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Radio Access Technologies for Sustainable Deployment of 5G Networks in Emerging Markets

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Abstract

The fifth generation (5G) mobile-enabled digital transformation, which promises unprecedented high data rates and mobility, improved broadband access, and low latency in cloud services, has huge potential for alleviating poverty, ensuring universal broadband access, and making the transition to a low-carbon economy more feasible in emerging telecommunication markets. However, the operating environment of emerging economies is characterized with majority low-ARPU (Average Revenue per User) multi-SIM subscriber base, diverse settlement patterns ranging from low density rural areas to rapidly expanding ultra-dense urban informal settlements, highly unreliable power grid networks, pure mobile networks built without existing wired infrastructures and rigid regulatory frameworks that stifle business and innovations. In this paper, current research activities on key radio access technologies of 5G are reviewed to evaluate their considerations for the unique attributes and ecosystem of emerging economies. The survey includes ultra-densification of multi-tier heterogeneous networks, millimeter wave (mmWave) communications, massive multiple-input multiple-output (MIMO), spectrum sharing networks, and dynamic backhaul sharing. The contribution of this paper will ensure an inclusive implementation of the on-going 5G standardization towards achieving the envisioned 2030 Sustainable Development Goals (SDGs).

Keywords: 5G; multi-tier heterogeneous networks; millimeter wave communications; massive MIMO; spectrum sharing; SDG

INTRODUCTION

The advent of smart wireless devices has increased mobile Internet access for social mobile applications, and cloud-based services [1]. However, the proliferation of these devices and mobile internet applications is increasingly creating a wide gap between mobile traffic demand and state-of-the-art cellular network capacity. Hence, the need for significant improvement in cellular network capacity to efficiently and effectively deliver better quality of service to both people and connected things. The development of 5G cellular technology will introduce disruptive changes in the main concepts of cellular networks in order to cover broad range of use cases and adequately satisfy the anticipated mobile users' requirements [2, 3]. Unlike in the previous evolution of 2G through 4G, the architecture of 5G cellular networks must be designed with the aim of improving users' experience [4]. Primarily, 5G networks are expected to efficiently support massive (10 to 100 times) ubiquitous connections, provide extremely low (1 ms) latency, and deliver significantly high network capacity [5-7]. Besides conventional voice/data service delivery, 5G is expected to support robust Internet of Things (IoT) and Machine-to-Machine (M2M) communication services [8, 9].

The digital transformation, which runs on the enabling platform of 5G technology, has huge potential for amplifying efforts of developing economies towards achieving envisioned 2030 Sustainable Development Goals (SDGs) [10]. Provision of electronic health (e-health) services will bridge the access gap to medical services in rural areas [11, 12]. Electronic learning (e-learning) platforms offer cost-effective solution to the challenges of access to quality education in developing countries [13, 14]. Enhanced wireless technologies will improve the operational efficiency of 'Internet of Agricultural Things' for more transparent and safer food production and supplies to end hunger [15]. Smart infrastructure provides massive machine-type communication where sensors could be embedded in highways [16].

However, several use cases and contextual attributes that underpin the initial 5G research and standardization [17, 18] are still strongly influenced by early adopters in developed economies. Whereas, emerging markets have some peculiar factors that can frustrate successful deployment of the transformational technology, thereby further pushing the hope of attaining sustainable development to the far future. Most of developing countries are faced with potential obstacles such as a majority low-ARPU (Average Revenue per User) multi-

SIM subscriber base, diverse settlement patterns ranging from low density rural areas to rapidly expanding ultra-dense urban/periurban informal settlements, highly unreliable power grid networks, pure mobile networks built without existing wired network infrastructure, and rigid regulatory frameworks that stifle business and service innovations. This is even more typical of most countries in sub-Saharan Africa. Hence, these unique features of the operating environments must be well accommodated in the on-going 5G research and standardization. To achieve such, deliberate efforts must be taken to adopt technologies, techniques, and efficient methods that adequately account for these extreme factors.

In this paper, we provide an extensive review on the key radio access technologies of 5G with a view of evaluating their considerations for the unique attributes and ecosystem of emerging economies. This include: ultra-densification of multi-tier heterogeneous networks, mmWave communications, massive MIMO, spectrum sharing networks and dynamic backhaul sharing.

