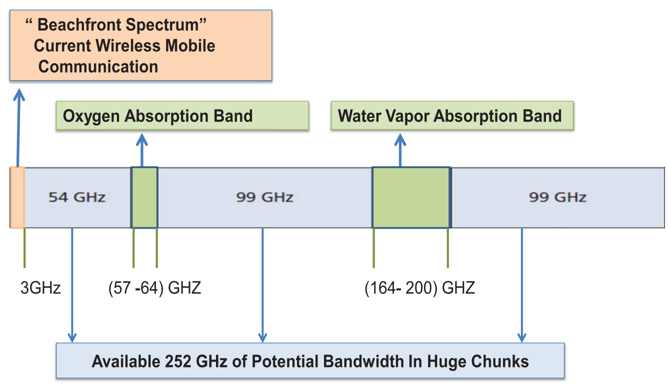

Fig. 1. Mm-wave Spectrum Availability in 3 $\sim$ 300 GHz.

B. mm-Wave—New Horizons in Radio Spectrum

Capacity for wireless communication depends on spectral efficiency and bandwidth. It is also related to cell size [5]. Cell sizes are becoming small and physical layer technology is already at the boundary of Shannon capacity [6]. Naturally, it is the system bandwidth that remains unexplored. Presently, almost all wireless communications use spectrum in 300 MHz to 3 GHz band, often termed as "sweet spot" or "beachfront spectrum" [2], [7]. This band derives benefits from its reliable propagation characteristics over several kilometers in different radio environments [8], [2]. The expectation from sub mm-wave band to accommodate the exploding mobile traffic and connectivity seems questionable [8]. Thus, for increasing capacity the wireless communications can not help, facing the new challenges of high frequency bandwidth. The key essence of next generation 5G wireless networks lies in exploring this unused, high frequency mm-wave band, ranging from 3 $\sim$ 300 GHz. Historically, collision avoidance radars are the first to exploit this mm-wave spectrum [9]. The US Federal Communication Commission (FCC) opened the spectrum between 59 $\sim$ 64 GHz and 81 $\sim$ 86 GHz for unlicensed wireless and peer to peer communications respectively [9]. Radio astronomy, radars, airport communications and many military applications have already been using the mm-wave bands over the last few decades. As shown in Fig. 1, of the huge 3 $\sim$ 300 GHz mm-wave spectrum, only 57 $\sim$ 64 GHz and 164 $\sim$ 200 GHz is un-suitable for communications. Even a small fraction of available mm-wave spectrum can support hundreds of times of more data rate and capacity over the current cellular spectrum [8]. Thus, the availability of a big chunk of mm-wave spectrum is opening up a new horizon for spectrum constrained future wireless communications [8], [9].

C. 5G: Vision and Motivation

The combined effect of emerging mm-wave spectrum access, hyper-connected vision and new application-specific requirements is going to trigger the next major evolution in wireless communications - the 5G (fifth generation) [7], [10], [11]. As shown in Fig. 2, 5G wireless communications envision magnitudes of increase in wireless data rates, bandwidth, coverage and connectivity, with a massive reduction in round trip latency and energy consumption. Fig. 3 demonstrates the broad overview of 5G standardization activities [12]. It points out that the first standard is expected to mature by 2020. Group Special Mobile Association (GSMA) is working with its partners towards the ultimate shaping of 5G communication. Blending the different research initiatives by industries and academia, eight major requirements [7], [10], [11] of next generation 5G systems are identified as:

1) 1 $\sim$ 10 *Gbps data rates in real networks*: This is almost 10 times increase from traditional LTE network's theoretical peak data rate of 150 Mbps.
2) 1 *ms round trip latency*: Almost 10 times reduction from 4G's 10 ms round trip time.
3) *High bandwidth in unit area*: It is needed to enable large number of connected devices with higher bandwidths for longer durations in a specific area [10].
4) *Enormous number of connected devices*: In order to realize the vision of IoT, emerging 5G networks need to provide connectivity to thousands of devices [10].
5) *Perceived availability of* 99.999%: 5G envisions that network should practically be always available.
6) *Almost* 100% *coverage for 'anytime anywhere' connectivity*: 5G wireless networks need to ensure complete coverage irrespective of users' locations [10].
7) *Reduction in energy usage by almost* 90%: Development of green technology is already being considered by standard bodies. This is going to be even more crucial with high data rates and massive connectivity of 5G wireless [10].
8) *High battery life*: Reduction in power consumption by devices is fundamentally important in emerging 5G networks [10].

With these eight above-mentioned requirements, wireless industries, academia and research organizations have started collaborating in different aspects of 5G wireless systems. Table I shows the vision of 5G from different globally famous wireless vendors and operators. Ericsson [13] expects 5G development should start in a backward compatible way with existing 4G LTE networks. This will help in continuing services using the same carrier frequency to traditional devices. Ericsson is also collaborating with South Korean market leader SK Telecom, for demonstrating 5G networks at 2018 winter Olympics [13]. Qualcomm [14] is developing and driving 4G and 5G in parallel to achieve the maximum potential. The unified platform should help in improving cost and energy efficiency, while enabling a vast range of new services. Huawei is collaborating with international trade associations, many universities, governments and ecosystem partners to establish crucial 5G innovations [15]. Docomo network has identified two important trends: (i) pervasive wireless connectivity (ii) extensive rich content delivery in real time [16]. It believes integration of both the higher and lower frequency bands holds the key to 5G deployment. The lower frequencies will be responsible for basic coverage and the higher frequencies will provide high data rates [16]. Optimizing spectrum usage, revolutionary advances in 5G, dense small cells and improved performance are key concepts of Nokia's realization for 5G wireless [17].

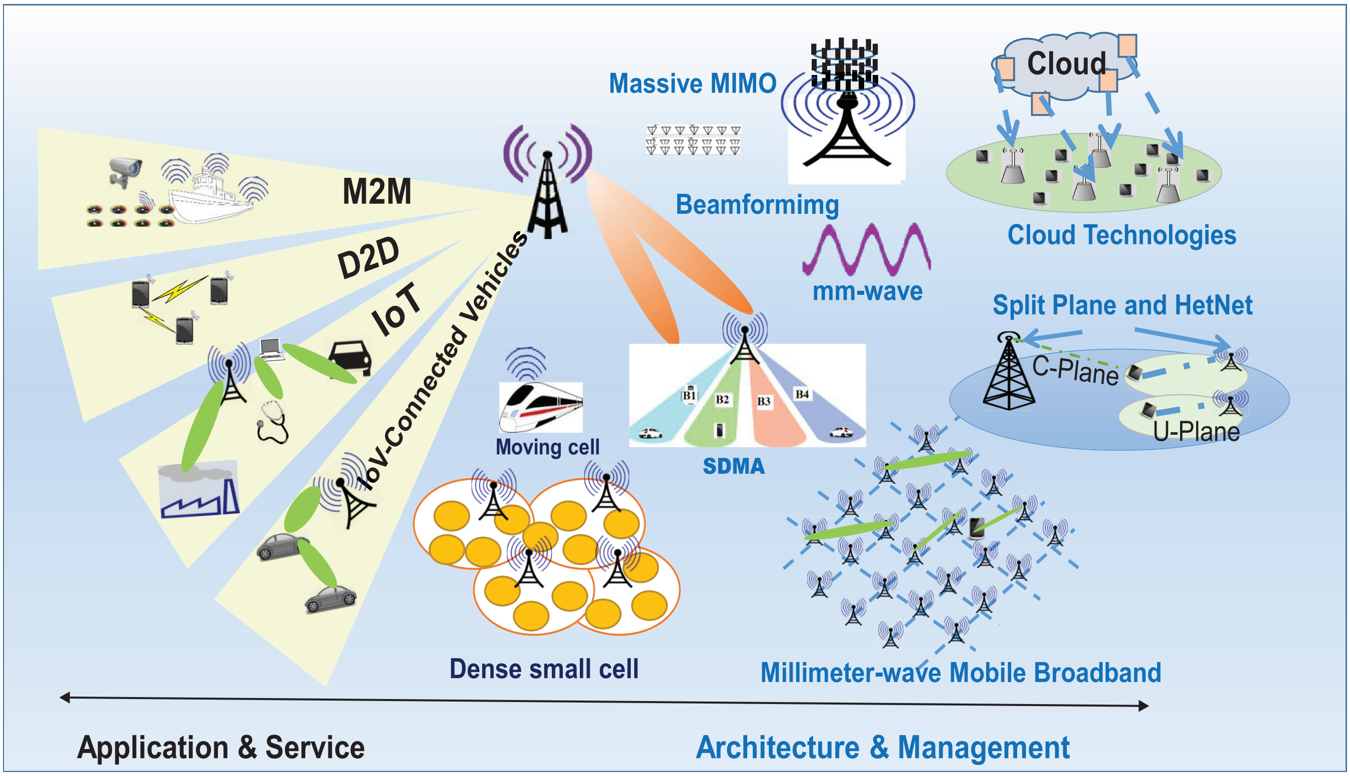

Fig. 2. Schematic Diagram of Next Generation 5G Wireless Networks.

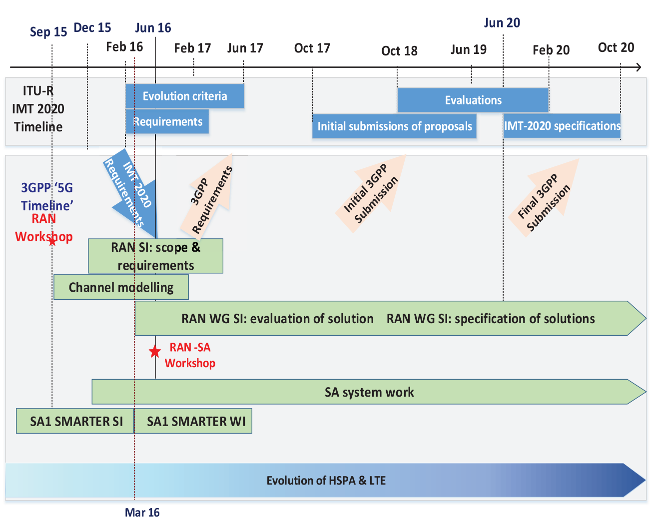

Fig. 3. A Broad Overview of 5G Standardization Activities (3GPP Tentative Timeline) [12].

Billions of autonomously connected diverse devices, leading to the beginning of IoT is Samsung's vision for 5G [18]. METIS (Mobile and wireless communications Enablers for the Twenty-twenty (2020) Information Society) and HORIZON 2020 are the major 5G research project initiated and funded by the European Union (EU) [19], [20], [21]. To deploy 5G in alignment with the market demands, 5GPPP is working for early agreements with major stakeholders [19] for multitenancy and single digital market [19]. IEEE Communication Society's "5G Training and Certification" [22] initiative is coordinating 5G training at IEEE-sponsored workshops and conferences, with the process of developing a 5G certification program. Collaborative research and development efforts between South Korea, Japan and China have resulted in the formation of 5G forum [23]. An overview of various 5G activities is presented in [26].

TABLE I
VISION 5G: INDUSTRIAL AND RESEARCH PERCEPTIVE

Market Player	Key Vision
Ericsson [13]	• Networked Society • Affordable and sustainable
Qualcomm [14]	• Enabling novel services • Connecting industries and devices • Improved user experience
Huawei [15]	• Massive capacity& connectivity • Diverse services, applications, users • Network deployment scenarios
Docomo 5G [16]	• Extensive and enriched content • Everything connected wirelessly
Nokia Solution Networks [17]	• Heterogeneous deployments • Augmented reality& tactile Internet • Sufficiently accurate channel models
Samsung Electronics [18]	• Internet of Things (IoT) • Enhanced multimedia experience • Extensive Cloud Computing
5GPP, METIS (EU) [19] - [21]	• Software driven 5G • Multi-tenancy • Scalable and sustainable
5G Training [22]	• Disruptive technology Directions • Architecture and key technologies • Personal mobile Internet, D2D
5G Forum [23]	• Commercialization of 5G by 2020 • Intertwining heterogeneous networks
5GNOW [24], [25]	• Abandon synchronism & orthogonality • Unified frame structure concept • Universal Filtered Multi-Carrier

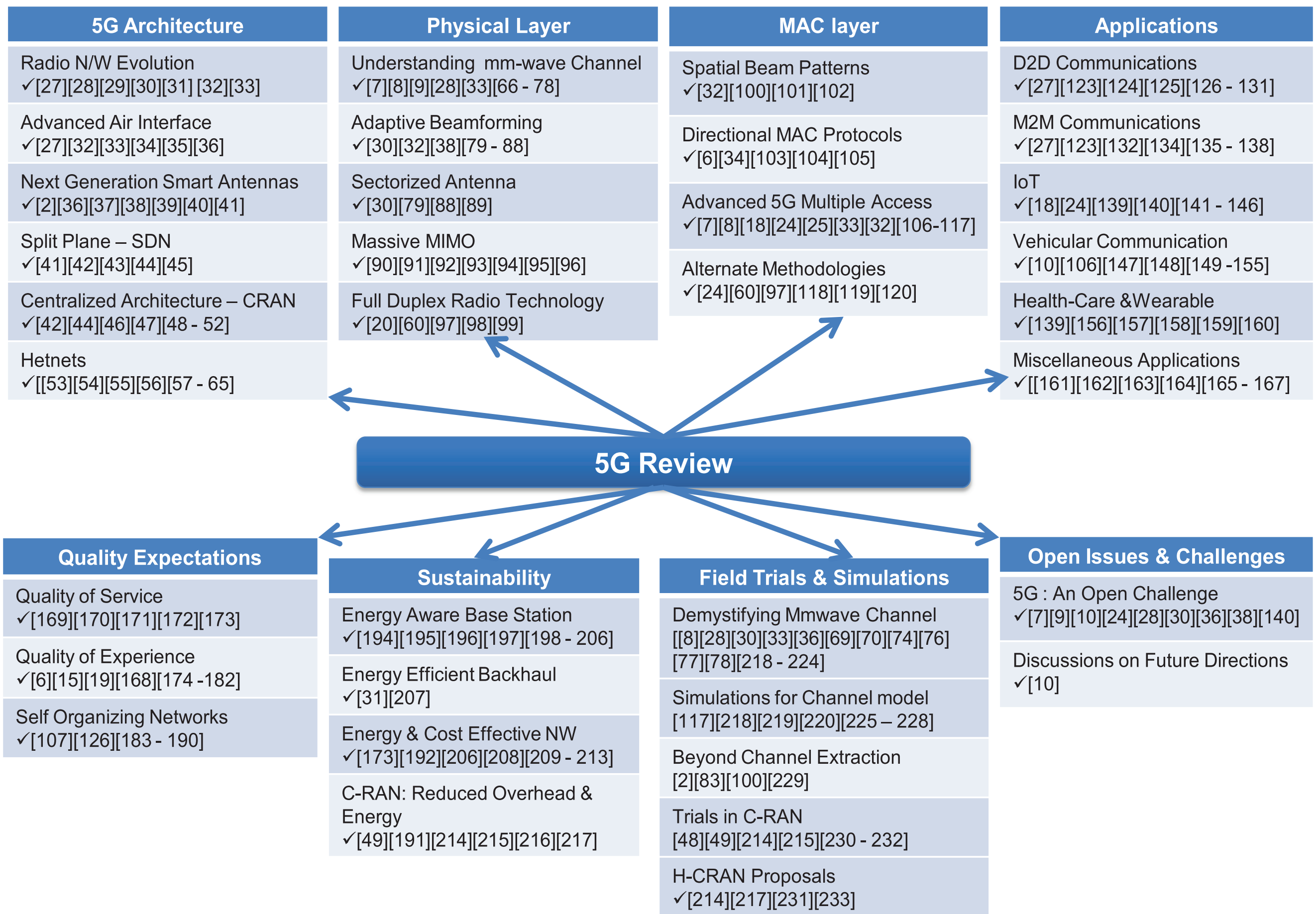

Fig. 4. Overall Organization of Our Survey on 5G Wireless Communications.

The above-mentioned advantages and vision of next generation 5G wireless networks motivate us to perform a detailed literature survey. Fig. 4 shows the broad outline of our survey. The rest of the paper is organized as follows: Section II states the architectural requirements for dense, user centric 5G network. It also includes advances in cloud computing and HetNets relevant to 5G wireless. In Section III, we discuss the new, mm-wave based physical layer aspects of 5G wireless networks. Subsequently, we review the changes required in MAC layer to support the physical layer modifications in Section IV. Next, we take a look into the novel killer applications of 5G wireless in Section V. Section VI provides a review of quality and network management. Major research works related to sustainability and energy-awareness are described in Section VII. Major field trials and simulation experiments, related to 5G wireless, are demonstrated in Section VIII. We point out open research issues and future research directions in Section IX. Finally Section X concludes our survey.

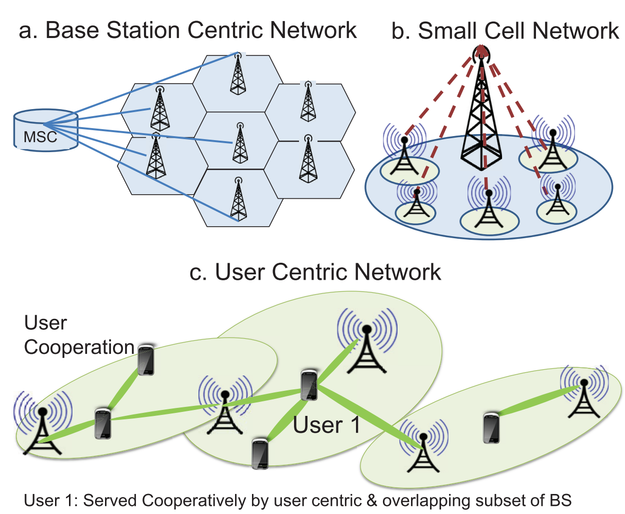

Fig. 5. Shift from BS Centric to User Centric Architecture.

II. 5G Architecture: A Paradigm Shift

With the requirements of sub-millisecond latency and bandwidth limitation in traditional wireless spectrum, cellular networks are now poised to break the Base Station (BS) centric network paradigm. Fig. 5 depicts this gradual movement from BS centric to a device centric network. The increase in demand by wireless industry motivated the advancement towards much smaller cell deployment from the initial macro hexagonal coverage. Researchers these days are focused on ways to design user centric networking. User is no longer the final resolution of the wireless network but is expected to participate in storage, relaying, content delivery and computation within the network.

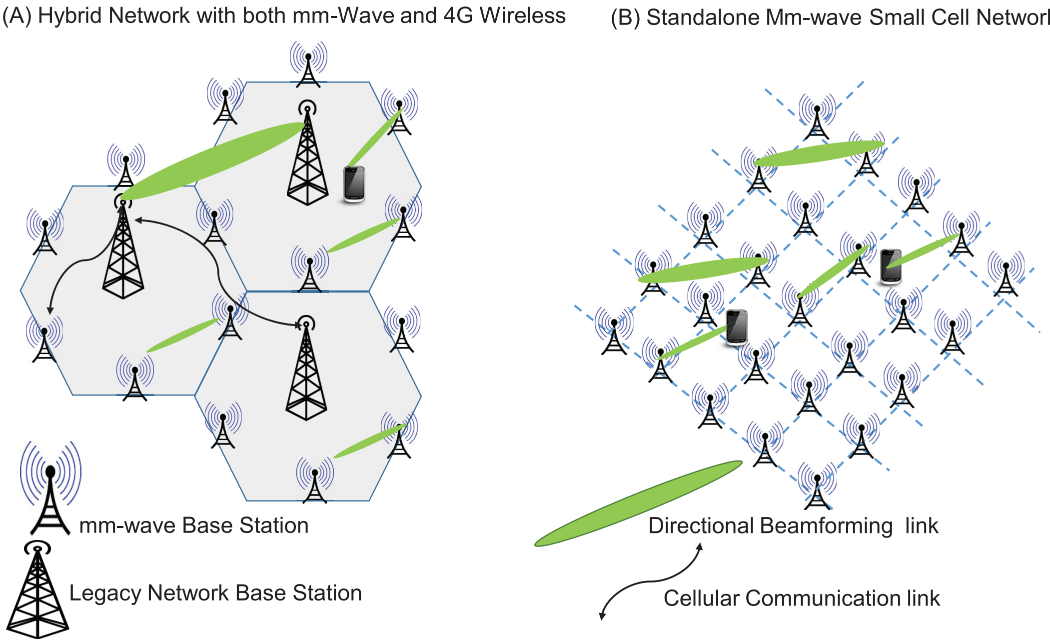

Fig. 6. Standalone and Hybrid mm-wave Network Architecture.

Future networks are expected to connect diverse nodes in different proximity. Small, micro, pico and femto cell deployment is already underway. Thus, dense 5G networks will have high co-channel interference, which will gradually render the current air interface obsolete. This pushes in the concept of sectorized and directional (energy focused) antennas, as opposed to the age-old omnidirectional antennas. Therefore, Space Division Multiple Access (SDMA) and efficient antenna design are utmost necessary. Decoupling of user and control planes, along with seamless interoperability between various networks are expected to strengthen the foundation for 5G systems. In this section we discuss the requirements for 5G network architecture, changes in air interface and design of smart antennas. Emerging technologies, like SDN, Cloud-RAN and HetNets are also discussed.