The remainder of this paper is arranged in the following order: section 2 reviews current low-cost (affordable) and energy-efficient techniques for 5G network capacity enhancement in emerging economies; section 3 provides the implementation challenges and enumerates future research directions for the practical realization of SDGs in Africa and other emerging markets; section 4 summarizes the review findings of keys techniques that should be implemented in order to incorporate Africa's context into the on-going 5G standardization.

RADIO ACCESS TECHNOLOGIES FOR SUSTAINABLE 5G NETWORKS

A. Ultra-Densification of Multi-Tier Heterogeneous Networks and Mobile Data Traffic Offloading

Considering the growing demand for wireless data traffic in recent years, it may be practically impossible for state-of-the-art cellular network architecture to satisfactorily meet users' requirements in a sustainable manner [19]. Ultra-densification of base stations is one of the simple ways of increasing cellular network capacity. This technique will also enhance self-organizing, minimize cost, and reduce power consumption in future cellular networks [20]. Deployment of low-power nodes is a cost-efficient means of reducing the traffic burden on macro cells in a way to increase the network capacity. 5G radio access networks will employ multiple radio access technologies in a multi-tier heterogeneous environment. This will involve ultra-dense deployment of small cells, relays, and distributed antenna systems that operates on both microwave and millimeter wave bands. It will, in turn, improve the overall capacity of future wireless systems. In addition, 5G network capacity may be further enhanced by carrier aggregation [21, 22]. Also, the outage probability at cell edges of traditional macro cells is usually high due to uneven allocation of network resources. This degrades service delivery for cell edge users. However, the outage probability can be significantly reduced by deploying micro cells, pico cells, or femto cells at the cell edges of macro cells.

Several efforts have been made to ensure the sustainability of ultra-densification of multi-tier heterogeneous networks. Sambo et al. [23] achieved high spectral efficiency and significant power savings through competitive network configurations. Soh et al. [24] introduced active/sleep modes in macro cell base stations. Provided that there is a Low Power Wide Area Network (LPWAN) in overlay to transport wakeup signaling and handle emergency services, the broadband cells may be shut down completely to reduce energy consumption [25].

Mobile data traffic offloading is a means of managing the augmented mobile data traffic on the cellular network. In this case, primary wireless communication network offload part of the data traffic to a secondary wireless system to deliver higher data rates, improve network capacity, and ensure better user experience [26]. Nowadays, smart wireless devices are capable of both cellular networks and Wi-Fi, making data offloading from cellular networks to Wi-Fi a potential solution to the anticipated explosive mobile data traffic. Lately, third generation partnership project (3GPP) introduced multi-mode Integrated Femto-Wi-Fi (IFW) small cells, which operate at both licensed bands and unlicensed bands through cellular and Wi-Fi interfaces respectively. Therefore, mobile devices in future 5G networks may enjoy concurrent use of 3GPP, IEEE, and other technologies for better service delivery. Although Wi-Fi network offers an excellent channel bandwidth, the coverage and energy efficiency of the network may be quite unsatisfactory [26]. He et al. [27] presented an elaborate investigation on the recent development in Wi-Fi offloading. In this way, macro-eNodeB (MeNB) offers economic incentive to small-eNodeBs (SeNBs) while the technology reduces the load on the MeNB, improving the spectral efficiency. MeNB ensures control coverage and the SeNBs are solely responsible for data transmission. With the inherent capability to dynamically turn off the SeNBs whenever the traffic load reduces, decoupling the control signaling and data transmission functionalities further improve the energy efficiency of heterogeneous networks. In addition, traditional cell attachment techniques does not incorporate uplink channel states, deteriorating the spectrum efficiency.

Wang et al. [28] suggested a dynamic traffic offloading technique, which considers the delay tolerance of data traffic. Ho et al. [29] proposed a game based data offloading technique. Yang et al. [30] considered both channel quality and cell load in best-fit techniques for downlink and uplink cell attachment that effectively perform data traffic offloading with significant improvement in cell-edge data rates. Meanwhile, the results obtained in [31] demonstrated that the network performance can be significantly improved by balancing the spectral and energy efficiencies tradeoff during the medium load condition. Whereas, the performance gain for spectral efficiency and energy efficiency majorly demand the load level and the radio access node power consumption characteristics. Zhang et al. [32] determined the number of SeNBs that can be turned off as the traffic load changes using two sleeping methods, random and repulsive techniques, with vertical inter-layer offloading. On one hand, the random technique turns off the SeNBs based on certain probability and the expected proportion of idle SeNBs decreases linearly as the traffic load increases. On the other hand, only the SeNBs close to MeNBs are tuned off in repulsive technique and the scheme performance is independent of the changes in traffic load. To improve network efficiency, more MeNBs may be densely deployed to give room for more SeNBs to be turned off.

B. Millimeter Wave (mmWave) Communications

Researchers are currently considering the suitability of mmWave frequency spectrum for 5G wireless communications due to unavailability of bandwidth in the lower frequency bands [33, 34]. Despite the spectral efficiency that can be achieved with network densification, mobile traffic offloading, and modern frequency allocation and regulatory procedures, much more bandwidth is still needed to cater for the exponential mobile traffic expected beyond 2020 [35]. Figure 1 shows the microwave and mmWave spectrum band available for wireless communications.

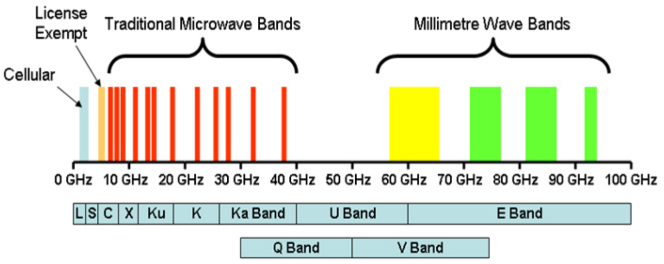

Figure 1: Microwave and mmWave Spectrum Bands for Wireless Communications [33]

Already, mmWave communications have many applications that are suitable for both in-home and outdoor point-to-point applications. In addition, they play an important role in wireless backhaul for outdoor [35]. Seemingly unfortunate, the range and cell coverage of mmWave radios are limited by the propagation characteristics of mmWave communications, particularly for outdoor scenarios. However, excluding the 57-64 GHz and 164-200 GHz bands, about 252 GHz spectrum of the 3-300 GHz mmWave band can be exploited for mobile broadband communications [35]. This is clearly shown in Figure 2.

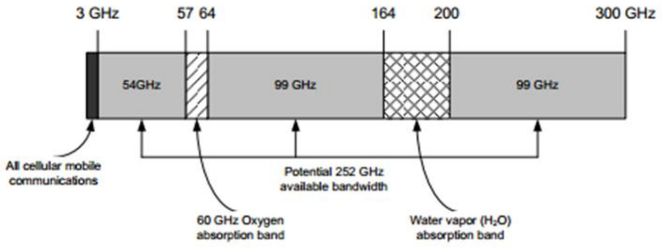

Figure 2: mmWave Spectrum Band prone to Absorption [35]

The under-utilized mmWave frequency spectrum can be used to augment the already saturated radio spectrum bands for future broadband cellular communications. More so, mmWave carrier frequencies utilize simple air interfaces, eliminating the need for complex techniques to achieve efficient spectral efficiency. Similarly, considering the fact that unique hostile propagation features of millimeter wave frequencies restrict the cell range within a few hundreds of meters, the huge spectrum can be most effectively exploited when employed for ultra-dense heterogeneous networks [36, 37].

Until recently, mmWave spectrum band has been considered unviable for mobile access and backhaul due to technical and regulatory constraints. However, current successful deployment of test beds [34, 38-41] which use the mmWave technology for mobile access and emerging regulation and standardization framework motivate the integration of mmWave communications into various proposed 5G architectures [42]. The introduction of millimeter wave radio access and backhaul capabilities will facilitate significant network capacity enhancement in future wireless communications. Specifically, the challenges of scarce spectral resources for both radio access and backhauls in ultra-dense heterogeneous small cell networks will be effectively addressed [43-45]. With the large available spectrum in the mmWave band, small cells operating at mmWave frequencies can deliver higher data rates while mmWave backhaul provide a cost-effective high backhaul capacity to connect access points of the small cells. Figure 3 shows typical joint deployment scenarios of microwave and millimeter wave communication systems in heterogeneous networks. The implementation of millimeter wave communications in self-backhaul ultra-dense heterogeneous networks offers higher spatial multiplexing gain and larger bandwidths for multi-gigabit peak data rates [46]. Meanwhile, the coverage capability of millimeter wave cell can be significantly increased by reflecting the mmWave to the non-line-of-sight (NLOS) areas with low received power levels using multiple passive-reflectors. A detailed explanation of the design approach can be found in [47].