A. Radio Network Evolution

Overall layout of 5G wireless networks breaks the rules of BS centric cellular concept and moves towards a device centric topology [27]. 5G network proposes the use of higher frequencies for communication. The propagation and penetration of mm-wave signal in outdoor environment is quite limited [28]. Thus, node layout can not follow traditional cellular design or even any definite pattern. Rappaport and his group [28] propose site specific node layout for 5G radio network design. For instance, ultra dense deployment is necessary in areas requiring high data rates, like subway stations, malls and offices [29]. Line of Sight (LOS) communication is undisputed preference over Non Line of Sight (NLOS) communication [28], [30]. Alternately, reflected, scattered and diffracted signals still might have sufficient energy, which needs to be explored when LOS is completely blocked [30].

5G cellular technology needs to work with an enormous number of users, variety of devices and diverse services. The primary concern therefore, is the integration of 5G BSs with the legacy cellular networks (e.g. 4G, 3G and 2G) [31]. Different configurations like, mm-wave BS grid systems, mm-wave integrated with 4G systems and mm-wave standalone systems are proposed by Farooq and his team at Samsung Electronics [32], [33]. Large beamforming gains extend the coverage, while reducing interference and improving link quality at the cell edges. This feature enables mm-wave BS grids to provide low latency and cost effective solutions [32]. Fig. 6(A) shows a hybrid system of mm-wave (5G) and legacy 4G network. It proposes a dual-mode modem, enabling the user to switch between the two networks for better experience [32]. Alternately, mm-wave spectrum can also be used only for data communications, while control and system information can be transmitted by using traditional 4G networks [32]. On the other hand, as shown in Fig. 6(B), standalone 5G systems [32] operate exclusively on mm-waves. Such systems envision the use of same mm-wave spectrum for both backhaul and wireless access links. The concept of narrow beams allows acceptable spectrum overlap and also improves link quality between BS grids and large number of users [33]. Thus, the radio networking in 5G communications is expected to be much different from legacy networks. Evolution in radio would also change the schematics of the air interface.

B. Advanced Air Interface

Small radio wave lengths of mm-wave propagation demands small antenna sizes. This enables the use of large number of smaller antennas. Controlling phase and amplitude of signal, using array antennas, helps in enhancing electromagnetic waves in the desired direction, while cancelling in all other directions [34]. This necessitates the introduction of directional air interfaces. Fig. 7 shows this change of air interface from omni-directional transmission to a directional one. Highly

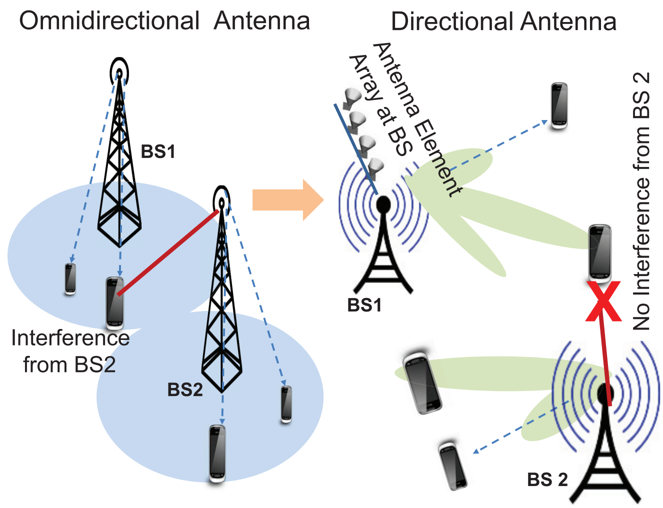

Fig. 7. Conventional Omnidirectional Antennas and Smart Beamforming Directional Antennas.

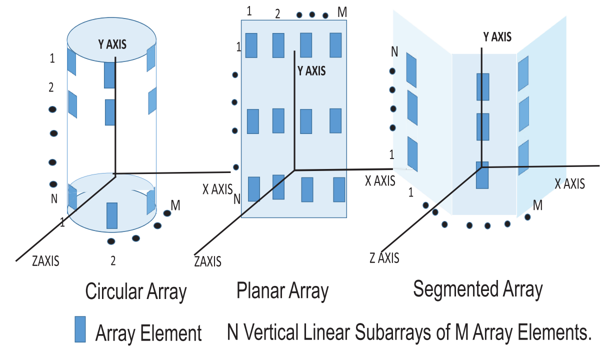

Fig. 8. Three Major Array Configurations for Smart Antennas.

directional radiation patterns could be secured by using adaptive beamforming techniques, resulting in the introduction of Spatial Division Multiple Access (SDMA) [33]. Effective SDMA improves frequency reuse for beamforming antennas at both transmitter and receiver [35]. We defer the details of antenna training, beamforming and SDMA till Section III and Section IV respectively.

However, the hardware challenges, more precisely, the high power consumption by mixed signal components might constraint these advantages. It might not be possible to connect every antenna to high rate Analog to Digital (A/D) and Digital to Analog (D/A) converters [27]. Hybrid architecture, integrating analog and digital beamforming, with the optimal beamforming weights, can provide possible solutions [27]. Details of analog and digital beamforming forming concepts are discussed in [32]. Sectorization of BS into multiple sectors also relaxes the hardware constraints. However, this raises further challenges in synchronization and data transmission, which needs to be resolved [36]. Optimal antenna configurations for different beamforming techniques enhance performance. For instance, horn antennas at transmitter, patch antennas at receiver and special antenna arrays in high rise urban environment for vertical steering of the beam, would enable efficient communication [36]. Vast BS deployment and need for LOS communication could be eased by the separation of uplink and downlink. Multiple nodes can facilitate different transmissions to use different communication paths at different channel conditions [27]. Understanding of the fundamental techniques of directive air interface along with its advancements would lay strong foundation for the efficient 5G communication.

C. Next Generation Smart Antenna

Successful deployment of 5G networks depends on the effective antenna array design. This exploits the advantages of change in air interface. The multi-beam smart antenna array system should be used to realize SDMA capabilities. Smart antennas help in interference mitigation, while maintaining the optimal coverage area and transmit power reduction of both mobile handset and BS [37]. Moreover, for the same physical aperture size, more energy can be transmitted at higher frequency by the use of narrow beams [38]. Smart antenna implementation enables the same channel to be used by different beams [37]. This reduces one of the major problems of wireless communications: co-channel interference. Use of beamforming antennas, with fractional loading factor, further dilutes the co-channel interference problem [39]. Application of highly directional beams do not necessarily require any fractional loading. Infrastructure expenses and complex operations impede indiscriminate use of directional antennas. However, even less complex antennas are capable of providing considerable capacity gains [39]. Therefore, a smart antenna design, optimized over directional gains, cost and complexity is very important for development of 5G wireless communications.

Vertical planar subarrays steer the beams in horizontal plane by varying the weights associated with the subarray elements [40]. The subarray configurations are crucial for beam steering. Fig. 8 demonstrates three different possibilities to arrange an antenna subarray: (i) circular, (ii) planar and (iii) segmented. Better coverage of circular subarray makes it more suitable for wireless communications [37]. While curvature allows wider beam steering, linear configurations have better directivity, but limited scan-angle range [40]. Instead of circular or linear, simple segmented configurations can also be carefully designed to achieve the required level of directivity and scan range [40]. Generally, horn antennas have higher gains over all other antennas. An array of horn antennas provide high power output required at BS [41]. The space, size and power are constraints at the mobile device. Hence, more simple patch antennas are suitable candidate for devices [36]. Generally space, not the size, limits the deployment of sophisticated smart antennas at both BS and MS. However, Samsung's experiments at 28 GHz bands with patch antennas in popular handset have shown promising results [2].

D. Agility and Resilience by Splitting of Plane—SDN

The changes in architecture and air interface emphasizes on small cells and increased number of antennas. Configuration and maintenance of many servers and routers, in such a dense 5G deployment, is a complex challenge. Software Design Network (SDN) offers a simplified solution for this complex

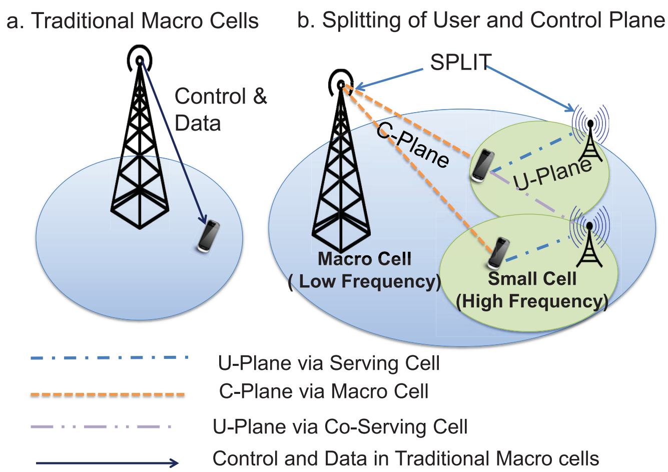

Fig. 9. Control Plane and User Plane Separation.

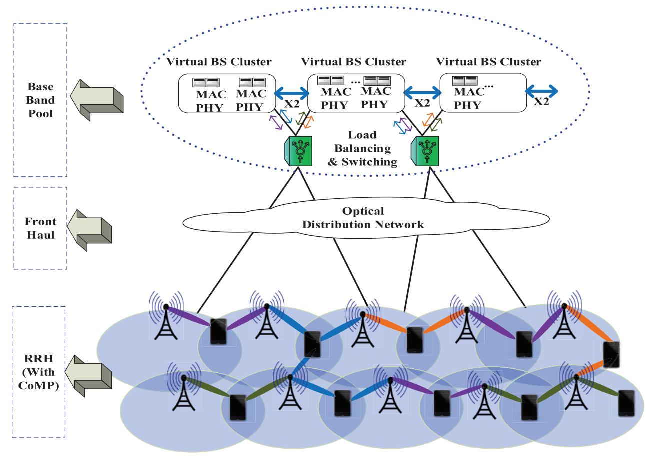

Fig. 10. Cloud Radio Access Network (C-RAN) Architecture.

challenge. SDN considers a split between control and data planes, thereby introducing swiftness and flexibility in 5G networks [41], [42]. Fig. 9 depicts the segregation of user and control signals. Increase in user plane capacity thus becomes independent of control plane resources. This endows the 5G network with high data at the required locations, without incurring control plane overhead [42]. SDN decouples the data and control planes by using the software components. These software components are responsible for managing the control plane, thereby reducing hardware constraints [43], [44]. Interaction between the two planes is achieved using open interfaces, like Open Flow [45]. It also facilitates switching between different configurations [45].

SDN can step over OSI layers to remodel networks for a complete automated administration. Redundant interfaces are reduced by controllers, which assign policy to routers for monitoring functions [44]. SDN applied to Radio Access Networks (RAN) presents itself as a SON solution [45]. SON algorithms optimize RAN by control plane coordination at a coarse granularity, while leaving the fine granular data plane unaffected [45]. Although, SON provides high gains, improvement in data plane requires cooperation of multiple BS for data transmissions. Coordinated Multi Point (CoMP) transmission facilitates cooperative data transmission at a very fine time scale [45]. Cloud RAN also offers a viable solution by decentralizing the data plane. Data and control signals can be routed through different nodes, different spectrum and even different technologies to manage the network density and diversity.

E. Centralized Architecture—Cloud RAN

Cloud Radio Access Network (C-RAN) resolves some of the major problems associated with increasing demands for high data rates [46]. Wireless industry is working on measures to enhance network capacity by adding more cells, implementing MIMO techniques, establishing complex structure of HetNets and small cell deployment. However, inter-cell interference, CAPital EXpenditure (CAPEX) and OPerating EXpenditure (OPEX) impedes these efforts. C-RAN offers to improve system architecture, mobility, coverage performance and energy efficiency while at the same time reducing the cost of network deployment and operation [46]. C-RAN is based on fundamentals of centralization and virtualization. The baseband resources are pooled at BaseBand Unit (BBU), situated at remote central office (not at the cell sites) [47]. In traditional cellular networks, the Internet Protocol, Multi-protocol functionality and Ethernet are extended all the way to remote cell sites [47]. Fig. 10 shows a typical C-RAN architecture, with BBUs from many remote sites centralized at a virtual BBU pool. This results in statistical multiplexing gains, energy efficient operations and resource savings [46]. Virtual BBU pools further facilitate scalability, cost reduction, integration of different services and reduction in time consumption for field trials [46]. Remote Radio Heads (RRH), comprising of transreciever components, amplifiers and duplexers enable digital processing, analog-digital conversions, power amplification and filtering [46], [47]. RRHs are connected to BBU pool by single mode fibre of data rate higher than 1 Gbps [47]. This simplified BS architecture is paving the way for dense 5G deployment by making it affordable, flexible and efficient [42]. Powerful cloud computing ability can easily handle all complex control processes [44].

China Mobile is strongly advocating C-RAN as it improvise fundamentals for network construction, deployment, cost structure and flexible end user services [48]. Infrastructure sharing protocol [49], proposed by Mohammad Banikazemi of IBM, provides cost effective solutions for dense deployment, along with backward compatibility [49]. By shifting the RF frontend to BBUs, radio frequencies are generated in the BBU itself. Transmissions are carried out by a shared cloud-radio over fiber infrastructure. This enables the use of analog RF, aiding many services and operators to coexist without any significant interference [49]. Moreover, SDN creates options to seamlessly merge cloud applications with wireless networks through programmable interfaces. Recent researches have proposed SDN based, virtual networks with cloud as a backbone [50]. Small cell deployment can sometimes be difficult, expensive and constraint by site topology. This makes backhaul network for small cells a critical infrastructure. A heterogeneous backhaul technology integrating both, the fixed broadband access and wireless LOS backhaul is the most

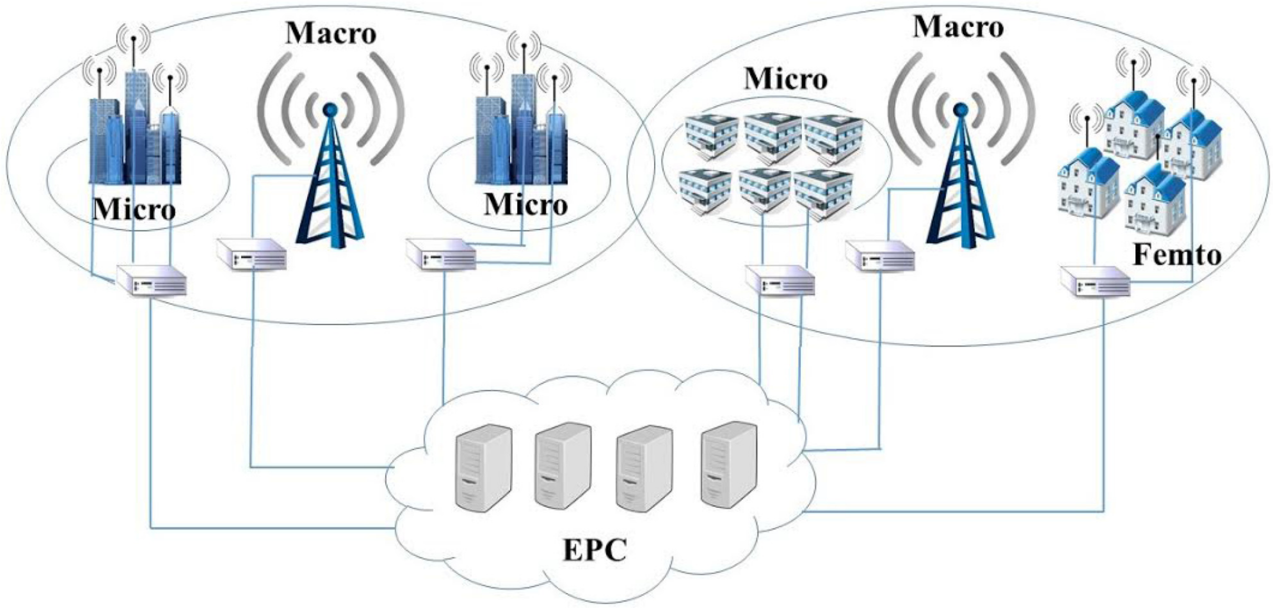

Fig. 11. Coordinating Cells in HetNet Architecture.

suitable. Thus, a standardized interface is needed for designing and optimizing RAN along with backhaul network [51]. Dynamic adaptation of routing nodes [51], proposed by Peter Rost of NEC Europe Laboratories, considers RAN as a service (RANas) for flexibility in RAN centralization. RANas concept proposes centralized cloud platform with packaging and delivering functions, depending on the actual network requirements [51]. Capacity limits and system-level optimization of uplink C-RAN are studied under practical finite-capacity backhaul constraints in [52]. Compress-and-forward relay strategy is considered for transmitting compressed version of received signals from BSs to central processor. Level of quantization noise introduced by the compression is considered key parameter in backhaul design [52]. Cloud computing based radio access encourages shared pool of configurable resources enabling minimal deployment, management and operational efforts.

F. Heterogeneous Approach—HetNets

Another way to handle the wireless traffic explosion, expected in 5G communication, is deployment of large number of small cells giving rise to Heterogeneous Networks (HetNets) [53]. HetNets are typically composed of small cells, having low transmission power, besides the legacy macrocells. By deploying low power small BSs, network capacity is improved and the coverage is extended to coverage holes [54], [55]. Moreover, the overlap of all small, pico, femto cells with the existing macro cells, leads to improved and efficient frequency reuse [56]. Fig. 11 shows the concept of HetNets. Deployment of HetNets calls for a coordinated operation between traditional macro cells and small cells for mutual interference reduction [56]. Researchers at University of Manitoba, Canada emphasize on multi-tier networks and interference upgradation for 5G communications [57]. Various interference management challenges in 5G hybrid networks are addressed in [57]. The interference between the macro and second tier cells in 5G HetNets is addressed by reverse Time Division Duplex (TDD) protocol in [58]. It facilitates local estimation of both the intra-tier and inter-tier channels. In reverse TDD mode BS is in downlink operation when the Small-Cell Access (SCAs) operate in uplink and vice versa.

Researchers from Qualcomm Technologies Inc. and Samsung Mobile Solutions Lab emphasize on both network and device side interference management techniques [59]. Advanced receiver with capabilities to take advantages of interference signals structure (including modulation constellation, coding scheme, channel and resource allocation) are considered as key drivers [59]. Inappropriate Radio Access Technology (RAT) can generate unnecessary signalling overhead [60]. To mitigate these issues in multi-RAT, efficient RAT handover decisions and optimized partitioning of common resources are proposed in [60]. Concurrent utilization of multiple RATs improves capacity and connectivity. However, joint use of multiple networks has not received much research attention. Smart coupling between multiple RATs promises, further capacity and coverage improvement in HetNets [61]. In [62], authors introduce various radio resource management schemes for femtocell enabled HetNets. Cross-tier and co-tier interferences are addressed, while maintaining optimized radio resource utilization, fairness and QoS. Various frequency scheduling algorithms and frequency reuse techniques enhance HetNet performance [62]. Spectral resource allocation strategies [56] also present the potential to solve interference problem. Cooperative and distributed radio resource management algorithms for enabling random HetNet deployment are discussed in [63]. The work in [64] proposes optimization of BS and device association in downlink HetNets under proportional fairness criterion. An overall framework of green HetNets, for balancing energy efficiency and spectral efficiency, is provided in [65]. Two-tier heterogeneous network, proposed in [58], promises improved network performance by co-locating Massive MIMO BS and low-power SCAs. While massive

TABLE II
MAJOR RELATED WORKS IN 5G NETWORK ARCHITECTURE

Work Area	Related Work	Key Points
Radio Network Evolution	[27], [28], [29], [30], [31], [32], [33]	• Dense deployment of multiple BS. • Limited mm-wave penetration. • LOS/ NLOS communication. • Standalone mm-wave/hybrid with legacy network.
Advanced Air Interface	[27], [32], [33], [34], [35], [36]	• Electromagnetic waves controlled by antenna array. • Directional Radiation. • Beamforming hardware challenges. • Beamforming in analog and digital domain.
Next Generation Smart Antenna	[2], [36], [37], [38], [39], [40], [41]	• Narrow beam and SDMA capabilities. • Circular/planner/segmented subarray. • Application specific antenna type.
Splitting of Plane - SDN	[41], [42], [43], [44], [45]	• Different data and control plane. • Software design networks and open flow. • SON for RAN optimization. • CoMP
Centralized Architecture with C-RAN	[42], [44], [46], [48], [47], [49], [50], [51], [52]	• Centralized platform • Baseband unit / Radio receiver head • RAN as a service. • Backhaul and fronthaul.
Heterogeneous Approach - HetNets	[53], [54], [55], [56], [57] to [65]	• Small cells with varying transmission power. • Coordinated operation. • Interference of diverse cells.

MIMO reaps conventional benefits by ensuring outdoor mobile coverage, SCAs equipped with cognitive and cooperative functionalities act as main capacity-drivers for indoor and outdoor low mobility users. However, backhaul represents one of the major bottleneck in dense SCA deployment. In contrast to legacy wired backhaul, SCAs are likely to be connected via an unreliable wireless backhaul infrastructure [58]. Characteristics of error rate, delay, capacity and deployment cost are expected to vary from case to case. Thus, wireless backhaul links provide a viable and economical alternative [58]. For simplified deployment, operation, management and round-the-clock optimization of HetNets, cloud assisted platform is advocated in [53]. Moreover, cloud based intelligent handoff and location management can ensure seamless connectivity in HetNets [53]. Thus, we believe heterogeneous connectivity of small cells is the major building block of the emerging 5G architecture. The directivity and small cell design, together with advances in resource allocation are promising for higher coverage and data rates of 5G communication. Table II summarizes major works related to 5G network architecture.