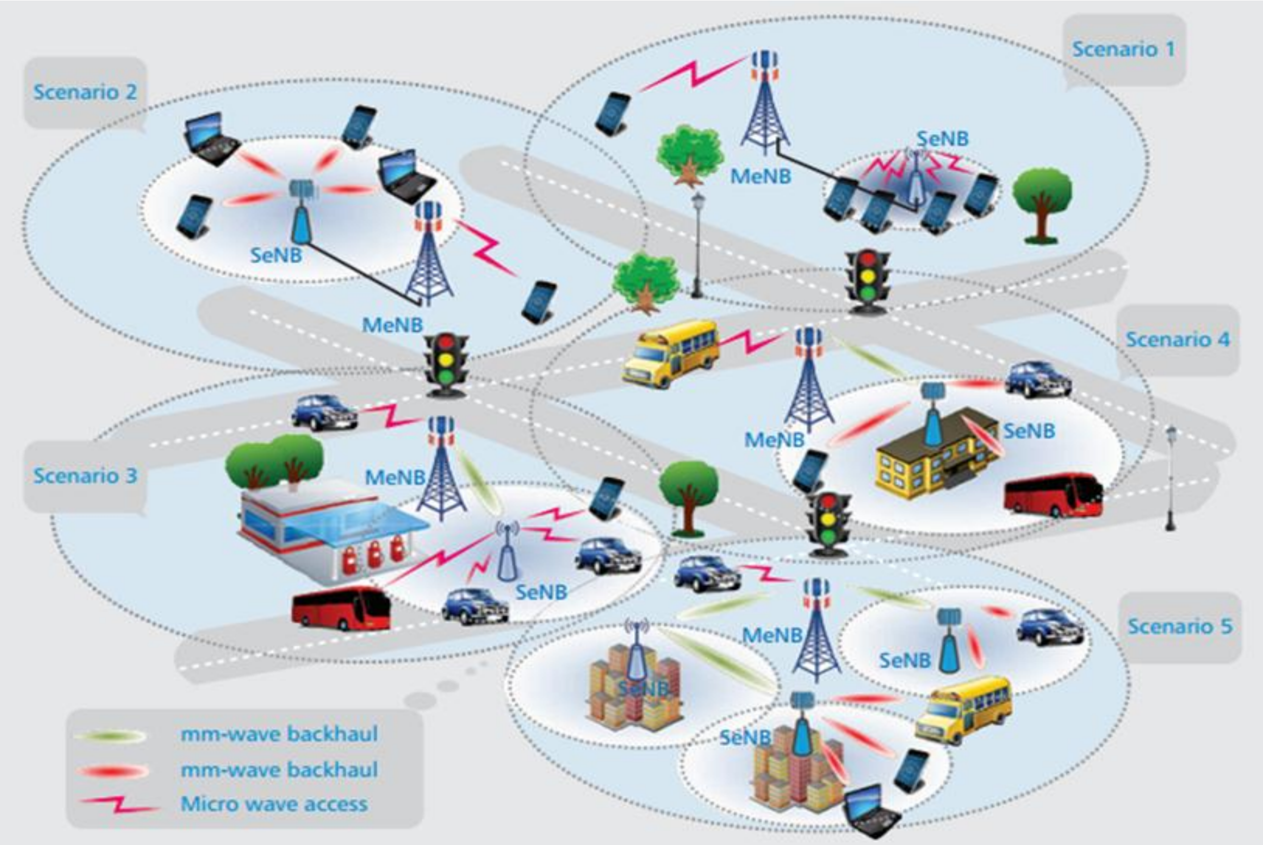

Figure 3: Deployment Scenarios of Heterogeneous Networks in 5G [35]

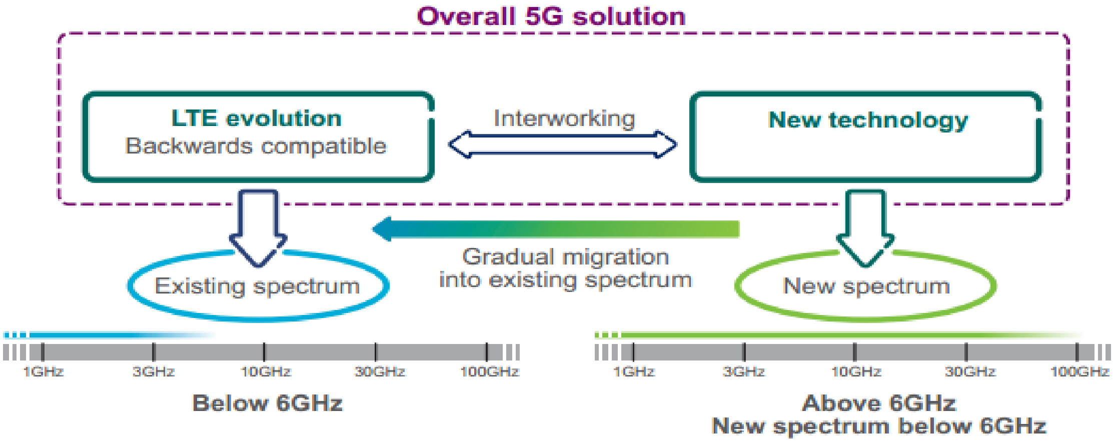

Figure 4: 5G Radio Access Spectrum [8]

Panzner et al. [48] modeled in-band wireless schemes to facilitate practical deployments of mmWave access nodes including cost-effective wireless backhaul links to the egress point(s) within the same frequency band. Meanwhile, ultra-dense deployments of small cells encourage multi-hop backhaul network where the traffic of small cells that could not be connected directly to the core network are forwarded to neighbouring small cells until they reach the core network. This kind of backhaul network can easily maximize the use of millimeter wave frequencies to deliver high capacity backhaul since the backhaul link coverage is within a few hundreds of metres. Similarly, the readily available spectrum can be utilized for fixed wireless access with optimized dynamic beamforming and massive MIMO infrastructure to achieve high capacity with wide area coverage [49]. Niu et al. [50] fully exploited spatial reuse in the mmWave cellular networks in designing a path selection criterion for joint concurrent transmission scheduling for the radio access and backhaul of small cells in the mmWave band to improve system performance and enhance user experience [50].

Emerging wireless M2M and IoT applications require cost-effective and network resource efficient physical layer methods to deliver higher data rates for both radio access and backhaul communications. Meanwhile, future cellular networks will not be operated solely at mmWave frequencies; small cells of higher frequencies will be deployed to underlay the traditional macrocell networks operating at microwave frequencies for coverage and to leverage existing network capacity. Figure 4 shows the overall 5G solution for radio access [8] which enables the integration of new air interface with LTE evolution backward compatibility. Consequently, advanced radio resource management schemes are needed to support the joint radio access and backhaul communications that is anticipated in ultra-dense heterogeneous networks.

Unified radio access and backhaul network can adequately mitigate interference among pico-cells in ultra-dense heterogeneous environment, supporting very low latency inter-base station communication. Multiplexing backhaul and access on the same frequency band can equally handle the difficulties of data backhauling and inter-base station peculiar to ultra-dense cellular networks, without any detriment to the radio access capabilities [51]. Dynamic resource allocation algorithms for joint wireless access and backhaul in [52] achieves a tradeoff between capacity and fairness guarantee. Yanping and Xuming [46] dynamically allocated bandwidth for the access links and backhaul links through a joint scheme of user association and resource allocation in self-backhaul ultra-dense networks to balance two-hop link resources.