III. PHYSICAL LAYER DESIGN ISSUES

Blending 5G architecture over existing wireless systems requires a novel approach to make the process smooth and fast. Hence, it is critical to understand the physical layer technologies and integrate them for maximum performance and minimum overhead. In this section, we discuss existing and upcoming physical layer technologies imminent for 5G deployment. More precisely, we explore physical layer concepts, like the understanding of channel, its characteristics, requirements of beamforming, beam training, massive MIMO and full duplex technology.

A. Understanding mm-wave Wireless Channel

The emerging mm-wave frequencies raise many new challenges in mobile wireless communications. The primary challenge is un-availability of any standard channel model. Technical understanding of channel behaviour presents new architectural techniques, different multiple access and novel methods of air interface [28]. Moreover the biological safety at mm-wave frequencies is also under scrutiny [66]. Nonionizing and thermal characteristic of mm-waves for safety concerns is analyzed in [66]. Technically, Farooq et. al. in Samsung Electronics [8], [33] suggest wireless channel characterization by propagation loss, signal penetration, doppler and multipath.

1) Propagation Loss: The free space loss is estimated by the equation: $L_{FSL} = 32.4 + 20\log_{10} f + 20\log_{10} R$, where L_{FSL} primarily accounts for the transmission loss of mm-waves, R represents transmitter-receiver distance and f is the carrier frequency [8]. It seems that losses are prominent at higher frequencies. However, it is true only for the path loss at a particular frequency intervening two isotropic antennas [8]. Shorter wavelengths enable dense packing of smaller antennas in a small area, thereby challenging the use of isotropic antennas for future 5G networks. Research works [33], [67] related to free space loss show that for the same antenna aperture area, compared to their longer counterparts, shorter wavelengths should not suffer any major disadvantage. In addition, mm-wave links are capable of casting very narrow beams. For instance, a 70 GHz link is four times narrower than a 18 GHz link [9]. This results in the application of many links in close proximity [9]. Furthermore, recent research works [8] have also demonstrated that directional transmission of narrow beams reduces interference and increases spatial multiplexing capabilities for cellular applications. The apprehensions of degraded performance of mm-waves under downpour is not supported well by any conclusion. Thus, the mm-wave links are expected to perform flawlessly [9]. However, mm-wave link performance depends on many other factors, like distance between the nodes, link margin of the radios and multipath diversity [9].

2) Penetration and LOS Communication: For an effective system design, there is an impending need to understand mm-wave propagation in diverse environments. To fathom the propagation characteristics in indoor and outdoor environment, it is essential to determine the behaviour of propagating signals through and around common structures, foliage and human beings [68]. Understanding diffraction, penetration, scattering and reflection of mm-waves in different possible environments lay the foundation for 5G network deployment.

Signal outage investigations and comparison of reflection coefficients for building materials, like tinted glass, clear glass, drywall, doors, cubical and metallic elevators by Rappaport and his group revealed that the common outdoor building materials present high penetration resistance to mm-waves [28]. Moreover, indoor environment structures, like drywall, whiteboard, clutter and mesh glass are also found to significantly impact attenuation, multipath components and free-space path loss [69]. Propagation measurements by Sylvain Collonge of RNRT French project (feasibility study of communications at 60 GHz bands for domotic applications) [70] characterize the behaviour of high frequency waves in office environments. Indoor channel impulse responses confirm that human bodies create considerable obstruction to mm-wave propagation. Movement of people generate shadowing effects, which could be mitigated by larger antenna beam width and introduction of angular diversity [70]. From the available propagation results [8], [28], we can conclude that outdoor mm-wave signals are mostly confined to outdoor. Very little signal penetrate indoor through glass doors, open doors and windows. The indoor-outdoor isolation emphasizes the need for different nodes to serve different coverage sites [8], [28]. However, this characteristic of isolation helps in confining the energy in the intended area [28]. Moreover, separation of indoor and outdoor traffic relaxes overhead associated with radio resources allocation and transmit power consumption [71]. Overheads further reduce significantly by flexible clustering, efficient user selection and adaptive feedback compression in macro-plus-smallcell scenarios [72]. Interestingly, small cell architecture is already under deployment in dense urban areas. For instance, in urban Japan, inter-BS distance is around 200 meters only [7]. Thus, application of LOS propagation in small cell environment looks promising for mm-wave communications. Ensuring LOS would require massive antenna deployment without any predefined pattern. The site specific random deployment is expected to vary from case to case. An exemplar diagram of random, dense and site specific LOS communication is presented in Fig. 12. The challenges associated with LOS communications automatically necessitate investigation into Non Line of Sight (NLOS) propagation and the required fundamental support.

3) Multipath and NLOS: In wireless communications, multipath is the effect of signal reception in antenna by more than one paths [73]. According to Sylvain Ranvier and Mikko Kyro of SMARAD center of excellence, Helsinki University of Technology [74], [75], multipath characteristics of channel is well described by choosing the delay spread as a validation parameter. Root Mean Square (RMS) of Power Delay Profiles (PDP) helps in probing the multipath effects in mm-wave communication. Understanding of multipath is likely to enable NLOS problem mitigation. LOS link might not always be possible in dynamic outdoor environment. Hence, it is important to explore possibilities of partially obstructed LOS and NLOS links. The measurement in [76] noted mean

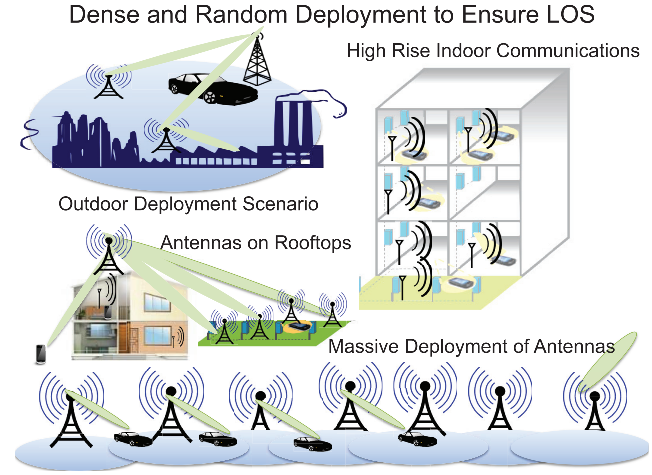

Fig. 12. Massive & Dense Deployment for LOS Communication.

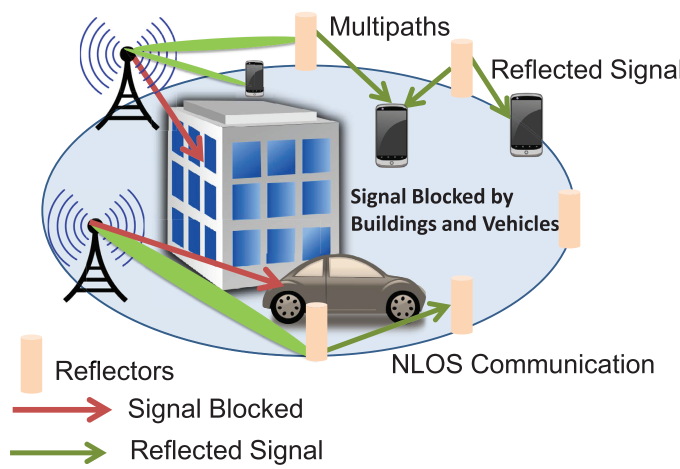

Fig. 13. Multipath and NLOS Communication.

rain attenuation, short-term signal levels in rain, attenuation through vegetation, glass and wide-band power delay profiles. Compared to clear, dry weather conditions more multipath components are detected during rain. Numerous multipath components at diverse pointing angles could be utilized for link improvement [28].

Building corners, edges and human activities might not always completely attenuate LOS link. Rather, these often cause shadowing. Reflection coefficients for different surfaces suggest the possibility of reasonable signal levels in shadow area [77]. It is also observed that wider beam-width antennas give accurate estimation of received signal. On the other hand, smaller beam-width antennas have advantages of spatial directivity. Appropriate combination of beam widening techniques explores the advantages of varying characteristics in small areas. Moreover, the best combination of antenna angles also endows the system with high SNR and low RMS delay spread [78]. Communication in NLOS paths requires equalizers, which introduces new challenges of high latency, increased power consumption and low data rates [70], [78]. Knowledge of multipath statistics assist in designing equalizers and selecting modulation techniques [76]. Appropriate combination of existing and current channel statistics helps in resolving most of the NLOS propagation challenges. As shown in Fig. 13, the delay

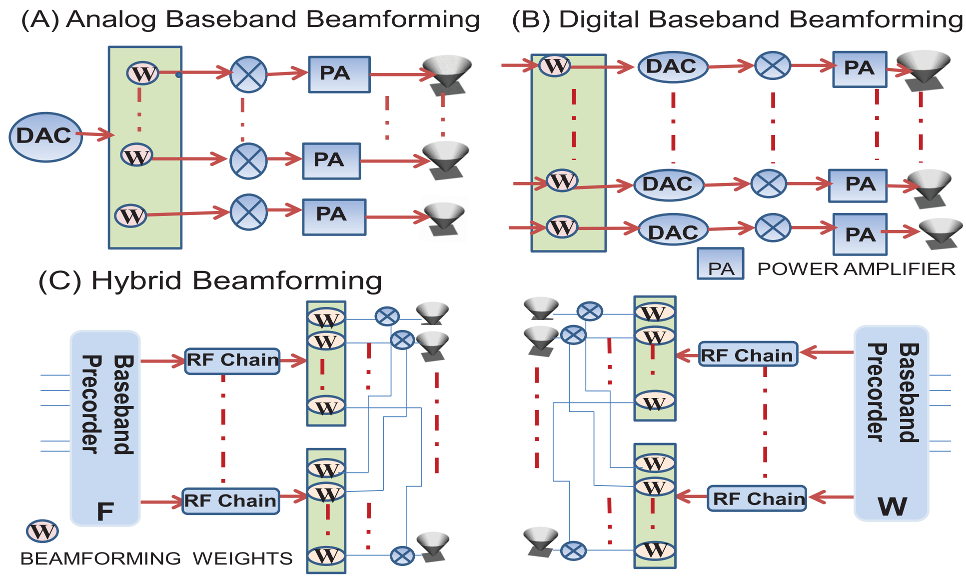

Fig. 14. Digital, Analog and Hybrid Beamforming for Energy Focus in Desired Direction.

domain channel model, proposed in [74], uses reflected signals from arbitrarily placed scatterers for point to point prorogation.

4) Doppler: Carrier frequency and mobility characterize the Doppler effect. Received incoming waves have different shift values, thus resulting in a Doppler Spread [8], [33]. Doppler induced time-selective fading is easily alleviated by packet sizing and suitable coding over coherence time of the channel [30]. Moreover, reduced angular spread in narrow beam transmissions, inherent to mm-wave propagation, further reduces Doppler spread [8], [33]. Therefore, it is unlikely that doppler effects could raise any significant challenge in 5G networks.

B. Adaptive Beamforming

As mentioned before, in Section II, design of smart antennas is vital for effective mm-wave communications. Moreover, directional beams are also integral to emerging 5G networks. In this subsection, we discuss how beams are created, controlled, trained, steered and measured using smart antenna design.

1) Creating and Controlling the Beam: Understanding of mm-wave beamforming algorithm is essential to focus energy in the desired direction. Different configurations of antenna arrays and sub arrays, with designated beamforming weights, steer and control the beams. Beamforming is possible in analog, digital or RF front end [32]. Beamforming weights are applied in digital or analog domain to create directive beams [38]. Fig. 14 demonstrates beamforming in analog, digital and hybrid domains. In digital beamforming, coefficients are multiplied per RF chain, over modulated baseband signals, before or after Fast Fourier Transformation (FFT) at transmitter or receiver respectively. Whereas, the analog beamforming is done by applying coefficients to modified RF signal in time domain itself. Digital beamforming offers better performance at increased complexity and cost. On the other hand, analog beamforming is a simple and effective method with less flexibility. Hybrid beamforming architecture provide sharp beams with phase shifters at analog domain and flexibility of digital domain [38]. For large antenna array, it is expensive and complicated to use separate transceivers for every antenna element. It not only causes rise in component cost, but also increases power consumption [79]. Frederick and his team of Nokia Solutions and Networks propose 5G communications with MIMO, RF and hybrid beamforming architecture to address some such challenges [79].

For mm-wave frequencies, efficiency of RF components is usually poor, thus imposing the power amplifiers to operate only at maximum power. Hence, the control of array is done by phase shifters [80]. There is also a proposition to use narrow beams for data and broader beams for control channels [80]. Dallas Technology Lab of Samsung Electronics have proposed beam broadening by splitting the antenna array into multiple logical sub arrays without increasing antenna spacing [80]. Conventional beamforming schemes focus on maximal ratio combining i.e maximization of desired signal and zero forcing (interference nullification) [81]. The work in [81] provides a new beamforming algorithm for sum-rate maximization in virtual cell networks. The solution achieves a balance between the desired signal maximization and interference minimization.

2) Antenna Training Protocols: It is implicit from previous sections that beamforming by the steerable and highly directional antennas is significant for future 5G development. Unfortunately, it raises significant new challenges in complicated communication protocol design. As shown in Fig. 15(a) users are beam aligned with the transmitter, while in Fig. 15(b) communication between transmitting and receiving antennas is not possible as the corresponding beams are either non-aligned or are attenuated. Hence, beamforming training protocol for discovering the best beam direction pair is very crucial [82]. Steerable beams can be used at mobile hand set and BS for RF communication and backhaul coordination [30]. Early work on mm-wave antenna pointing protocols used

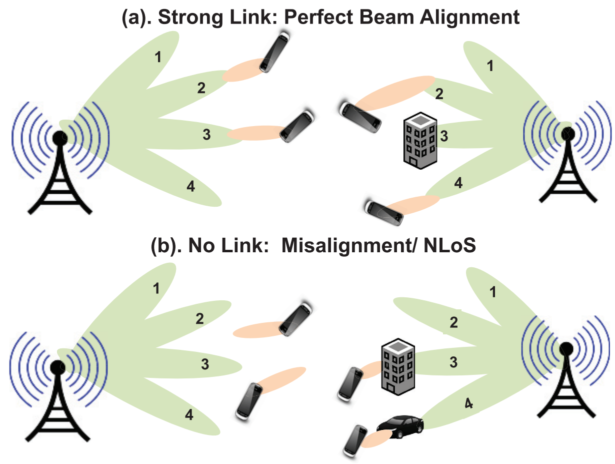

Fig. 15. Antenna Training: Beam Steering for Link Alignment.

pseudo noise sequences. With narrowband pilot signals and multipath angular spreads, antenna pointing directions could be efficiently determined [30].

Authors in [83] have proposed Singular Value Decomposition (SVD) based transmit precoding and receive combining method. It is employed for training antenna coefficients in multistage iterative fashion. For systems with lower number of RF chains and large number of antennas, this training method is very effective. It brings down the computational complexities in mm-wave communication [83]. Researchers at Stanford University have emphasized on identification of beam errors for effective handling of beamforming architecture [84]. Beam coding is a beam training technique, which assigns a unique signature code to every beam angle. Simultaneous steering of coded multiple beam angles, in a training packet, helps in fast estimation of the best angle pair. Moreover, the technique shows robustness in NLOS environment, critical for future mm-wave communication [82]. Note that, the network has to ensure that the mobile device is within the beam of the antenna. An antenna tracking system, applied in directional satellite communication, is useful [85]. The concept is based on obtaining high received signal by moving the axis in small steps. Accuracy and performance depends on the step size and SNR [85].

3) Angle of Arrival Estimations: For outdoor mobile channels, knowledge of time-varying Angle of Arrival (AOA) and Doppler spread characteristics is necessary. As compared to LOS, antenna pointing for NLOS scenario produces higher path loss and multipath delay spread. Adaptive beam arrays for narrow beam steerable antennas demonstrate that links could be created by illuminating surrounding objects in NLOS antenna [86]. In [30], the AOA distributions are generated for every transmitter. Azimuth angle combinations for all links are plotted for receiver and transmitter. Experiment and results point out that the transmitter at BS should point at the receiver direction, with a beam steering of atmost 60° [30]. Knowledge of AOA is also useful for finding alternate paths for NLOS scenario. In case of a blockage, the device needs to switch to the next available alternate path. The conventional method is to identify alternate paths by ranking signal strengths of all training beam pairs. In [87], authors from Stanford University have proposed alternate path identification, by utilizing the angle of arrival values. The concept is similar to successive interference cancellation scheme in multi-user detection. Low estimation errors and improved performance are identified as key benefits [87]. In order to achieve lower redundancy, with energy and bandwidth conservation, AOA information is also used by Directional Self pursuing Protocol (DSP). Directional antenna and on demand route discovery for the shortest path are special cases of DSP for enhancing efficiency and reliability of wireless broadcasts [88]. AOA measurements with PDP spread and propagation losses are performed, with various configurations of elevated transmitters and receivers, for understanding the typical 5G BS locations in [30].

C. Sectorized Antenna

With a myriad of antennas, it is difficult to obtain the channel information at every individual antenna element in MIMO integrated mm-wave system. We defer the survey of MIMO concepts till next Subsection. Moreover, mm-wave MIMO systems are constraint by need of RF beamforming to overcome poor link budget [79]. The problem can be mitigated by using switched narrow beams for both transmitter and receiver. Data transmission is achieved by selecting the best transmit-receive beam pair [79]. Switched beam systems employ fixed antenna patterns for transmitting or receiving from specific directions. A sectorized antenna model is considered ideal for these systems. Fig. 16 shows that multiple antennas can be constructed to traverse a fixed arc-like sector. These arc creating antennas provide high gain over a confined range of azimuths [89]. The range of each transmitting node is divided into overlapping sectors [88]. For transmission or reception, the node is configured to switch on one or several sectors. Jointly covered transmission range is usually more effective than omnidirectional mode [88]. At the same time, it also demands less hardware requirements. Moreover, the beam combining protocols and Spatial-Division Multiple Access (SDMA) could be employed along with FDMA or TDMA techniques to increase spectrum capacity and frequency reuse [30].

D. Massive MIMO System

By using simple, linear signal processing techniques, massive MIMO provides BS with a huge number of antennas. Fig. 17 demonstrates a massive MIMO enabled BS. The grid of antennas is capable of directing horizontal and vertical beams. Massive MIMO significantly enhances spectral and energy efficiency [90]. Every single antenna is positioned to achieve directivity in transmission [91]. Coherent superposition of wave fronts is the underlying principle of massive MIMO technology. Emitted wavefronts add constructively at the intended location and reduces their strength everywhere else [92]. Hence, the spatial multiplexing at massive MIMO enabled BS increases capacity by several magnitudes [91]. Such a design requires effective algorithms for massive MIMO system model, with advances in modulation techniques [90]. Increase in number of antennas cannot render highly correlated channel vectors as

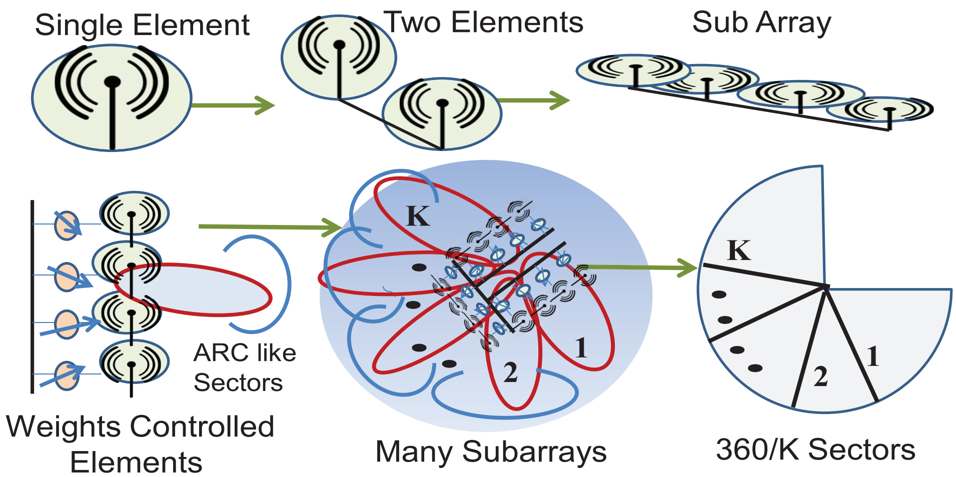

Fig. 16. Sectorized Antenna Model: Multiple Antennas at Transmission Node for Dividing Range into Overlapping Sectors.

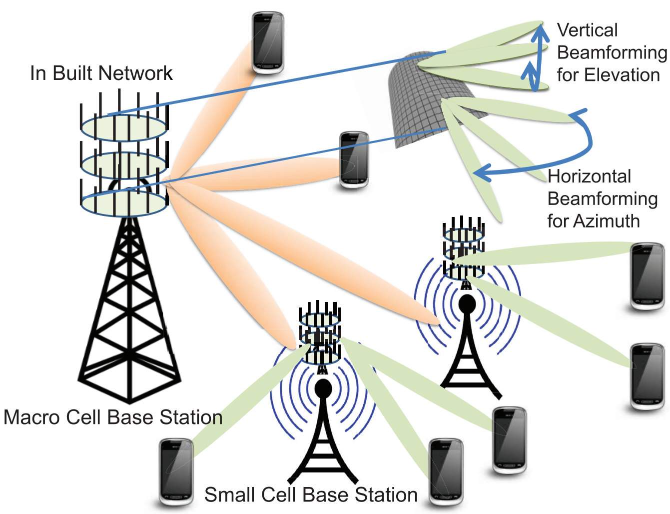

Fig. 17. Massive MIMO and Beamforming.

orthogonal. Thus, authors in [90] suggest that user scheduling algorithms should be critical to massive MIMO systems. Time Division Duplexing (TDD) is the preferred choice for massive MIMO systems to avoid the complexity associated with channel estimation and channel sharing in Frequency Division Duplexing (FDD). More investigations into frequency correction algorithms, such as direction of arrival based frequency correction, covariance matrix and spatio-temporal correlation would enable use of FDD in massive MIMO systems [90]. Researchers usually propose 2D grid configuration and deployment of antenna arrays in massive MIMO systems. However, 3D and distributed array structures also present good candidature and require further investigations [90].

Massive MIMO deployment schemes, distributed antenna arrays and directional antenna arrays are proposed in [91] for future BS design. Moreover, inexpensive and low-power components can be used to build massive MIMO [92]. Channel state information, associated with large number of BS antennas for massive MIMO systems and coordination among different cells induces a huge amount of information exchange overhead. This impedes system performance with limited-capacity backhaul links. Efficient multicasting with massive MIMO, in noncooperative cellular networks, is explored in [93]. In order to achieve better energy focus and reduced spatial interference, the work in [94] proposes a new massive MIMO design by integrating an electromagnetic lens with large antenna array.

Comparison between Small Cell Networks (SCN) and massive MIMO is done in [95]. The energy efficiency of SCN is found to be larger than massive MIMO. Reduction in the size of antenna array and related electronic circuitry makes the small cells, with low frequency mm-wave transmission, a suitable candidate for massive MIMO. Hence, an efficient combination of the two technologies is expected to give better results [90]. Moreover, the spatial and temporal freedoms of massive MIMO can help in managing residual self-interference [96]. Thus, the work in [96] utilizes MIMO radios in fast fading channels, with imperfect channel estimation, to achieve full duplex rates. Concept of full duplex is elaborated in the next subsection.

E. Full Duplex Radio Technology

A new physical paradigm of receive and transmit on the same frequency channel simultaneously i.e Full Duplex (FD), offers to double the spectral efficiency of a point-to-point radio link [97]. Crosstalk between the transmitter (Tx) and the receiver (Rx), path loss, fading and internal interference impede the popularity of simultaneous communication on the same frequency channel [97]. However, recent developments in RF and beamforming antenna design technologies encourage FD transmission in the same frequency band [20], [60]. Moreover, advances in MIMO techniques present effective methods of self interference reduction in spatial domain, enabling successful FD relaying inspite of interferences [98]. Full duplex promises to double the capacity, improves feedback and latency mechanism, while maintaining the security in physical layer [60]. Furthermore, full duplex eliminates hidden node problem in contention based networks [60]. Simultaneous scheduling of uplink and downlink on the same resource block causes every FD transmission to suffer from self interference challenges not only from within but from neighboring cells as well [97]. Thus, reduction of Self-Interference(SI) is the major challenge to be

TABLE III
HIGHLIGHTS OF PHYSICAL LAYER RESEARCH IN 5G WIRELESS NETWORKS

Work Area	Related Work	Key Points
Understanding mm-wave Channels	[7], [8], [9], [28], [33], [66] to [78]	• Propagation loss and penetration • LoS, NLOS • Doppler • Multipath/Power Delay Profile
Adaptive Beamforming	[30], [32], [38], [79] to [88]	• Adaptive beamforming • Angle of arrival • Antenna training
Switched Beam	[30], [79], [88], [89]	• Sectorized antenna model • Overlapping sectors • Cost effective
Massive MIMO Systems	[90], [91], [92], [93], [94], [95], [96]	• High number of antennas per BS • Coherent superposition of waveforms • Inexpensive low power components • MIMO / small cell combination
Full Duplex Radio Technology	[20], [60], [97], [98], [99]	• Offers to double the spectral efficiency • Limited by crosstalk b/w Tx & Rx, pathloss • Limited by Self Interference (SI) • Active & passive SI cancellation • Improves feedback and latency

addressed in implementation of full duplex [99]. SI cancellation categories are broadly classified as passive and active cancellations [98], [99]. Passive SI cancellation exploits directional antennas, absorptive shielding and cross-polarization to isolate transmitter and receiver. Active technique utilizes information of node's transmit signal to cancel the interference [98]. 5G networks with beamforming technology, massive MIMO deployment, centralized architecture and small cell design appear to be conducive for FD realization. Intelligent device scheduling with suitable rate and power assignment can enable high capacity gains from FD operations [97]. We believe, the understanding of evolutionary and revolutionary physical layer technologies will have a profound impact on the future 5G wireless communications. Works related to physical layer advancements are highlighted in Table III.

IV. MAC LAYER MAKEOVER

Physical layer modifications, mentioned in Section III, make MAC layer changes inevitable. In this section, we discuss amendments required in MAC protocol, multiple access, multiplexing and frame structure. We also present upcoming concepts of RACH, Cognitive Radio and Full Duplex Reception and Transmission.

A. Default Approach: Spatial Beam Patterns

SDMA, shown in Fig. 18, is a natural fit for adaptive antennas, beamforming and device centric 5G architecture. Beamforming coefficients need to be trained beforehand for achieving desired spatial beam patterns, required for successful implementation of Spatial Division Multiple Access (SDMA) [100]. In order to support SDMA, BSs are required to simultaneously transmit and receive multiple beams in different directions [32].

Digital baseband beamforming, discussed in Section III, is beneficial for such multiple beam transmissions and receptions [32]. Accurate computations of channel matrices, beamforming vectors and feedback mechanisms are very crucial for effective

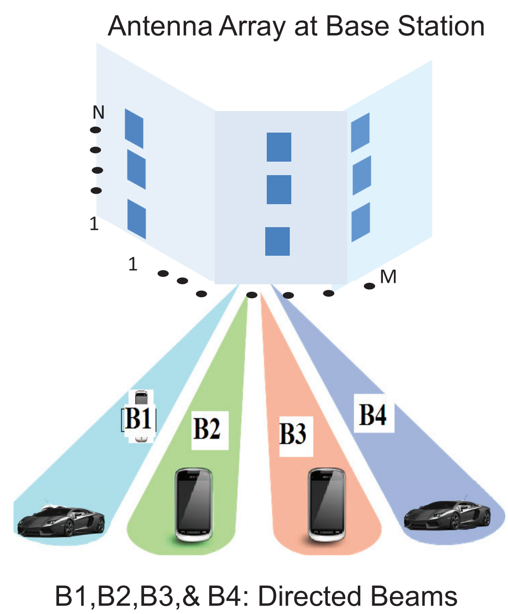

Fig. 18. Spatial Division Multiple Access (SDMA).

SDMA implementation. However, for large number of antennas and small number of RF chains, traditional estimation and feedback procedures are inadequate. Thus, for smaller number of RF chains, an antenna training protocol is proposed in [100]. Pengfei Xia's team, in Samsung Electronics [100], have successfully estimated optimal beamforming vectors even without the explicit channel knowledge. Low training overheads further accentuates advantages of iterative antenna training protocol over conventional estimate-and-feedback process, especially for myriad antenna systems working in GHz frequency range. Primary requirement of SDMA is enabling adaptive antennas to steer the energy in desired direction. Another important requirement is assessment of direction and angle of arrival for RF links between BS and mobile device [101]. An algorithm considering SINR, AoA, channel environment and angle of departure for user selection in SDMA system is proposed in [101].

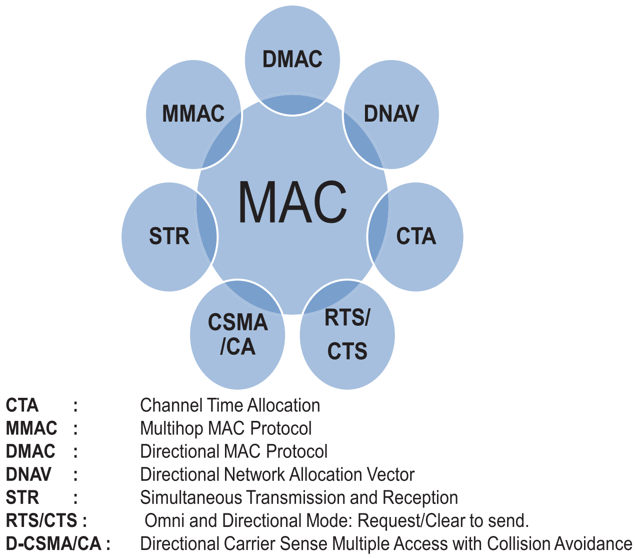

Fig. 19. Directive MAC Protocol-Key Features.

A new MIMO SDMA-OFDM system model is proposed in [102]. BS's receiver exploits array antenna of 'P' elements, while each of the 'L' simultaneous mobile users employs a single transmit antenna. The complex signal vector is a function of the n^{th} sub carrier of the k^{th} OFDM symbol, received at the p^{th} element of the antenna array [102]. By adjusting the sub carriers' weights, error signal power could be minimized. It also proposes a genetic algorithm for weight calculations. The performance can be further enhanced by increasing the number of array elements 'P' [102].

B. Directional MAC Protocols

A MAC protocol that exploits spatial features could effectively increase the network capacity. Major MAC layer protocols, relevant for 5G wireless networks, are listed in Fig. 19. In [103], multiuser MAC protocols are proposed based on directional Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The proposed analysis is based on Markov Chain model of multiuser SDMA. Interference reduction in directional and adaptive beamforming aids BSs in simultaneous communication with many users in the same multiuser group [103]. With the Physical layer technologies nearing the Shannon capacity, concurrent transmissions and receptions at the same time and frequency effectively doubles the spectral efficiency and throughput [6], [103]. Simultaneous transmissions and receptions, with efficient neighborhood activity detection, also resolves the hidden node problem in contention based networks [6]

TDMA with time partitioned in super frames is a suitable candidate for 5G communications. Super frames are composed of many time slots, called Channel Time Allocation (CTA) [104]. In every CTA, many local links communicate concurrently to exploit the spatial reuse [104]. Directionality can also be added to MAC protocol, which sends RTS and CTS. Different papers have proposed different configurations, advantages and disadvantages for RTS/CTS transmissions in both omni and directional mode [34], [104]. RTS/CTS packets could be transmitted on every beam to enhance performance [34]. The nodes need to transmit in the same direction from where it received the CTS/RTS. Directional Network Allocation Vector (DNAV) table helps in tracking directions where the node must (or must not) initiate a transmission. DNAV is integral to the directional MAC protocol, in which the upper layer is assumed to be aware of its neighbors [105]. However, DNAV suffers from problems of deafness, hidden node, under-utilization and dead-lock. In [105], the researchers discuss multihop MAC (MMAC) protocol, which outperforms Directional MAC by integrating Direction-Omni (DO) and Direction-Direction (DD) neighbor identifying techniques. A DO neighbor node receives directional transmissions from neighboring directional nodes, even if it is in an omni mode, itself. A DD neighbor node receives directional transmission when, beamform aligned with the directional neighbor [105].

C. Advanced Multiple Access Techniques for 5G

The availability of huge spectrum in mm-wave systems enables Carrier Aggregation to increase system Bandwidth [106]. mm-wave channels are characterized by wide comprehensible bandwidth and small delay spread. This makes shorter Cyclic Prefix (CP) and wider subcarrier spacing [106]. Choice of OFDM is preferred, as it is efficient and less sensitive to time offsets [106]. Flexibility, support for multiple bandwidths and simple equalizer design are some of the major advantages of OFDM. ETRI, Korea have used OFDM multiplexing [106] for analyzing mobile broadband communication systems in high speed trains. In [8], [33] authors have proposed OFDM and single carrier FDM for mm-wave Mobile Broadband systems (MMB). MMB frame structure configuration is presented in [8]. The transmission time interval for MMB system is composed of 62.5 microsecond slot duration. 1 ms subframe, 10 ms frame and a 40 ms superframe, are chosen for simulations in [33]. Reasonable clock accuracy and cost has made 30.72 MHz frequency and its multiples a good choice for sampling rate selection [33]. 520 ns CP provides comfortable margins to adjust the longest paths. A subcarrier spacing of 480 KHz enables coherent bandwidth for most multipaths in mm-wave mobile communication. With MMB frame structure of 1/4 CP, the link budget analysis manifests Gbps data rates [33]. Similar analysis with a frame structure of 1/8 CP also points out such high data rates [8]. Lower channel delay spread helps in reducing frequency selective fading in OFDM [102]. Authors in [32] believe, OFDM might prove to be an effective choice for mm-wave broadband networks, provided the technical considerations are not ignored.However, diverse user requirements, tactile Internet and ultra-low latency demands make synchronization and orthogonality (integral to OFDM) a big challenge. An asynchronous approach appears more promising over sophisticated synchronization algorithms that require more spectrum and power resources [24]. Critical time budget demands reduced frame duration. A symbol duration of 67 microseconds in OFDM is not a promising option [24]. Interleave Division Multiple Access (IDMA) [24], for generating signal layers, needs further investigation. Similarly,

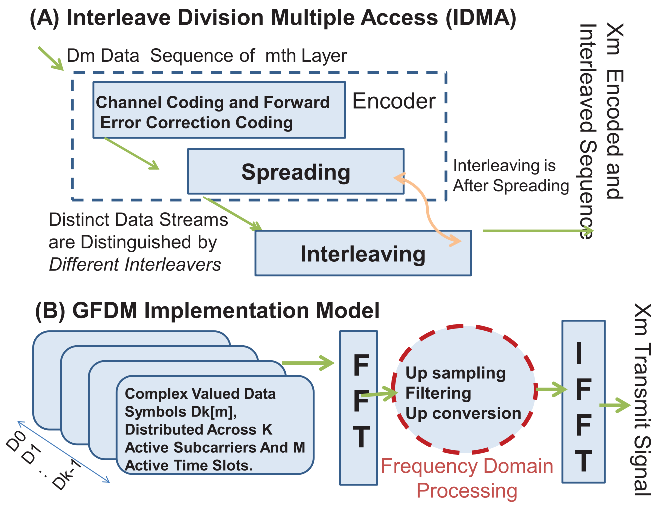

Fig. 20. Overview of IDMA and GFDM Implementation.

to leverage synchronization and orthogonality, Sparse Code Multiple Access (SCMA) and Non Orthogonal Multiple access are also recently proposed for consideration in 5G communications [107].

IDMA is a special case of CDMA. Instead of considering a spread sequence specific to the user, IDMA uses specific interleaves for user segregation [108]. As shown in Fig. 20 (A), a single low rate encoder combines channel coding, forward error correction coding and spreading as one block [109]. The spreading is not assigned as a different and special task [109]. Interleaves generally utilize a less complex iterative multiuser identification concept at the receiver [108]. Sparse code multiple access (SCMA) combines QAM symbol mapping and spreading. Multi dimensional codeword from SCMA codebook are directly mapped over incoming bits [110]. SCMA has less complexity but better performance, while comparing to low density version of CDMA [110].

According to researchers from Vodafone, the new physical layer would need adaptation to novel concepts, such as Generalized Frequency-Division Multiplexing (GFDM) or Filter Bank Multi-Carrier (FBMC) [111]. Fig. 20 (B) shows Generalized Frequency Division Multiplexing (GFDM) - a key candidate to overcome the challenges of 5G system. Transmission of a block frame, composed of M time slots and K sub carriers, is the fundamental concept of GFDM. Its flexibility and block structure helps in fulfilment of low latency requirements of 5G systems [24]. Researchers have also proposed GFDM implementation by integrating FFT/IFFT algorithms in [112]. Filter Bank Multi Carrier (FBMC) is another key enabling technology for emerging 5G MAC [18]. FBMC is natively non-orthogonal and do not require complex synchronization [7]. Thus, it offers to reduce signalling overheads which in turn would improve latency and enhance user experience in sporadic traffic environment, expected in dense and diverse 5G wireless connectivity (comprising of D2D, M2M, IoV and IoT applications). Differences between FBMC and OFDM are highlighted in Table IV. Pulse shaping filter per sub carrier in FBMC helps in further reducing overheads. Staggered Multi-Tone (SMT) and Cosine modulated

TABLE IV
COMPARISON BETWEEN OFDM AND FBMC

FBMC	OFDM
Natively non-orthogonal and asynchronous.	Strict orthogonality requirements.
Spectrum agility and better adjacent channel leakage performance.	High spectral Leakage and high peak to average power ratio.
Redundant cyclic prefix (CP) is dropped and an upgraded control of out-of-band emission.	Cyclic prefix is integral to OFDM.
Frequency localization of prototype filter makes waveforms less sensitive to BS timing errors between different cells.	Severe degradation is observed in system performance due to timing errors between BSs.
Better gains are achieved than existing techniques at cost of increase in complexity.	Flexibility, support for multiple bandwidths and simple equalizer design are major advantages.
Requires further investigations for use in 5G.	Preferred in legacy network, as it is efficient and less sensitive to time offsets.
[113], [117], [7], [115], [116]	[106], [116]

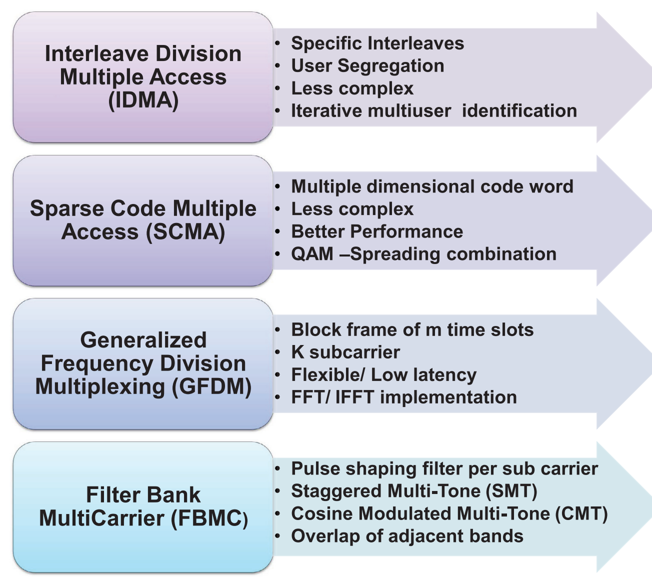

Fig. 21. Multiple Access for Future Technology.

Multi-Tone (CMT) are important FBMC methods for maximizing bandwidth efficiency [113], [114]. SMT uses offset QAM and CMT pulse amplitude modulation for transmitting symbols. Both allow overlap of adjacent bands to maximize bandwidth efficiency. Universal Filtered Multicarrier (UFMC) proposed by 5GNOW group is another non-orthogonal waveform. It advocates bundling of subcarriers. UFMC offers to reduce filter length and increase robustness against inter-carrier interference [25]. Key features of emerging multiple access propositions are listed in Fig. 21.

D. Alternate Methodologies

We now discuss major changes infusing new MAC features in 5G wireless networks.