Extensive use of millimeter wave uplink bandwidth will cause excessive power consumption and large peak-to-average power ratio at UEs. Therefore, in a bid to save more energy during time division duplex (TDD) millimeter wave operations in future 5G heterogeneous cellular network, millimeter wave should be mainly utilized for downlink transmissions while microwave bandwidth complements uplink transmissions. Knowing that spectral efficiency is a logarithm function of base station-to-user density ratio in an ultra-dense cellular network, millimeter wave uplink can be decoupled to allow each conventional radio access node operating at microwave band to receive mmWave signals [53]. Semiari et al. [54] jointly considered both mmwave propagation characteristics and economic factors in the spectral resource management of heterogeneous small cell backhaul network by allowing small-eNodeBs (SeNBs) that employ broadband fiber backhaul to allocate their frequency resources to SeNBs with wireless backhaul using carrier aggregation.

It is important to develop cost-effective network architecture that utilizes appropriate efficient channel estimation, beamforming, and other communications and signal processing techniques since millimeter wave communications employ massive antennas at both transmitter and receiver ends to provide enough antenna gain that can compensate for the high attenuation in the frequency band [55-61]. For single-carrier frequency-domain equalization (SC-FDE) based mmWave systems, channel estimation is done by performing an iterative calculation of small perturbations with the first-order approximation. In addition, an iterative receiver compensates for the phase noise in signal demodulation with the decision feedback result [62]. Adaptive one-bit compressed sensing channel estimation can be employed at low-resolution mmWave receivers [63, 64]. In a different method for compressed sensing based channel estimation, the antenna subsets selected and the baseband combining were jointly designed [65]. As the number of antennas increases, the exponential growth in estimation complexity and the overhead required for pilot symbols and feedback makes the acquisition of channel state information (CSI) more demanding. An accurate and efficient CSI can be obtained with direct estimation of desired second-order statistics of the channel while bypassing the intermediate recovery of the instantaneous channel matrix itself. A faster channel estimation with low computational complexity and reduced overhead in training and feedback can be performed using a diagonal-search orthogonal matching pursuit (DS-OMP) algorithm which properly utilize the joint sparsity structure of the channel covariance matrix [66].

Heterogeneous mmWave dense networks are more prone to blockage of mmWave links, experience different user speed, and susceptible to poor QoS. Therefore, new connection and mobility management approaches that effectively considered the hostile mmWave propagation behavior must be developed. Maamari et al. [67] reduced the probability of signal outage that result from increasing interference from strong line-of-sight radio access nodes, shadowing, and blockage by exploring the feasibility of radio access node cooperation in the downlink of millimeter wave heterogeneous networks. Enhanced inter-beam handover (IBH) adopts an inter-beam coordinated scheduling and exploits the small-sized low layer messages to reduce handover failure rate and signaling overhead [68]. In narrow-beam communication, especially in the context of high mobility, innovative solutions must be developed to solve the problem of establishing association between users and radio access nodes for initial access and for handoff. As future 5G cellular systems operate numerous narrow beams, handover and radio resource management concept proposed in [69] improves the performance of fast-moving UEs. Mesodiakaki et al. [70] jointly maximize the network energy and spectral efficiency, while maintaining users' QoS requirement, to handle the problem of user association that is encountered as a result of the multi-hop backhaul architecture. A play out buffer presented in [71] regulates and effectively maintain video play out quality for high mobility UEs with frequent intermittent link outages experienced in urban areas due to the hostile propagation features of millimeter wave frequencies.

Recent advances in modern semiconductor technology will greatly reduce the cost and power consumption of millimeter wave communication systems and make other propagation challenges increasingly surmountable. Dussopt et al. [71] designed integrated antennas, antenna arrays and high-directivity quasi-optical antennas for high data-rate 60-GHz communications. Considering recent advances in low cost sub-terahertz semiconductor circuitry, the use of repeaters is a potential strategy of enabling mmWave systems, which suffers high transmission during transmission, with seamless coverage. Inter-symbol interference can be avoided in orthogonal frequency division multiplexing systems with the design of cyclic-prefix length aided by the distribution of excess delay through multiple Amplified-and-Forward Repeater (AFR) hops. Designing AFR with a channel coherence bandwidth finite impulse response filter based channel equalizer significantly increase channel coherence bandwidth and effectively reduce bit error rate [72].