1) Random Access Channel (RACH) and multicell operations important for future communications are not compatible with orthogonality. Moreover, sporadic traffic generations from M2M and IoT applications can not be

TABLE V
REVIEW OF MAJOR MAC LAYER CHANGES

Work Area	Related Work	Key Points
Spatial Beam Patterns	[32], [100], [101], [102]	• Steer energy in desired direction • Computation of parameters • MIMO SDMA-OFDM model
Directional MAC Protocols	[6], [34], [103], [104], [105]	• CSMA/CA • Directional MAC • Multihop MAC • RTS/CTS • Directional network allocation vector
Advanced 5G Multiple Access	[7], [8], [18], [24], [25], [33], [32], [106] till [117]	• Carrier Aggregation for increased bandwidth • Shorter Cyclic Prefix • Orthogonal Frequency Division Multiplexing • Interleave Division Multiple Access • Sparse Code Multiple Access • Generalized Frequency Division Multiplexing • Filter Bank Multi Carrier
Alternate Methodologies	[24], [60], [97], [118], [119], [120]	• Random Access Channel • Cognitive Radio • Simultaneous transmission and reception

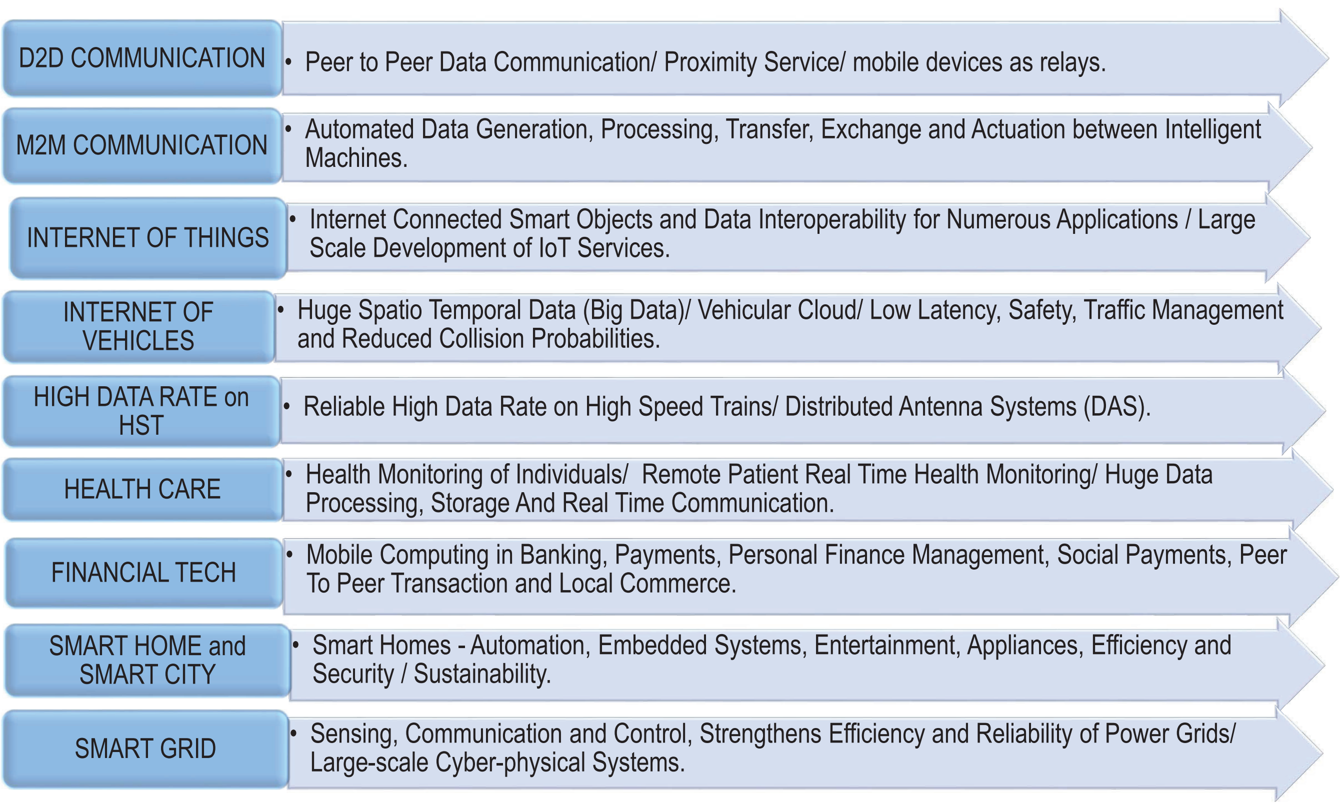

Fig. 22. Applications of 5G Communication.

avoided. Such devices have to incorporate bulky synchronization procedures of random access, specifically designed for orthogonality. Alleviating synchronization requirements enhance network performance and improve user experience. Hence, non orthogonal waveforms are proposed to carry sporadic traffic for asynchronous signalling, specially over the RACH [24].

2) Cognitive radio is one of the promising technology, aimed for improved resource utilization. It prescribes the existence of both licensed and unlicensed radio nodes on the same bandwidth. Dynamic spectrum allocation algorithm are of prime importance in cognitive networks [118]. Routing and resource allocation for mesh networks using cognitive radio techniques are analyzed in [118]. The design scheme is proposed for higher traffic load and lower delay. Both the characteristics are fundamental to 5G systems. Hence, further developments in cognitive radio are expected to support and enhance emerging 5G networks.

3) Efficient and novel MAC protocols are critical to fully exploit the capabilities of full duplex design discussed in Section III. Full duplex enables nodes to transmit and receive a designated packet simultaneously at the same frequency. Researchers in [119], propose to improve

TABLE VI
KEY DIFFERENTIATORS FOR EMERGING APPLICATIONS IN 5G WIRELESS

Scenarios	**Limitations of Legacy network & What 5G offers?**
D2D Communications	Limitations of Legacy network • Add-On Technology thus requires higher computational overhead. • Multiple wireless hops entails a multifold waste of signaling resources as well as higher latency [27]. • Requires mitigation of potential interference between the two links. What 5G offers? • Native support in 5G wireless [27], [126]. • Infrastructure centric communications utilizes base stations, while ad hoc D2D communications focuses on local traffic . • 5G wireless devices are expected to deal local traffic directly instead of relying data through a base station [128]. • Beamforming directive antennas offer to mitigate interference between the two links.
M2M Communications	Limitations of Legacy network • Legacy network typically operate with a few hundred devices per base station. • Not designed for M2M envisions of massive number of connected device [27]. • Low latency and real-time operation are stringent requirements for critical applications as healthcare. • Small data blocks transmitted sporadically from diverse devices. • Which is very different from current communication scenarios. • Control and channel estimation from massive diverse devices would add immense overheads in legacy network. • Add on Technology. What 5G offers? • New mm-wave spectrum can easily accommodate proliferation of devices. • Low latency is one of the key 5G requirements and would resolve time critical issues. • Non orthogonality and new waveforms could potentially answer sporadic traffic [24]. • C-RAN and SDN architecture relaxes tight coupling between the data and control planes. • Native support in 5G wireless [27].
Internet of Things	Limitations of Legacy network • In traditional ubiquitous computing, only a limited number of sensors are connected to the applications. • However, IoT envisions connection of billions of sensors over the Internet [140]. • Understanding sensor data and interpreting it automatically is challenging. • IoT application domains is a challenging task in current networking. • Security, privacy, and trust increase the IoT challenge significantly in current communication scenarios. What 5G offers? • 5G offers paradigm shift in architecture, multiplexing and networking. • Promises extended coverage, higher throughput and lower latency. • Connection density of 1000x bandwidth per unit area, and 10-100x number of connections [10]. • These could be the key differentiators in establishment of IoT.
Internet of Vehicles	Limitations of Legacy network. • Complexity of distributed control of hundreds of thousands of cars is to be taken as a serious challenge [148]. • The communications must be secure and fast to prevent disasters. • Current processing environment lacks swiftness, dedicated spectrum , intelligence and learning capabilities. What 5G offers? • 5G offers small cell site specific environment. • It also offers dedicated links, cloud capabilities, content-Centric Networking and low latency commitments. • 5G promises are very appealing for future vehicular communications.
Smart homes, cities & grids	Limitations of Legacy network. • Smart homes, smart cities & smart grids increases dense and diverse connectivity , manifolds. • Supporting this rapid increase in data usage and connectivity is extremely daunting task in 4G LTE cellular systems. What 5G offers? • The main differences in 5G compared to 4G would be greater spectrum availability at untapped mm-wave spectrum. • Highly directional beamforming antennas, longer battery life, reduced outage probability. • Greater bit rates in larger parts of coverage area, lower infrastructure costs and • Higher cumulative capacity for many simultaneous users in both unlicensed and licensed spectrum [28]. • These differentiators possess capabilities to address enormous data rates and connectivity in smart cities, homes & grids.

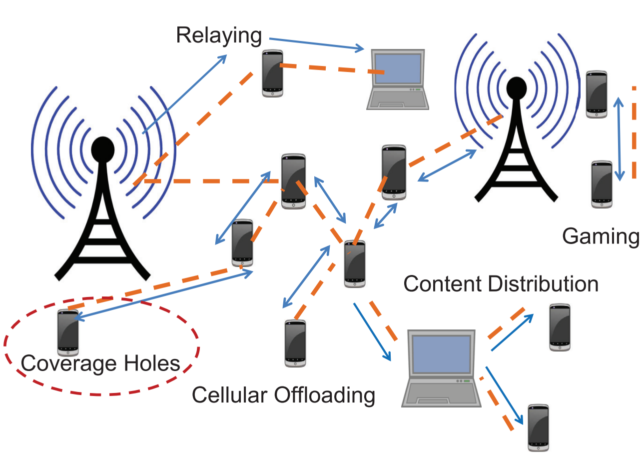

Fig. 23. Use Cases of Device to Device Communications.

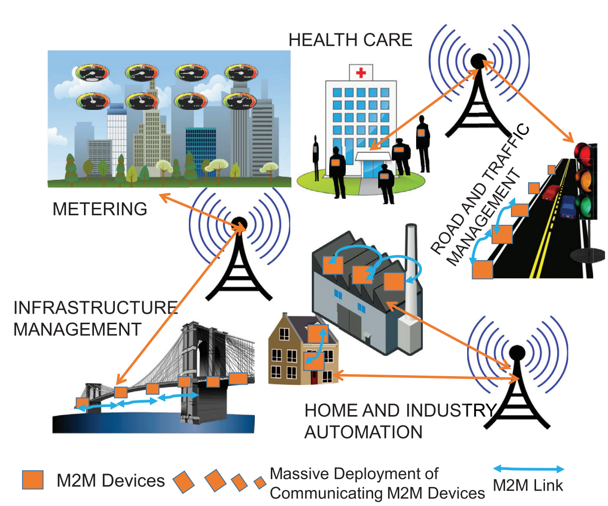

Fig. 24. Applications of Machine to Machine Communications.

network throughput by Asymmetrical Duplex (A-Duplex) MAC protocol. A-Duplex establishes packet-alignment based dual link between two different half duplex clients and full duplex Access Point (AP). Hence, full duplex and half duplex may coexist in same application environment [120]. A MAC protocol with Request To Send (RTS)/Full-Duplex Clear to Send (FCTS), supporting both bidirectional and unidirectional techniques, is proposed in [119]. FD is expected to play a crucial role in achieving low latency requirements of 5G networks [60]. Smart device scheduling along with suitable rate/power allocation enable high capacity gain from FD operation [97].

With the advancement in physical and MAC layer technologies, like mm-wave spectrum, multiple antennas, small cells, adaptive beamforming, massive MIMO, SDMA, cognitive radio, STR, 5G networks are expected to bring a big paradigm shift in the communication industry, while introducing novel applications. We highlight the major MAC layer features in Table V.

V. Emerging Applications

A wide variety of new emerging applications is the major guiding force behind the commercial roll out of 5G wireless systems. 5G architecture is expected to provide network solutions for a wide range of public and private sectors, like energy, agriculture, city management, health care, manufacturing and transport, with improved software services [19]. Apart from the enormous number of connections, 5G networks also have to support diverse nature of devices and their associated service requirements [121]. Although research and development in some of these applications are already underway in 4G wireless, original 4G LTE standards, 3GPP LTE Release 8.0 [122] did not include support to any of these applications. Rather, these applications were spawned later, and started explosive increase in wireless data usage, thereby imposing additional burden on resource constrained 4G wireless networks. Naturally, later versions of 4G LTE networks, often termed as "LTE Advanced" gradually started to include these applications. On the other hand, it is expected that massive bandwidth of 5G mm-wave communications will provide a native, de-facto support for these emerging applications. In this section we present some of these killer applications, like, D2D communications, M2M communications, IoV, IoT and Healthcare. Major existing and future applications of 5G wireless and their important features are highlighted in Fig. 22. We delineate key differentiators for emerging applications in 5G Wireless from its 4G counterpart in Table VI.

A. D2D Communication

Device centric nature [27] of 5G wireless is expected to enable the devices in proximity to communicate directly bypassing the cellular BS [123] for sharing relevant contents. Fig. 23 shows different D2D communication scenarios. A comprehensive review of D2D communications is available in [123]. We briefly highlight the major research works relevant to the context of emerging 5G wireless communications. Major recent research activities in D2D include game theoretic pricing schemes [124], social networking prototypes (e.g. Qualcomms FlashLinQ) [125], public safety networks [123] and maximum allowable distance estimation for commercial roll out [127].

An adhoc D2D network of 5G wireless devices, using group key agreement and routing control process, is proposed in [128]. Low latency, energy efficiency and scalability are vital to 5G networks. Thus, it is essential to decrease the control signalling and end to end latency in network assisted D2D communications [129]. Nokia Research Center proposes, smart mobility management, D2D-aware handover and D2D triggered handover solutions [129]. These system level improvements can support a reliable vehicle to vehicle communications in 5G wireless. Spectrum sharing, interference management, multi-hop communications and energy efficiency are major challenges in hyper dense 5G mobile environment and require further investigation [130], [131].

B. M2M Communication

Like D2D communications, M2M communications are also expected to have native support in 5G wireless [27]. Major features of M2M communications involve automated data generation, processing, transfer and exchange between intelligent machines, with minimum human intervention [132]. Fig. 24 delineates that unlike local D2D communications, M2M communications connect massive number of devices, like smart metering, sensors and smart grid equipments, along with wide coverage areas [123].

M2M communications envision umpteen number of devices with small data, sporadic transmissions, high reliability, low latency and real time operation. Major reviews of existing M2M research works include various commercial, hardware and research platforms [133] as well as major architectural enhancements, network functionalities and implementation challenges [134]. We provide a short overview of the major M2M research works relevant to our context. Joint use of carrier aggression and relay station in OFDMA-based 5G wireless is proposed in [135]. Latest advances and developments in architecture, protocols, standards and security for M2M evolution from 4G to 5G wireless are discussed in [136]. Network uncertainty and mobility often lead to complex interference within M2M networks themselves, as well as between M2M networks and cellular networks [137]. We expect the cognitive radio to emerge and assist in developing novel cognitive M2M architecture for sensing and using the available frequency bands [132]. Cognitive Radio technology driven Smart Objects (CRSOs), with high energy efficiency and environmental knowledge are expected to improve M2M communications performance, required for IoT technology [138].

C. Internet of Things (IoT)

As shown in Fig. 25, IoT envision millions of simultaneous connections, involving a variety of devices, connected homes, smart grids and smart transportation systems [18]. This vision

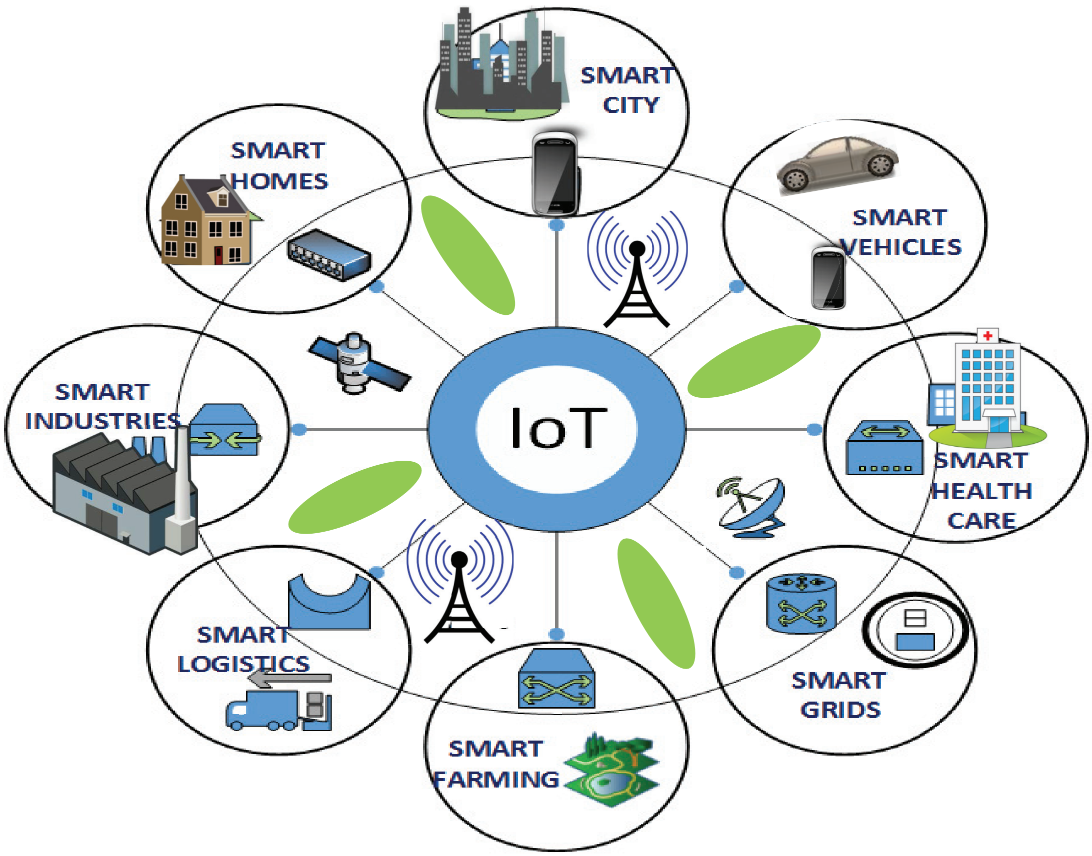

Fig. 25. Internet of Things (IoT): Connecting "Anything, Anyone, Anytime, Anyplace".

could be eventually realized only with the advent of high bandwidth 5G wireless networks. IoT enables internet connections and data inter-operability for numerous smart objects and applications [139]. Six unique challenges [140] of IoT include (i) Automated sensor configuration, (ii) context discovery, (iii) acquisition, modeling and reasoning (iv) selection of sensors in 'sensing-as-a-service' model [140] (v) security-privacy-trust and (vi) context sharing. Implementation of IoT is complex, as it includes cooperation among massive, distributed, autonomous and heterogeneous components at various levels of granularity and abstraction [141]. The concept of cloud, offering large storage, computing and networking capabilities, can be integrated with diverse IoT enabled devices [142]. A high level design of cloud assisted, intelligent, software agent-based IoT architecture is proposed in [141]. Smart objects, enabled with 5G wireless are expected to form the basis of large scale IoT design and roll out [141]. More recently, Social Internet of Things (SIoT) is also coming up for exploring the relationship between objects and form social networks [143]. Concepts, reviews and challenges of SIoT are presented in [144], [145]. We expect IoT will gradually transform the current Internet from the human centric interactions to a M2M platform [24] equipped with 5G wireless. This ubiquitous connectivity of autonomously communicating, IoT-enabled devices is the basis of 5G wireless [18]. To advocate IoT on a global scale, ITU-T's IoT Global Standards (IoT-GSI), proposes unified approach for technical standard developments [146].

D. Advanced Vehicular Communications

Development in IoT automatically leads to the evolution of Internet of Vehicles (IoV) [147]–a network of interconnected vehicles for robust traffic management and reduced collision probabilities [10]. High bandwidth, pervasive availability, and low latency of 5G wireless is assuring smart and intelligent vehicular communications. Emerging vehicular cloud is responsible for all essential services and applications, like content search routing, spectrum sharing and dissemination [148]. IoV involves very huge spatio temporal data (Big Data), which needs to be processed and delivered with high safety and security. IoV is also expected to explore roadside cooperative, as well as non-cooperative relay nodes [147]. Cooperative and non cooperative Bayesian coalition games, using learning automata, is conducted in IoV [147] for VANET. Vehicles, as smart and interactive social objects, form the basis of Social IoV (SIoV) [149]. SIoV leverage VANETS and develops a vehicular social networking platform, based on cyber physical architecture [149]. Intelligent Internet of Vehicles Management System (IIOVMS), with cloud assisted data processing, over a wide number of vehicles helps in traffic management [150]. Dedicated Short Range Communication Working Group (DSRC), presents IEEE 1609 standards for Wireless Access in Vehicular Environment (WAVE) [151], [152]. Society of Automotive Engineer (SAE) standards, along with IEEE standards for vehicular communications are elaborated by John B. Kenney of Toyota InfoTechnology Center in [153]. To address the limitations of WAVE, Vehicular IP in WAVE (VIP-WAVE) framework is also proposed in [154].

Providing a reliable high data rate on High Speed Trains (HST) is another crucial challenge [106]. Exploring the advantages of Distributed Antenna Systems (DAS) and mm-wave communications, a network architecture for high speed trains is proposed in [106]. It consists of many digital units, multiple Radio Units (RU) and Terminal Equipments (TE). Communication links are formed between the RUs of the digital units and of the TEs [106]. A distributed architecture with an access point in every carriage, for preventing any temporary outage and enhancing the QoE, is proposed for 5G connectivity [155].

E. Health Care and Wearable

Advancements in sensing and communication technology have opened up new possibilities for health monitoring [156]. US census bureau projects an ageing world in less than 30 years from now [157]. Wearable technology promises to provide health care solutions to growing world strained by the ballooning ageing population [157]. Devices with capabilities of measuring multiple physiological signals in ambulance like environment are being developed in [158]. The record of multiple physiological signals over a long time period helps in understanding the disease pathophysiology [158]. Improved addressing, extended security services and higher bandwidth enables new possibilities of healthcare [159]. Emerging 5G wireless and Body Area Network (BAN) are facilitating a paradigm shift in realtime remote patients' health monitoring. The major constraint in real time data collection and monitoring is bandwidth limitation. Higher bandwidth and data rates of 5G wireless [159] are expected to resolve this bandwidth constraints. Comfort, physical, psychological and social aspects of wearable devices are discussed in [160]. These capabilities require huge data processing, storage and real time communications. An IoT based system, endowed with big data and cloud computing concepts, for emergency medical services is presented in [139]. 5G wireless is expected to resolve big data challenges of realtime health care applications bringing benefits to the mankind [139].

F. Miscellaneous Applications

Apart from the above-mentioned applications, the financial industry, with increasing businesses and customers, also requires strong computing and data processing [161]. Application of grid computing in financial industry is discussed in [161]. 5G based future mobile networks have a huge potential to transform different financial services [162], like banking, payments, personal finance management, social payments, peer to peer transaction and local commerce.

Sensing, communication and control increases efficiency and reliability of power grids, thereby modernizing them to Smart Grids (SGs). SGs use wireless networks for energy data collection, power line monitoring, protection and demand/response management [163]. Comparisons between smart and existing power grids are given in [164]. Smart information and smart communication subsystem are integral to smart grids [164]. Smart grids seamlessly link physical components and wireless communications representing large-scale cyber-physical systems [163]. Wireless technology is already being explored for efficient real time Demand-Response (DR) management [165]. High bandwidth and low latency of proposed 5G are expected to resolve many challenges associated with SG demand response.

Similarly, smart homes, with roots in automation, embedded systems, entertainment, appliances, efficiency and security is an active technical research area [167]. Smart cities, with fundamentals of sustainability are gaining momentum. Major concepts of IoT, M2M, Cloud computing, integrated with 5G are very persuasive in these research areas [167]. We summarize the major related works in existing and future applications of 5G wireless in Table VII.

VI. Quality Expectancy of 5G Networks

5G is expected to deliver high Quality of Service (QoS) and Quality of Experience (QoE). Emerging applications, like video-conferencing, video on demand, online gaming and online transactions are getting popular day by day. For assuring positive user experience, service providers are switching their focus on perceived end to end quality, referred as QoE [168]. Migrating to next generation 5G technologies, with advances in architecture, physical layer and control should be at par with the quality requirements. The 1 ms end-to-end round trip delay [10], perceived 99.999% availability [10] and 100% geographical coverage [10] are essential for the eventual realization of the vision of 5G. Hence, 5G cellular networks should be able to deliver QoS, QoE, reliability and security, at par with fixed networking and its advances [15]. The concepts of Self Organizing Networks (SON) is expected to help 5G wireless in achieving high levels of automation and enabling improved QoS and QoE. In this Section we highlight major advancements in QoS, QoE and SON, as these are fundamental for effective future 5G communications.

A. Improving Quality of Service (QoS)

Ultra high definition and 3D video content are not a distant future [169]. However, it is hard to guarantee real time, high quality multimedia traffic in time varying wireless channels [169]. As compared to wired networks, wireless networks have limited resources and shared medium [170]. Abundance of mm-wave spectrum and deployment of beamforming antennas in 5G wireless networks are expected to significantly reduce the resource and sharing constraints. The spare resources could be efficiently utilized for higher QoS guarantee [170]. However, design of high quality multimedia applications in mm-wave environment is a technical challenge to be resolved [171]. Prevalent multimedia transmission protocols and technologies cannot be directly employed to address technical challenges in 5G wireless channels, multimedia coding and transmission modes. Researchers in [171] propose QoS-aware multimedia scheduling scheme through precise propagation analysis and suitable countermeasure techniques to satisfy the QoS requirements in mm-wave framework. Mean Opinion Score (MOS),

TABLE VII
EMERGING KILLER APPLICATIONS OF 5G WIRELESS

Work Area	Related Work	Key Points
D2D Communications	[27], [123], [124], [125], [126], [127] to [131]	• Peer to Peer data communication. • Interference challenges. • Group key agreement. • Reduced latency.
M2M Communications	[27], [123], [132] till [138]	• Massive number of devices. • Automated data generation & processing. • Relay stations. • Converged mobile network. • Energy efficient& cognitive M2M.
Internet of Things (IoT)	[18], [24], [139], [140], [141], [142] till [146]	• Millions of simultaneous connections. • Cloud integrated with diverse devices • Software defined IoT • Agent based architecture • Interoperability of hubs • Social IoT
Advanced Vehicular Communications	[10], [106], [147], [148], [149] till [155]	• Vehicular cloud • Grid/Autonomous vehicle • Big Data • Social IoV • Intelligent IoV management systems • Distributed antenna in high speed trains. • Distributed load balancing • Architecture: RAT for HST. • Low latency/safety/QoS/QoE
Health Care & Wearable	[139], [156], [157], [158], [159], [160]	• Health monitoring • Multiple physiological signals • IoT/cloud for healthcare.
Miscellaneous Applications	[161], [162], [163], [164] till [167]	• Smart grids • Smart homes. • Smart cities. • Financial technologies

reflects the degree of user satisfaction [171]. It is utilized for performance comparison between proposed QoS scheme and traditional distortion driven scheduling for different scenarios of 60 GHz and 70 GHz. Multimedia based research work on mm-wave proposes high data rate and short distance applications in residential communities, universities, conference rooms, vehicles, and so on. Many such potential multimedia applications are analyzed and possible solutions provided in [171]. Researchers in [172] propose a client based QoS monitoring architecture to overcome the impediment of server-side QoS monitoring. Metrics like bandwidth, error rate, signal strength, etc. are utilized along with traditional RTT delay to determine the offered QoS. Moreover, client-based service monitoring architecture promises progress towards predicting service failures, degradations and optimal resource provisioning by delegating the monitoring role to the clients [172]. Traditional QoS model and parameters may not be sufficient to address new challenges imposed by emerging 5G applications and services. Investigations into novel QoS metrics and delay bound models would strengthen 5G mobile wireless networks. Application specific time sensitivity of different devices is another challenge in QoS provisioning. A new QoS architecture, with heterogeneous statistical delay bound over wireless coupling channel, is proposed in [169]. A colored conflict graph is proposed in [170] for designing several interference and QoS aware schemes for emerging networks with beamforming antennas. For multi-class traffic, reduction in call blocking and handoff failure is likely to improve QoS. Dynamic energy efficient bandwidth allocation schemes are proposed in [173] for an improved system quality. Designing an efficient QoS model in contention-based beamforming environment, is an open issue to be addressed for success of high quality future networks. We believe a comprehensive study of inter dependencies in wireless links under directional protocols would help in developing algorithms to resolve QoS problems.

B. Refining User Experience: QoE

Performance metrics for 5G era are highly focused on QoE [6]. Growth of subscriptions, advertisement-based business models and content delivery are fuelling almost exponential growth in video traffic over the Internet. Soon, video over Internet is expected to surpass television in terms of number of viewers [174]. However, Internet video ecosystem lacks regularized quality measurement techniques [174], [175]. Traditional QoS metrics, comprising of packet loss, loss rate, network delay, PSNR and round-trip-times are now considered not effective for video over mobile Internet [176], [177]. QoE, on the other hand, emphasises on user's perceived satisfaction [176]. For holistic user experience, technical conditions of QoS remain vital, but not sufficient [177]. Fig. 26 gives relation between QoS and QoE [177]. Higher QoS does not necessarily mean a higher QoE [178]. Interactiveness, feeling of the products, ability to serve purposes and fitting into the entire context are some of the major experience defining QoE features [179]. Important QoE features are listed in Fig. 27.

Incidentally, QoE is more subjective and hence difficult to measure. However, some objective quality models based on QoS parameters are developed to indirectly estimate QoE [180]. Elaborate discussions on advancement in video quality

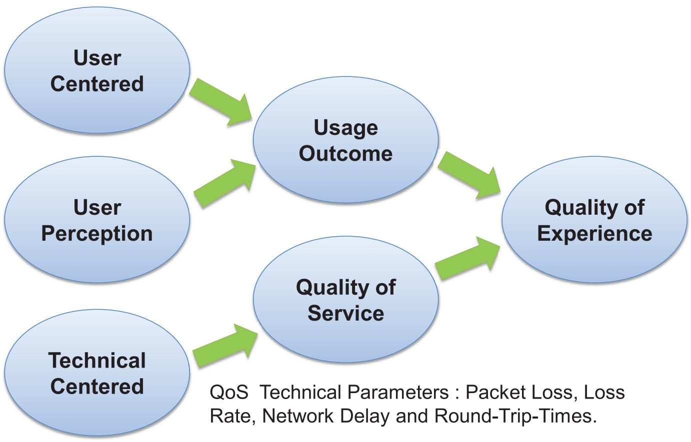

Fig. 26. Relation between QoS and QoE.

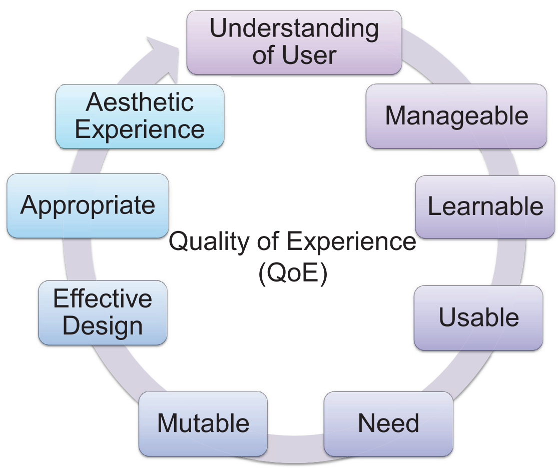

Fig. 27. Important QoE Defining Features.

assessment methods, QoE based video applications and future research directions of QoE are presented in [180]. Changing network conditions is one of the major QoE challenge in video streaming over Internet. HTTP Adaptive Streaming (HAS) enables improvements in QoE by reducing interruptions of the video playback and higher bandwidth utilization [181]. A comprehensive study of QoE aspects of adaptation dimensions and strategies for HAS is covered in [181]. Researchers in [182] emphasize on routing of live streams through the mobile network operators' infrastructure for substantial refinement in QoE with respect to higher bitrate streams, low jitter, reduced startup delay and smoother playback. Leverage of the proximity information by network operators enables effective routing through its nodes without traversing the data through the content provider network. This provides a better experience especially while sharing live social video.

Parameter buffering, startup time, bitrate, and number of bitrate switches impact QoE. However, complex counter-intuitive ways and their relationship with user experience are unpredictable. QoE is further complicated by diverse compounding factors of the nature of the content itself (e.g., user interest, genre). Authors in [174] propose to address interdependency as a machine learning problem by utilizing predictive

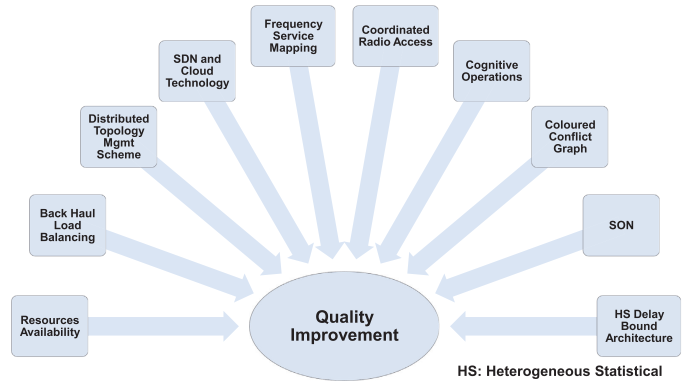

Fig. 28. Key Concepts for Quality Improvement.

model from empirical observations. Further, QoE is compared with QoS for Content Distribution Network (CDN) applications in [168]. A predictive model of user QoE for Internet video is suggested by researchers of Carnegie Mellon University and University of Wisconsin Madison in [174], [175]. In [168] authors have discussed importance of correct selection of Key Quality Indicators (KQIs). For instance, service availability, accessibility, access time and continuity are reliable for network service measurement. On the other hand, key indicators for telecom applications are success rate of connection establishment, hand off, throughput, error blocking and call drop rate [168].

Maintaining high user experience in diverse and complex 5G environment requires coordinated radio access and management at both user and network levels [6]. For further improvements in QoS and QoE, network and service management need to evolve by exploring advances in automation, cognitive operations and big data [19]. Moreover, mapping of the required services to the best possible resources and frequency, SDN and cloud technologies should be advantageous [15]. Fig. 28 represents important work for improving network quality. This quality can be further enhanced by introducing Self Organizing Network (SON), to automatically configure and manage different network technologies [126].

C. SON Enabled Quality Management

Communication industry is undergoing an unprecedented growth, with myriad of smart devices and ever increasing broadband demands [183]. This is burdening the wireless networks with a mounting pressure on QoS, QoE, energy efficiency and capacity requirements [183]. Hence, self organization and self optimization of network parameters are identified as the key factors of wireless evolution towards 5G [184]. SON offers autonomic functionalities to wireless networks by self-configuration, self-optimization and self-healing. This leads to improved user experience and network automation by reducing human intervention [185], [186]. Configuration is essential during deployment, extension, upgrade, change and failure of any network node. Self configuration replaces conventional manual configuration process [183]. Legacy networks use periodic drive tests and log report analysis for optimization. However future dense networks need to continuously self optimize to control interference and improve capacity. Self healing involves remote detection, diagnosis and recovery actions to alleviate network impairments caused by any fault [183]. Fig. 29 lists important works in self configuration, self optimization and self healing. In [183], authors have presented a comprehensive survey of self organisation for future cellular networks. SON extends automation to cross-layer, inter-element, per-user functionalities, with significant additional operational and performance benefits [187]. John M. Graybeal of Alcatel-Lucent [187] has advocated self configuring and self-optimizing attributes of SON and extended SON [187] for reducing operational expenses and increasing network performance.

SON applications in the context of 5G faces many challenges [185]. Authors propose a new big data empowered SON (BSON) [185] with three distinct features: (a) complete intelligence about the network status, (b) prediction of the user behaviour and (c) dynamically associating the network parameters in response of the network. Integrating these capabilities in SON should help in meeting stringent QoS constraints of 5G. Neighbourhood small cell approach, discussed in [126], provides a cost effective solution for dense deployment by incorporating user driven plug and play operations. Robustness in such deployment is possible by using SON techniques [126]. Self-configuration, mobility management and backhaul load balancing can be realized, while maintaining a certain level of user quality [126]. Centralized SON implementation and its relation to SDN are discussed in [188]. Centralized SON controllers provide configuration information to the BS by analyzing various reports from BS and associated users [188]. It is a direct extension of SDN and very important for resource management at 5G small cells [188]. SON Configuration parameter Value (SCV) sets are capable of changing the behaviour of SON functionalities. This feature is instrumental in adapting the target values, based on run time context information [189]. Difference in target values and selection sets are reduced by SON Function Performance Model (SFPM). Network performance can be steered in an intended direction using SFPM [189]. For maximizing the performance, understanding, comparing and optimizing of online and offline SON solutions are extremely important. Concurrent capacity and coverage optimization are considered for comparison of offline and online SON solutions in [190]. Online solutions are advantageous, as these solutions do not require any simulation models, and all associated parameters are applied directly to the network. However, in order to maintain a high QoS, large changes in parameters should be avoided. This restricts the use of online SON [190]. On the other hand, sophisticated tools can be applied to offline SON for testing large number of parameters, albeit with difficulties in creating a precise environment [190]. In a sharp contrast to these evolutionary ideas, new revolutionary idea of self-healing hardware, with the concepts of electronic DNA is recently proposed. In this architecture, every electronic cell possesses a copy for SON functionalities [107]. We believe that SON capabilities promise enormous potential in improving quality, robustness and longevity of wireless networks. Further investigations are required to understand and implement different SON algorithms in emerging 5G scenarios. Proactive integration of these novel concepts, algorithms and results would be beneficial for next generation, dense 5G networks. Table VIII shows the highlights of QoS, QoE and SON related research works, relevant to 5G wireless.

VII. 5G: A Sustainable Future

A sustainable wireless network should not only be spectral efficient but also energy efficient [191]. Energy consumption and greenhouse gas emission are two imminent worldwide issues. Information and Communication Technologies (ICT) are responsible for a significant proportion of global energy consumption. In 2009 Deutsche Telekom forecasted a 12-fold increase in the power consumption by network core within a decade [192]. Power Consumption by backbone networks (routers, fibers, transmission) is approximately 12% of electricity consumption in broadband enabled countries. By 2020 it is estimated to increase to about 20% [193]. Power consumption of core and access network is estimated to be equal [192], [193] by 2017. As discussed in previous sections, the advent of 5G cellular networks is expected to witness manifold increase in number of connections and BSs. New applications will further densify the network. Thus, it becomes even more critical to incorporate green and sustainable technologies into future 5G wireless networks for significant energy saving. It is for the research community to explore areas like renewable powered sources, optimization of transmitting power, reduction in contention levels for energy saving, ways to overcome battery limitations, avoidance of any kind of leakages etc. for sustainable communication. Energy efficient ICT will not only create economical-ecological environment but would also encourage advancement of communication technologies in developing nations.

A. Energy Aware BS

BSs consume substantial portion of energy in wireless networks. A comprehensive review of energy efficient BSs with sleep-mode techniques in cellular networks is presented in [194]. Though, most of the previous work on energy efficiency are related to legacy wireless networks, similar concepts need to be extended to 5G networks as well. As 5G is yet to be deployed, integrating sustainability could be set as a rule. Authors of [195] propose traffic variation based BS deployment scheme, by analytically evaluating network energy consumption. In [196] green performance of small cells, with respect to resource allocation, interference mitigation, outage rates, and energy efficiency is analyzed for achieving the best uplink and downlink user performance. Reduced energy consumption and intercell interference are observed for LTE networks with small cells in [196]. Cell zooming technique for cost and energy effective cellular networks is proposed in [197]. In cell zooming, cell size is dynamically changed based on traffic load [197]. Power ratio based consumption model for green cellular networks, with adaptive traffic load balancing, is proposed in [198]. Results of [199] show that while offloading traffic from macro cells to energy efficient green cells, QoS is not compromised, given the outage constraint are applied. Moreover,

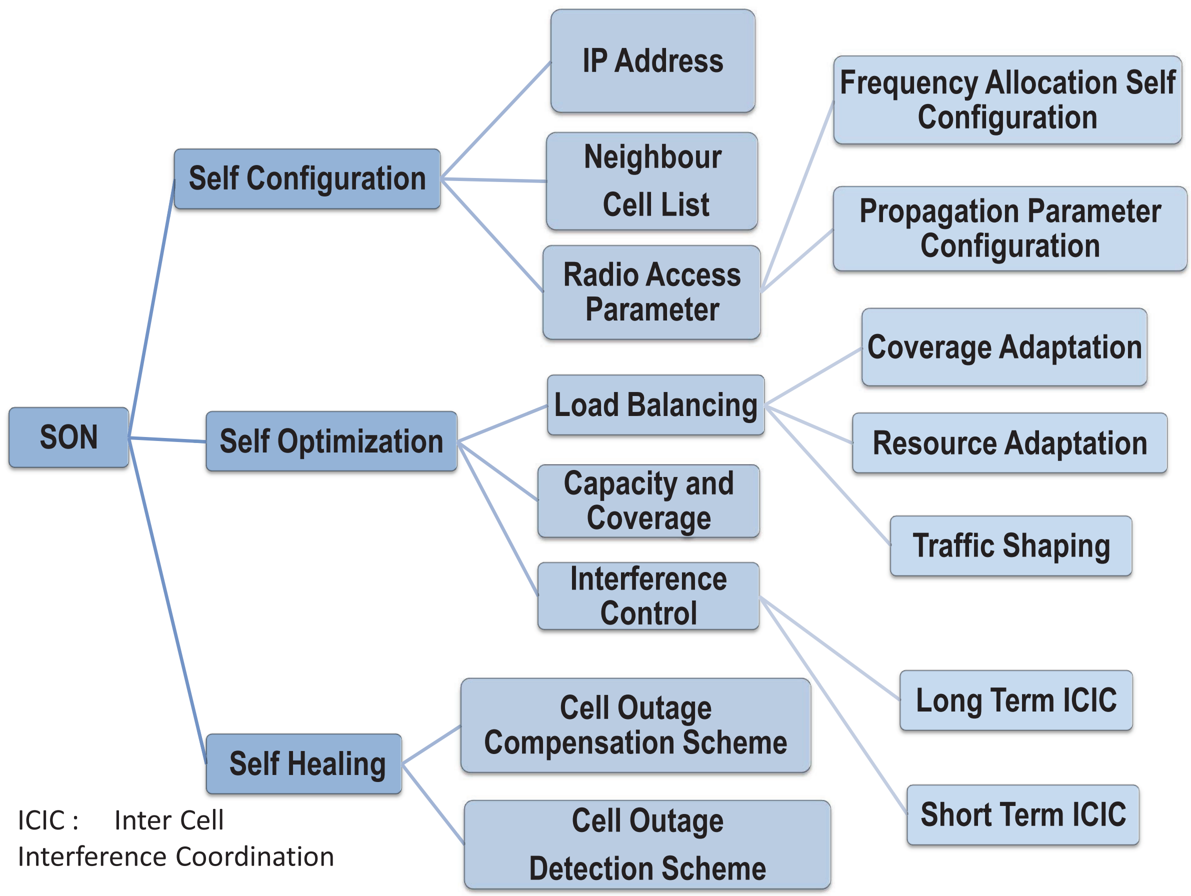

Fig. 29. Major Ongoing Trends in Self Organizing Networks.

TABLE VIII
OVERVIEW OF QOS, QOE, AND SELF-ORGANIZATION

Work Area	Related Work	Key Points
Reinforcing Quality of Service (QoS)	[169], [170], [171], [172], [173]	•Guarantee for high QoS/QoE •Colored conflict graphs •Spare resources for QoS improvement •Dynamic bandwidth allocation
Refining Quality of Experience (QoE)	[6], [15], [19], [168], [174] to [182]	•UHD/3D video content •User satisfaction •Interactiveness, product feel, ability to serve purposes •Predictive model of user QoE •SDN/cloud •Topology management
Self Organizing Networks	[107], [126], [183] to [190]	•Self configuration •Self optimization •Self healing •Big Data empowered SON (BSON) •Centralized SON •SON function performance model •Online/offline SON •eDNA/eCells

it is suggested that small cell BS can be powered by renewable energy sources, like, solar panels or wind turbines [199]. Lifetime of wireless devices could be extended by incorporating energy harvesting from ambient sources. However, for QoS constrained wireless applications, harvesting energy from these sources might not be vaiable [200]. Fig. 30 shows Docomo Eco Tower [201]–a solar powered BS. The hybrid systems exploit advantage of combining renewable energy resources at BS, especially in remote locations [202]. We believe energy harvesting from renewable sources has a lot to offer for catering green revolution in 5G networks and thus, an organized investigation would result in substantial energy saving.

For diverse and dynamic 5G wireless systems, involving many cells, efficient topology management becomes crucial. A centralized scheme requires to collect information of the entire network by central controller [203]. Minimum energy for random deployment can be achieved by a distributed protocol, with dynamic, reconfigurable links [204]. An adaptive traffic

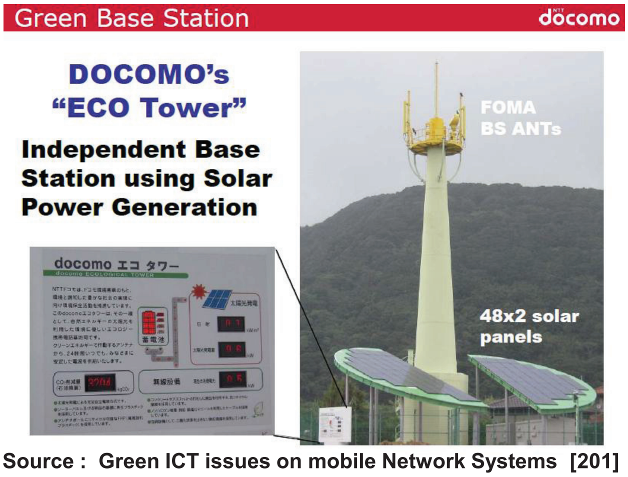

Fig. 30. Docomo Eco Tower [201]–An Example Green BS.

perception based topology management scheme is proposed in [203]. The proposed eNB is self driven and takes decision based on local traffic changes without any load information exchange. A good QoS and substantial power saving is observed by such self organizing systems [203]. A new cloud-aware power control algorithm is proposed in [205] for cloud enabled small cells. Energy consumed by hardware constitutes bigger part of the total energy consumption [206]. Therefore, researchers from Germany believe in shutting down of infrastructure nodes (or parts of it) with respect to traffic, as an important design aspect of energy-efficient wireless architecture. Authors advocate consideration of network infrastructure as a resource that could be occupied or released on demand [206].

B. Energy-Efficient Backhaul

To reduce manual interference and energy consumption, complex 5G network should have self organizing backhaul links [207]. A cognitive backhaul deployment scheme is proposed in [207]. Demand fluctuations result from dynamic backhaul link selection. This can be mitigated by reinforcement learning based resource assignment and topology management schemes [207]. Power and cost benefits are gained by using multiplexing backhaul [31]. Same frequency (inband), point to multipoint and NLOS mm-wave backhaul is presented in [31]. To make sure that backhaul does not become a bottleneck for green 5G wireless networks, it is viable to consider a mix of efficient technologies. Fibre, microwave or copper can be selected based on available infrastructure, cost, spectrum, operators, business model and QoS requirements. While wired backhaul offers advantages of higher reliability and capacity, it is neither a flexible nor an economical solution to dense 5G deployments. On the other hand, the wireless backhaul may suffer from unreliability issues. Moreover, the power requirements by dense wireless backhauls are yet to be emulated. Therefore, we believe formulations of efficient and viable backhaul solutions for small cell and site specific networks need a persuasiveness effort by the research community.

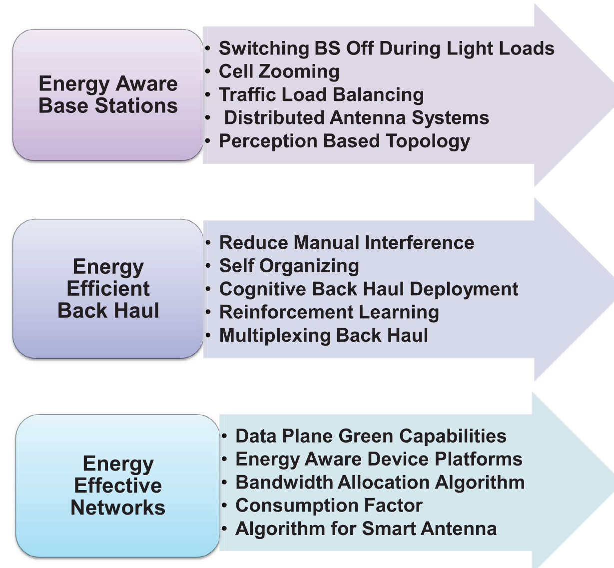

Fig. 31. Energy Efficiency in 5G Wireless.

C. Energy and Cost Effective Network

Success of future 5G roll out does not only depend on sophisticated architecture, but also on network's capabilities of performing complex operations in a scalable and energy efficient manner. Authors in [206] believe in sustainability analysis based on energy requirement by network operations, in contrast to analysis based on energy radiated by antennas in legacy networks. Fig. 31 delineates major research works in energy efficiency. A comprehensive review on green networking is presented in [192]. Innovative protocols, services and control to reduce and monitor third party energy wastage boosts network efficiency [208]. Green capabilities like idle logic, performance scaling and smart sleeping are key factors for the development of energy aware device platforms [208]. Energy spent on packet transmissions could be significantly reduced by minimizing the consumption rates. Energy consumption depends on factors like transmission power, transmission time, channel conditions, coding and modulation [173]. Other factors, like error detection probability, noise, interference, operating points and spectral efficiency should also be considered during analyzing performance versus efficiency tradeoff [209] in future 5G networks. A scheme for reducing energy consumption by novel bandwidth allocation algorithm is proposed in [173]. A figure of merit, called Consumption Factor (CF), is presented in [209], [210] for evaluating power efficiency of a communication link. It is defined as the maximum ratio of data rate to power consumption [209]. In mm-wave channels, CF provides better results for higher bandwidths, provided the signal is not severely attenuated [209]. Incorporating smart routing and broadcasting algorithms to directional antenna models should reduce cost and redundancy [211], [212] in emerging 5G networks. An analysis of various link cost algorithms, using steerable, switched beam antennas, shows no performance degradation [212]. This provides insight into the algorithm design for smart antenna. Novel broadcasting algorithms [213], for directional antennas, result in lower cost, redundancy and energy

TABLE IX
SUSTAINABILITY AND ENERGY-EFFICIENCY IN 5G WIRELESS NETWORKS

Work Area	Related Work	Key Points
Energy Aware BS	[194], [195], [196], [197], [198], [199], [200] - [206]	•Power saving green BS •BS sleep mode techniques •Traffic variation based BS deployment •Cell zooming •Traffic load balancing •Use of renewable sources •Adaptive traffic based topology
Energy efficient backhaul	[31], [207]	•Self organizing backhual •Multiplexing backhual •In band point to multipoint •mm-wave backhaul
Energy and Cost Effectiveness	[173], [192], [206], [208], [209], [210], [211], [212], [213]	•Innovative protocols •Green data plane •Bandwidth allocation algorithms •Consumption factor •Link based cost analysis
C-RAN and H-CRAN	[49], [191], [214], [215], [216], [217]	•Paradigm changes •C-RAN for user centric coverage •Power efficient radio heads •Heterogeneous CRAN

consumption. The concepts applied to directional antennas in conventional environment could be extended to 5G as well.

D. C-RAN to Reduce Overheads and Energy Drains

Efficient operations of ultra dense 5G networks, with a new air interface demand significant paradigm changes in baseband and radio frequency [214]. Recently liquid cells, soft cells and phantom cells [191] are emerging as new potential radio access architecture. Emerging C-RAN architecture, for user centric coverage, reduces overhead and energy consumption [191]. The cloud architecture, explained in Section III, enables simplification of conventional cell sites and shifts all processing to the centralized cloud data center [49]. Hence, conventional sites are transformed to power efficient radio heads [49]. While various C-RAN integrated mobile fronthaul and backhaul architectures are compared in [215], researchers in [216] point at expected increase in energy cost and carbon footprints at the data centers. Workload prediction, virtual machine placement along with workload consolidation, and resource overcommitment are discussed for energy-efficient management of cloud centers in [216]. Turning more number servers into lower power states and increasing the use of the already active servers, enables high energy savings in cloud data centers [216].

HetNets, discussed in Section III, simultaneously improve both the coverage and capacity. Heterogeneous C-RAN (H-CRAN) combines HetNet and Cloud architecture. Energy efficient resource allocations in H-CRAN is explored in [217]. Valuable energy saving is feasible by gradual evolution of C-RAN and its integration into the wireless networks [215]. For improvement of energy efficiency in H-CRAN, authors in [217] characterize user association with RRHs and high-power nodes. Energy-efficient optimization problem is formulated as a nonconvex objective function for the orthogonal-frequency-division multiple- access-based H-CRANs, with special emphasis on resource assignment and power allocation. Energy-efficient resource allocation solution is obtained by reformulation of an equivalent convex feasibility problem using Lagrange dual decomposition method [217]. We believe such innovative ways would allow development of energy aware 5G networks. A planned proactive approach with green as a norm should lead to a sustainable 5G communication. Major sustainability features and related works are listed in Table IX.

VIII. FIELD TESTS, TRIALS AND SIMULATIONS

In this section we provide a consolidated survey on important field trials, drive tests and simulation experiments for understanding 5G network evolution and associated mm-wave channels. We also highlight summary of research works and trials in the field of C-RAN and H-CRAN. Fig. 32 demonstrates major parameters, used for mm-wave channel measurements.

A. Demystifying mm-wave Propagation Measurements

Understanding of mm-wave propagation characteristics is necessary for creating the standard channel model for emerging 5G networks [28], [218]. Unfortunately, the volume of references for outdoor radio propagation models in mm-wave frequency band is very limited [218]. The study of propagation characteristics in different external environment is recently carried out in the University of Texas and New York Polytechnic campuses, at 28 GHz, 38 GHz, 60 GHz and 73 GHz bands, by using sliding correlator channel sounder [76], [78], [219], [220]. Responses of propagation parameters, like path loss, delay spreads, multipath and fading factors are observed for dense and light urban environments using sliding correlator channel sounder [76], [78], [219]. Penetration losses through various common building materials at 28 GHz mm-wave channels are summarized by Rappaport and his team in New York Polytechnic Institute campus, Brooklyn [28]. The test included transmission of +30 dBm power, using a steerable 10° beamwidth horn antennas of 24.5 dBi. Mechanically rotated 30° beamwidth horn antennas of 15 dBi are also considered for transmission. Similar horn antennas are used at the receiver as well. Penetration losses are analyzed by comparing the

Fig. 32. Measurement Parameters for Understanding Channel Characteristics.

transmitted and received power. At 28 GHz the reflection coefficients for different building materials are also compared [28]. Measurement based detailed statistical modeling of key channel parameters is performed for a realistic assessment of mm-wave micro and picocellular networks in a dense urban deployment [221]. It shows that, even in highly NLOS environments, strong signals could be detected 100–200 meters from BSs.

To emulate LOS and NLOS cases in a vehicular environment, in frequency range of 0.5 $\sim$ 16 GHz, a Vector Network Analyzer (VNA), with omnidirectional antennas, is used in [222]. Average Power Delay Profiles (APDP) are employed to extract the RMS delay spread. APDP is also considered to study scattering phenomenon at 28 GHz [77]. Researchers at Virginia Tech proposed Sampling Swept Time Delay Short Pulse (SSTDSP) channel sounder for illuminating walls with 7.5 ns pulse in 28 GHz frequency band [77]. The results suggest possibility of reasonable signal strength, when reflected from smooth surfaces [77]. Variety of obstructions in realistic environment is evaluated for emerging 'cell per room' concepts [69]. Theoretical free-space path loss, local area average path loss, local area min/max path loss, and local area min/max/average RMS delay spread are recorded for different transmitter-receiver locations in a single room environment [69]. The setup consists of channel sounder with pyramidal horn antennas at transmitter and receiver [69]. VNA based channel sounder is employed to estimate channel characteristics by calculating Channel Transfer Function (CTF). It uses parameters like, transmitter/receiver distance, number of multipath components, standard deviation of the scatterer location, reflection loss, transmit power, carrier frequency, gain patterns and system bandwidth [74]. The model is validated by comparing modelled and measured root mean square delay spreads (τ_{RMS}). The modelled τ_{RMS} is calculated using Channel Impulse Response, which in turn is derived from CTF [74].

Rappaport and his research team, in New York Polytechnic, has used a spread spectrum sliding correlator channel sounder for peer to peer, cellular and point to multipoint measurements at mm-wave frequencies [30], [76], [78]. For peer to peer study, average PDP measurements are made at every receiver location for different transmitter-receiver angle combinations at 38 GHz and 60 GHz [78]. Elevation angles for both transmitter and receiver are also incorporated for channel measurements. Scatter plots of path loss versus transmitter-receiver separation are analyzed in [78]. For point to point propagation at 38 GHz, horn antennas are employed at transmitter and parabolic reflector antennas are used at the receivers [76]. Relative received power, excess delay time, time and angle of arrival are employed to estimate the multipath characteristics [76]. Using steerable beam antennas of various gains and a variety of transmitter-receiver locations, coverage outages are studied in [30]. Extensive measurements of AOA, path loss and multipath delay spreads are conducted. Elevation of transmitter with respect to receiver is also considered in different field measurements. Interestingly, no significant outage is observed for measurements within 200 meters distance, irrespective of high or low BS transmitter location [30].

Channel sounder with horn and patch antennas are employed for understanding the obstruction phenomenon arising from human body [70] at 60 GHz. It characterizes parameters like attenuation, temporal fading, coherence bandwidth and delay window for analyzing the shadowing effects, arising from human activities [70].

Evaluations of wideband mm-wave outdoor propagation measurements at 28, 38, 60, and 73 GHz for BS to mobile, BS to BS (backhaul), peer-to-peer, and vehicular (V2V) scenarios are consolidated in [220]. For 28 GHz propagation, the very first 3-D measurement based mm-wave statistical channel impulse response model is presented in [220]. The data and models proposed in [220] are expected to assist researchers in the development of channel models and system analysis for emerging mm-wave small cell wireless communication systems.

In depth understanding of mm-wave channels is still in its nascent stages. As an elementary estimate, Farooque and his team at Samsung Electronics considered a 20 dB additional loss to address NLOS, shadowing and fading [36]. System level simulation aids in study of mm-wave performance with horn antenna array, arranged in hexagonal prism at BS and patch antennas at mobile device. Using transmitter and receiver power, distance, gain, propagation loss, fading, bandwidth, noise, SNR and efficiency, a typical link budget is estimated in [8], [33], [36]. Assuming round robin scheduling, simulation results with 40 dBm transmission power and a single stream transmission show a high throughput of 8.37 Gbps [36]. The link budget analysis, in [33], achieved a data rate of 2 Gbps over 1 km in urban mm-wave environment. For link improvement in NLOS scenario, Path Loss Exponents at 28 GHz and 73 GHz are analyzed for bi-beam, tri-beam and quad-beam combinations [223]. Fig. 33 represents major parameters for link budget analysis. 5G enhanced Local Area (eLA) [224]

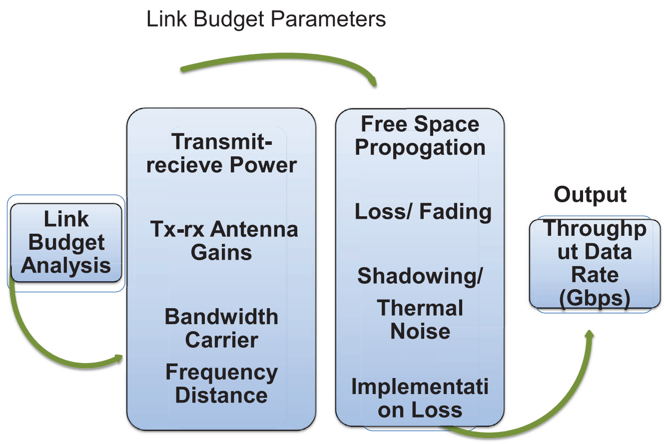

Fig. 33. Major Parameters for Link Budget Analysis.

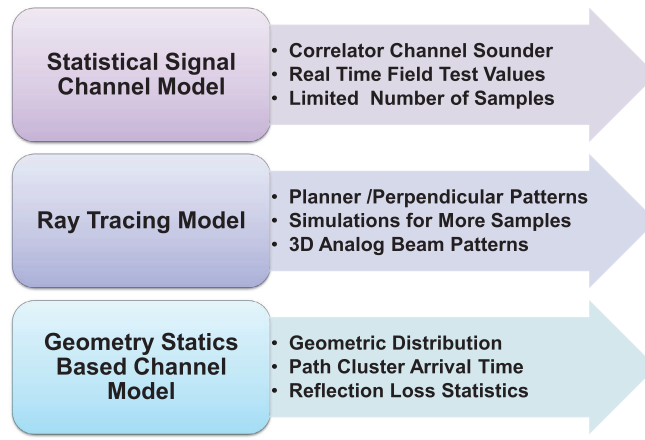

Fig. 34. Various Approaches for Channel Extraction.

access is designed to satisfy the requirements of 10 Gbps peak data rates, $\geq$ 100 Mbps cell-edge rates and $\leq$ 1.0 msec latency.

B. Simulation-Based Channel Extraction

Measurement campaigns are being carried out by researchers and industries to experimentally gather and analyse huge amount of data from different sites for market ready reliable mm-wave channel model. Although, the empirical experiments are accurate methods to extract reliable channel characteristics, number of field samples is a major limitation [225]. Ray-tracing simulation presents an alternate methodology for deriving the radio propagation characteristics [218]. It is expected to perform even better than hardware trials when measuring propagation results in shadow zones, where equipments cannot sense the signal power due to hardware limitations [225]. Moreover, there is no significant loss of accuracy between field measurements and ray-tracing simulations for wireless communication channel properties, such as path loss and RMS delay spreads [220], [226]. Received power results from the ray-tracing simulations were found to be in agreement with measured values in [226]. A simple and accurate propagation prediction method with low computational complexity is achievable by 3D ray launching. It uses geodesic spheres and distributed wavefronts to simulate electromagnetic propagation [220]. 2D and 3D ray tracing simulations have been used traditionally as well to avoid field test expenses. However, all the previous works are focused primarily on radio frequencies in sub mm-wave (less than 6 GHz) frequency band [218]. The work in [218] considers 3D analog beam patterns, by combining separately obtained planar and perpendicular patterns. In [225], authors use ray tracing simulations to derive large-scale channel model. Downtown of Ottawa and New York University (NYU) campus are modelled in 3D topology to re-evaluate line-of-sight probability, Ricean K factor, path loss equation and standard deviation of shadow fading based on the 3D distances [225]. Ray tracing in an outdoor environment is adopted to obtain multiple clusters of Multi Path Components (MPCs), and discrete isolated MPCs, to illustrate the performance of joint spatial division and multiplexing schemes in [219]. Recent 3GPP study item is focusing on 3D-channel model for elevation beamforming and full dimensional MIMO [227]. However, ray tracing approach becomes inflexible for large scale system level simulations, dealing with complex environment [117]. Hence, geometry statistics model, a combination of both ray tracing and statistical based channel, is proposed in [117]. It considers geometric statistics, like reflector geometric distribution, its relation with path cluster arrival and reflection loss statistics for channel modeling. Researchers in [228] have proposed 3GPP-like channel models for 28 GHz NLOS environments, by using synthesized timing from 3D ray-tracing. The modeling is based on empirical distributions of time cluster and spatial (lobe) channel [228]. We have listed the key features of channel models in Fig. 34. These channel models are fundamental to LOS/NLOS signal propagation at high frequencies in outdoor environments and open a plethora of possibilities for further investigations.

C. Beyond Channel Extraction

In [100], [83] authors have diluted explicit estimation of actual wireless channels and emphasised on a practical antenna training protocol for SDMA network. They proposed Single Value Decomposition (SVD) based multi-stage iterative method for antenna training [83], [100]. Two independent beamforming vectors enable transmit precoding and receive combing for SVD based systems [83]. In [100], Rayleigh fading channel is assumed for SDMA iterative antenna training protocols at 60 GHz. Samsung Electronics has recently claimed 7.5 Gbps data rate in stationary field trials [229]. It has also demonstrated an uninterrupted 1.2 Gbps data rates in mobile drive tests. The tests were conducted in indoor as well as outdoor settings at 28 GHz using indigenous hybrid array technology [229]. More recently, Rappaport's experiments also pointed out the possibility of 32 small radiators at smartphone to overcome space limitations in handset, while providing 360° coverage [2]. These field tests and trials are gradually setting up the stage for 5G roll out before 2020. Important features for design, testing and measurements of Physical Layer parameters are highlighted in Table X.

TABLE X
MAJOR PARAMETERS FOR DESIGN AND TESTING OF mm-WAVE COMMUNICATIONS

Design Parameter	Key Points
Carrier Frequency	• mm-wave in 3–300GHz • Frequencies: {5, 16, 28, 38, 60,73} GHz
TX-RX Distance	• Small distances: {200, 250, 500} Km
Antennas at BS	• Horn antenna • Pyramidal horn • Horn antenna array in hexagonal pattern
Antennas at mobile	• Horn antenna • Patch antenna • Parabolic reflector antenna
TX- RX power	• Gain pattern of transmitter antenna • Gain pattern of receiver antenna • Affects link quality
Environment	• Outdoor with common building materials concrete, drywall, tainted glass, clear glass etc. • Indoor with office boards, human activity etc. • Vehicular ad hoc networks
Transmitter elevation	• Transmitter position with respect to receiver.
Beamforming	• Steerable at different angles • Mechanically rotated antennas • Beam alignment & antenna training
Multipath Component	• Reflection from randomly placed scatterers. • Standard deviation of scatterer location.

D. Trials in C-RAN

As mentioned in Section II and Section VII, C-RAN provides improved system capacity and lower energy consumption. Most of the major wireless vendors and operators, like China Mobile, Huawei, Nokia, Samsung, Alcatel Lucent and Qualcomm have already shown significant interests in C-RAN technologies [230], [231], [214]. Operators like, NTT, KT, France Telecom/Orange, Telefonica, SoftBank/Sprint and China Mobile are also in support of small cell C-RAN [230]. China Mobile Research Institute, the pioneer of C-RAN, has published comprehensive survey on technology, advantages and challenges of C-RAN in [48]. They proposed a step-by-step approach to construct C-RAN for connecting $8 \sim 12$ macro sites with a maximum ring range of around 40 km [48]. China Mobile has already developed a C-RAN prototype in collaboration with IBM, ZTE, Hwawei, Intel, Datang Mobile, France Telecom Bejing Research Center, Bejing University of Post and Telecom, China Science Institute. The prototype successfully completed interoperability with user equipment using GSM-TDSCDMA [48]. In [215], energy consumption in backhaul and fronthaul optical access are compared using infrastructure owned by Orange, France. The experiments consider a 15 Km coverage area with unlimited fibres per link [215].

Some of the important technologies for C-RAN are elaborately discussed in [49]. Multi-Service small cell cloud Radio-Over-Fibre (RoF) access system is proposed by Gee-Kung Chang and his team in Georgia Institute of Technology [230]. Preserving independent backhaul configurations and using Wavelength Division Multiplexing (WDM) techniques, an in-building testbed, with two coexisting operators, was demonstrated in [230]. In [232], Samsung Electronics discusses importance of Cloud, in information and mobile technology with a focus on cell edge performance and network densification for LTE-Adv systems. Emphasis is laid on redesigning the platforms for "content-centric networks" [232].

E. H-CRAN Proposals

We have already highlighted HetNet and cloud technologies for 5G cellular networks in Section II. Communication between adjacent BSs is a significant challenge in HetNets. By combining advantages of HetNets, C-RAN and SDN, H-CRAN [231] is emerging as a key component in 5G communications [214]. Stochastic geometry, fronthaul constraints, resource allocation and standard developments are analyzed in [231]. Association of radio receiver heads and high power nodes with soft fractional frequency reuse is used in [217] for OFDMA based H-CRAN networks. Authors have proposed Lagrange dual decomposition method for non-convex fractional programming optimization to resolve energy efficient resource allocation problem in H-CRAN [217]. "Liquid Radio" - a flexible network design for Gbps data rates requirements of 5G networks, is proposed by Nokia Siemens Networks [233]. System-on-a-Chip (SoC) design provides a promising, yet simple antenna configurations for H-CRAN architecture [233]. Heterogeneous networks for off loading traffic and seamless blending of technologies is advocated in [233]. Software-defined H-CRAN design with new entity 'Node C', for different RANs of legacy communication is proposed in [214]. Node C is evolution of Node B (BS) with processing and networking functionalities for newly designed RRHs. A comprehensive summary of H-CRAN, including application architecture, system components, key technologies, large scale spatial signal processing, self organization and fronthaul optimization is presented in [214]. We provide a summary of the major field experiments related to 5G wireless in Table XI.

IX. OPEN ISSUES AND CHALLENGES

5G technological revolution is expected to have a profound impact on the future wireless communications. Comparing to the existing 3G/4G cellular systems, next generation 5G wireless have significant different features with more stringent performance and QoS requirements. Table XII provides this feature comparison between legacy and 5G wireless networks, in terms of major parameters. Hence, there are a wide variety of opportunities for future research works in wireless cellular systems. In this penultimate section we point out the major open research issues in emerging 5G networks.

A. 5G: Open Research Challenges

Ultra high data rates, extremely low latency, anywhere anytime coverage, huge energy saving–most of the promises made by 5G are associated with their respective challenges. We mention the key research issues raised by 5G wireless below:

1) *Introduction of mm-wave Spectrum:* 5G is expected to introduce mm-wave spectrum ($3 \sim 300$ GHz). Propagation characteristics of mm-waves are a little less conducive for wireless communication, as compared to current "beach-front spectrum" [7]. However, with the enormous bandwidth to satisfy overwhelming capacity demands, it offers a very compelling long term solution [9]. Hence, the very first challenge is to analyze the

TABLE XI
FIELD TRIALS AND SIMULATION EXPERIMENTS RELATED TO 5G WIRELESS NETWORKS

Work Area	Related Work	Key Points
Demystifying the Channel	[8], [28], [30], [33], [36], [69] [70], [74], [76], [77], [78] [218] till [224]	• Penetration losses comparison for different Tx-RX power. • Study of reflection coefficients for various building materials. • Vector network analyser for vehicular environment. • Average power delay profiles to extract the RMS delay spread. • Sampling swept time delay short pulse channel sounder. • Space path loss, local area average path loss. • Local area min/max path loss, min/max/average RMS delay spread. • Channel transfer function. • Different elevation angles for both transmitter and receiver. • Scatter plots of path loss v/s tx-rx separation. • Coverage outages. • Extensive measurements of AOA, path loss and multipath delay spread. • Link budget analysis.
Simulations for Channel model	[117], [218], [219], [220], [225] [226], [227], [228]	• Ray-tracing Alternate methodology for deriving the radio propagation. • Expected to performs better when measuring propagation in shadow zones. • 3D ray-tracing simulations for channel extraction at 28GHz. • planar and perpendicular patterns. • Simulation in agreement with measured values. • Geometric statistics model. • reflector geometric distribution and its relation for channel modeling
Beyond Channel Extraction	[2], [83], [100], [229]	• Practical antenna training protocol for SDMA network. • Single value decomposition based multi-stage iterative method. • Rayleigh fading channel assumption for SDMA iterative antenna training. • 3D ray-tracing simulations for channel extraction at 28GHz. • 7.5 Gbps data rate in stationary environment.
Trials in C-RAN	[48], [49], [214] [215], [230], [231], [232]	• Major vendors: China Mobile, Huawei, Nokia, Samsung, Alcatel, Qualcomm. • Major Operators: NTT, KT, France Telecom/Orange, Telefonica, SoftBank/Sprint. • Stepped approach to construct centralized network. • 8 to 12 macro sites centralized with maximum ring range of 40km. • Successful prototyping using GSM-TDSCDMA. • Energy consumption comparison: backhaul and fronthaul. • WDM techniques, an in-building testbed with coexistence of two-operators. • Redesigning of platforms for “Content-Centric Networks”.
H-CRAN Proposals	[214], [217], [231], [233]	• Stochastic geometry, fronthaul constrains, resource allocation. • Soft fractional frequency reuse for OFDMA based H-CRAN. • Lagrange dual decomposition method - non-convex fractional programming. • “Liquid Radio” a flexible network design (Nokia Siemens Networks). • Node C for converging different rans of legacy communication entities.

TABLE XII
COMPARISON BETWEEN LEGACY CELLULAR NETWORK AND PROPOSED 5G WIRELESS COMMUNICATION NETWORK

Feature	Legacy Cellular Network	Proposed 5G Network	Related Work
Carrier Frequency	Range (700MHz $\sim$ 3 GHz)	Mm-wave spectrum ranging from 3-300GHz	[8], [9], [27], [28], [32], [33]
Radio Network	BS centric	User centric and site specific	[27], [28], [29], [30], [31], [32], [33]
Density/Diversity	Limited	Enormous	[10], [27], [28], [32]
BS Density	High density deployment	Ultra high deployment micro/pico/femto cells	[8], [27], [28], [32], [33], [54]
Site Specific	Not necessarily	Key enabling feature	[28]
Air Interface	Omnidirectional	Highly directional	[27], [32], [33], [34], [35], [36]
Antenna Size	Large	Small antennas	[28], [32], [36], [37], [38], [40], [41]
Antenna Array	Not applicable	Array of small antennas - planner/circular/segmented	[8], [32], [36]- [38], [40], [80], [79]
Beamforming	Not essential	Key enabling technology	[28], [30], [32], [38], [78], [79], [80]
Antenna Training	Not applicable	TX-RX beams should point towards each other	[30], [82], [83], [85]
Channel Model	Available	Under study	[28], [69], [76], [77], [117], [218]
Penetration	No complications	mm-wave don't penetrate common materials/ humans	[8], [28], [68], [69], [70], [71]
LOS Communication	Not essential	Key enabling technology	[28], [30], [32], [76], [78]
Multipath	No complications	Assist in NLOS communication	[28], [70], [73], [74], [75], [77], [78]
MIMO	Limited MIMO capabilities	Massive MIMO	[8], [90], [91], [92], [95], [102]
Control and user plane	Single entity	Split plane (SDN)	[41], [42], [44], [45]
Cloud RAN	Improves performance	Simplifies BS for ultra dense deployment	[42], [46], [47], [49], [50], [51]
Multiple Access	TDMA/FDMA/CDMA/OFDM	SDMA/SCMA/IDMA/GFDM/FBMC/UFMC	[100], [101], [106] - [112]
MAC Directivity	Not applicable	DMAC/ Multihop MAC/ DNAV/ Directive RTS/CTS	[6], [34], [103], [104], [105]
Random Access	Synchronized	synchronous and asynchronous signalling	[24]
STR	Not feasible	Proposed	[6], [10]
Data Rate	Mbps	Gbps	[8], [10], [13], [15], [19], [16] [27], [28], [32], [33], [36], [229]

physics behind mm-waves, like atmospheric absorption, diffraction, propagation, Doppler, scattering, refraction, reflection, multipath and attenuation.

2) *Unavailability of Popular Channel Model:* Development of 5G mm-wave mobile communication requires fundamental understanding of radio channels [28]. Researchers are studying channel models for outdoor, indoor and fixed mm-wave communications. There is still an impending need for in depth investigation into the mm-wave channels in outdoor environments to perceive

effects of path loss, angular spread, delay spread, NLOS beamforming and blocking issues [36]. An in depth analysis of channel models lay foundation for new methods of air interface and multiple access [28].

3) *Site Specific Propagation:* mm-waves propagation is heavily dependent on environmental conditions, receiver and transmitter locations [30]. Thus, site specific cell design could be a key feature of 5G deployment. As this issue is not much investigated in legacy cellular systems, it requires further research.
4) *Antenna Array Design:* Smaller wave length of mm-wave frequencies, allow placement of hundreds of antenna elements in an array on a relatively small physical surface [28]. Large antenna arrays are capable to steer the beam energy and collect it coherently [7]. Thus, one of the focus of on-going research is directional narrow-beam communications. It changes the entire notion of the "cell" concept. There are abundant research challenges for architecture design of both BS and mobile device for attaining the desired directivity.
5) *Beamforming and Beam Training:* Directive beam is formed by controlling beamforming weights, depending on the beamforming architecture [38]. Design of real-time baseband modem, mm-wave RF circuitry and related software to facilitate beamforming technologies are interesting areas of research. Appropriate beam selection is required to ensure proper alignment of selected beams. It will be interesting to design and analyze performance capabilities of beamforming (BF) training protocols. Moreover, hidden terminal problem, neighbors location detection problem are inherent to directional transmissions. These enhanced complications need to be resolved.
6) *Massive MIMO:* Another serious challenge is to realize the vision of massive MIMO. It requires a completely different BS structure with a myriad of tiny antennas, driven by low-power amplifiers. Adoption of effective massive MIMO algorithms for 5G implementation could represent a major leap in future communications. Further research in theoretical studies, simulation, and testbed experiments are extremely vital.
7) *Novel Multiplexing:* Desirable spatial beam patterns can readily secure Spatial Division Multiple Access (SDMA). Benefits of SDMA, like reduced interference and multipath interference mitigation are crucial for small cell deployment and NLOS. Further research, not only in SDMA, but also in SCMA, IDMA, FBMC and GFDM is necessary for achieving low latency and high performance in future 5G networks.
8) *Non-Orthogonality:* Heterogeneous connectivity, densification and novel applications (M2M, IoT, IoV, FinTech, health monitoring, smart grids etc.) would make rigid paradigms of synchronism and orthogonality a huge challenge in future mobile scenarios [24]. Research efforts in non orthogonality and asynchronism domain would help achieve low latency requirements of 5G networks.
9) *Network Densification:* Small cell (heterogeneous) architecture is underlining feature of 5G. Thus, BS density is expected to be very high. Understanding of fast interference coordination and cancellation, SDN, Cognitive Radio Networks, and Self Organizing Networks (SONs) [28] enable dense network management. Although these are promising techniques for 5G communications, their deployment for 5G scenarios is yet to be explored.
10) *Backward Compatibility:* There is enormous scope for discussion on overall 5G architectural requirements. With massive deployment of LTE, the possibility of 5G architecture in any backward compatible way would be greatly beneficial and vital. Along with standalone 5G systems, researchers are exploiting feasibility for integration of 5G with legacy 4G/3G networks.
11) *C-RAN and H-CRAN:* C-RAN offers cost effective and energy efficient solution for dense 5G deployment. There is very little work explaining the contribution of C-RAN to 5G. Moreover, many researchers are working on combination of heterogeneous networks and C-RAN, termed as H-CRAN. It is more challenging to design 5G networks incorporating advantages of C-RAN and H-CRAN.
12) *Low Latency and QoE:* A round trip latency of 1 ms [10] is identified as a requirement of 5G. However, there is very little work explaining ways of achieving this stringent requirement. Low latency is also crucial for achieving high QoE. Investigation of QoE presents a number of research challenges due to it's subjective nature.
13) *Energy Efficiency:* Cost and energy consumption are major considerations for 5G. In lieu of high BS densities and increased bandwidth, power and communication overheads need to be taken care of. Despite a variety of work in energy efficiency, it still offers huge scope for improvisation, especially for novel 5G concepts. C-RAN and energy efficiency techniques could help in performance improvements. Research in energy aware realistic 5G model promises success in energy savings. Incorporating green BS, powered by renewable energy should be beneficial. But this involves further new research challenges.
14) *5G Applications:* 5G promises a plethora of new applications, with the ultimate vision of emerging IoT, incorporating billions of connected devices. This results, in a unique challenges of connection and configuration [140]. Previous works have mostly considered each application individually. Therefore researchers are encouraged to further explore various combinations of major 5G applications.
15) *Standardization:* Multiple forums and projects have been working to provide structure to 5G vision. 5G standardization is yet to start formally. However, a tentative time line is agreed upon.

A summary of open research issues crucial for 5G wireless networks are listed in Fig. 35.

B. Discussions on Future Research Directions

- Our detailed survey on research works in 5G communications reveal that mm-wave spectrum has a huge potential to provide solutions for high capacity demands. We

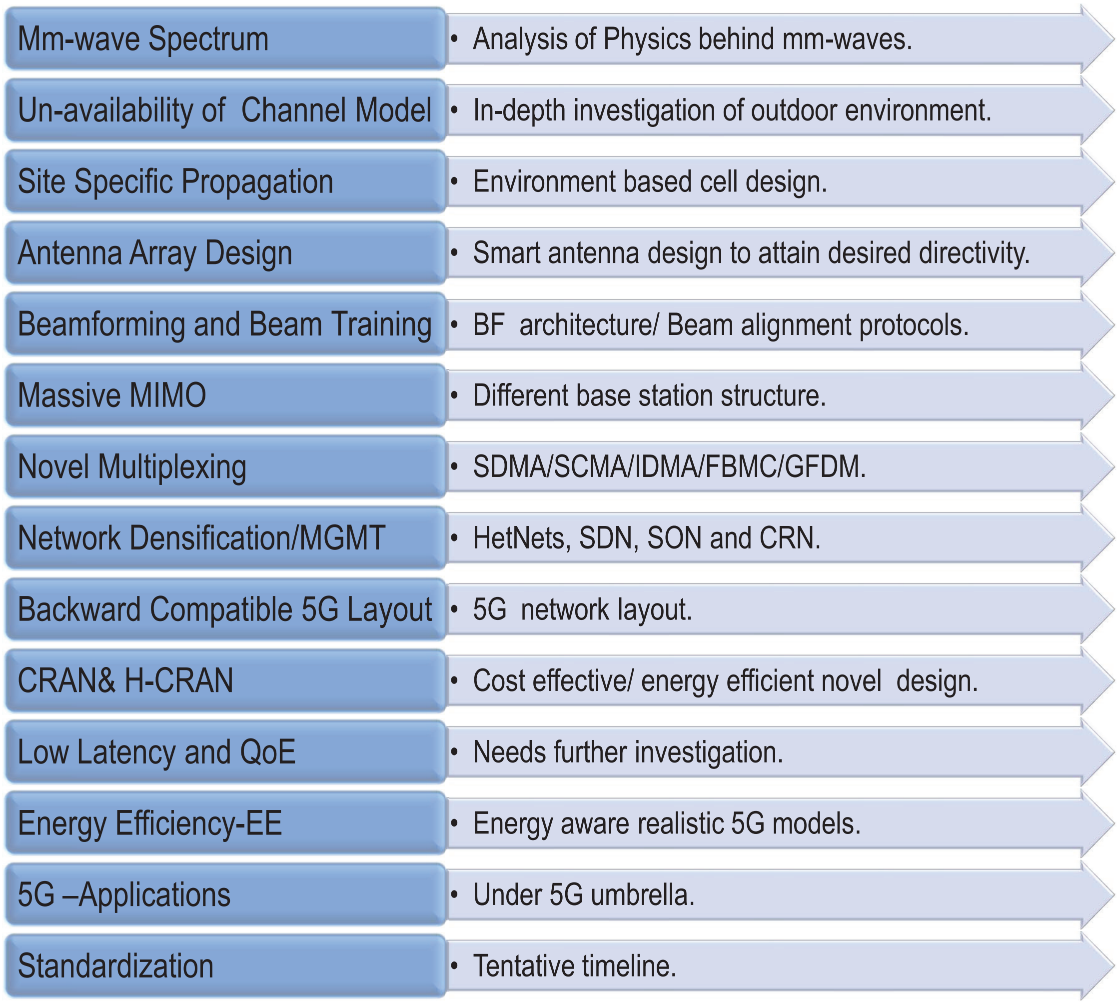

Fig. 35. 5G Open Issues for Future Research.

believe revisiting physics behind mm-wave would further enhance the knowledge base. Spectrum from 3 GHZ to 300 GHz is large and might show variations in itself. In depth knowledge in spectrum characteristics not only facilitates better network design, but also enable effective spectrum allocation. It further assists in creating effective channel models. Many research works are focused on investigating the behaviour of mm-wave wireless channels. Field trials, acquisitions, modeling, simulations and reasoning in different realistic environments should assist in channel extraction.

- Key components of 5G, like network densification and user centric requirements, will gradually enable a paradigm shift in network architecture, management and control. Large beam steering antenna arrays are regarded pivotal in 5G network design and need immediate attention. We believe incorporating efficient beamforming designs at BS, effective beam training protocols, accurate weight computations and reliable error corrections would enable smart antenna design.
- The challenges of dense network design and management could be mitigated through advancements in C-RAN, HetNETs, H-CRAN, SDN, Massive MIMO and SON. While designing aforesaid 5G network, these technologies are to be integrated.
- We feel directivity supporting MAC protocols will enhance spatial reuse and resolve LOS errors.
- As 5G offers availability of huge spectrum, to the emerging spectrum hungry applications, we feel there is an imminent need to put all the desired applications under one umbrella.
- Despite variety of exciting research works to improve energy efficiency, it still remains an open challenge. We believe there is a huge scope for discussions on sustainable 5G networks. With myriad of BSs and enormous connectivity, the problem is more serious in 5G. One appealing possibility is renewable energy powered green BS. Finally, we think that it is almost impossible for any single technology to converge all the requirements simultaneously [10]. Thus, we believe successful commercial roll out of 5G requires a cooperation between

academia and industries to uncover a plethora of new research challenge.

X. Conclusion

Rapid penetration of wireless connectivity, almost exponential increase in wireless data (multimedia) usage and proliferation of feature-rich smart devices are gradually setting the stage for next major cellular evolution towards 5G. Next generation 5G wireless systems are already promising a manifold increase in data rate, connectivity and QoS. A plethora of new applications, like IoT, smart grids and IoV are expected to be supported under the umbrella of 5G systems. In this survey we provide a comprehensive review of cellular evolution towards 5G networks. We begin with pointing out the new architectural paradigm shift, associated with the design of radio network layout, air interfaces, smart antennas, cloud and heterogeneous RAN. Subsequently, we give a detailed description of the underlying physical layer technology. This includes understanding of new physical channels, estimating new channel models with LOS/NLOS, novel antenna design, beamforming and massive MIMO. Next, we discuss the major MAC layer protocols and multiplexing schemes, like SDMA, IDMA and evolution of existing OFDM, required to efficiently support the new physical characteristics. Novel emerging applications, like D2D and M2M communications, IoT, Vehicular communications and Healthcare applications form the major driving force behind 5G. We digress into the details of these killer applications to understand the associated impact on the cellular evolution. As 5G is expected to offer a much better user experience, we highlight the new QoS, QoE and SON features, associated with the evolution of 5G networks. A major concern behind the massive roll out of 5G lies in increasing energy consumption and the associated greenhouse gas emissions and opex. This motivates us to make a review on energy aware BS, energy efficient backhaul and cost efficiency. In order to realize the current state of the implementation, we also look into the major 5G field trials, drive tests and simulations. Finally, we point out major existing research challenges and identify possible future research directions. We believe that our survey will serve as a guideline for major future research works in 5G wireless communications.

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