C. Massive Multiple-Input Multiple-Output (MIMO) Technology

Large-Scale multiple-input-multiple-output (MIMO) antenna system, which entails the use of a large number of base station antennas to serve a relatively small number of wireless devices for efficient spectral efficiency [73-79], is one of the main technologies that will productively address the highly envisaged future mobile data traffic explosion with high energy efficiency [80-82]. In K-tier heterogeneous cellular networks where macro base stations are equipped with large number of antennas and support multi-user transmission, the implementation of massive MIMO in macro cells can significantly enhance the performance of heterogeneous networks in terms of coverage and data rate as macro base stations with large antenna arrays can decrease the demands for small cells [83]. More importantly, emerging markets demand energy efficient networks due to limited power resources at mobile nodes in a contingency of universal energy saving. Therefore, there is need to minimize and optimize the total power consumption (including both dynamic and static power allocation) without compromising Quality of service (QOS) performance requirement. This is achieved by employing more effective and efficient resource allocation algorithms for power minimization.

The non-convex low complexity RZF beamforming technique can be employed for power optimization with soft cell coordination [84]. As a result of increase in energy consumption in the macro cell, the use of flexible cell association can improve the energy efficiency of heterogeneous networks by offloading data traffic to small cell. Similarly, serving limited number of users in the macro cells with massive MIMO can boost both spectral efficiency and energy efficiency [85]. When operated over small cells with reciprocity-based training, massive MIMO possesses the capacity to achieve large spectral efficiencies per unit area with low overheads [86]. Generalized spatial modulation (Gen-SM) schemes in multi-cell multi-user massive MIMO systems is identified as a potential high-throughput and energy-efficient technique for the fifth generation (5G) wireless networks. Although it offers less spectral efficiency, spatial modulation (SM) with a single active antenna per user is the most energy-efficient transmission mode among the Gen-SM class [87]. Previous studies revealed that 57% energy consumption of cellular system comes from the operator, predominantly used to power the base station. The base station energy consumption can be optimized with the Cellular Partition Zooming (CPZ) scheme where the base station can zoom in to maintain the coverage area or zoom out to save the energy with negligible impact on the transmission rate [88].

Millimeter wave cellular access networks can be deployed in dense urban outdoor scenarios by using large antenna arrays that support high beamforming gains to compensate for the high path loss at mmWave frequencies since the wavelengths in the spectrum band are smaller. Hybrid analog-digital MIMO beamforming technique is found to be more suitable for massive MIMO systems because conventional fully-digital beamforming techniques which require one radio frequency (RF) chain per antenna element is not viable for large-scale antenna arrays due to the high cost and high power consumption of RF chain components in high frequencies. Provided that the number of RF chains doubled the total number of data streams, a hybrid beamforming architecture whose overall beamformer is made up of a low-dimensional digital beamformer and an analog phase shifters based RF beamformer achieves the exact performance of fully digital beamformer, irrespective of the number of antenna elements. In cases of fewer RF chains such as a point-to-point MIMO system and a downlink multi-user multiple-input single-output (MU-MISO) system, desirable performance can be obtained using a heuristic hybrid beamforming design. These hybrid beamforming techniques are effective in practical cases where only finite resolution phase shifters are available and in scenarios where the resolution of phase shifters employed is very low [89].

Meanwhile, the hardware at the receiver can be simplified by replacing the phase shifters with switches [64]. Zhang et al. [90] handled the modulus constraints on the RF precoding and decoding matrices which phase shift network-based RF analog precoding imposed on mmWave massive multi-carrier single-user massive MIMO systems using two approaches: exploitation of the truncated higher order SVD of the common equivalent RF beamforming matrix available for all carriers; and performance of sequential low rank unimodular approximations for optimal unconstrained solutions [91]. The constrained capacity of generalized spatial modulation (GSM)-based transmitter equipped with as few as two RF chains is capable of minimizing both the transmitter cost and the energy consumption of mmWave communication system, approaching the performance of the full-RF spatial multiplexing having eight RF chains. In addition, the beamforming gain and the high data rate of GSM technique can be leveraged by employing an array of analog beamformers [92].

Alkhateeb and Heath [92] considered frequency selective hybrid precoding, with RF beamforming vectors taken from a quantized codebook, since mmWave systems will likely operate on wideband channels with frequency selectivity. The low-complexity algorithm developed which miserly selects the RF beamforming vectors using Gram-Schmidt orthogonalization for the design of hybrid analog/digital precoders outperforms the unconstrained approaches. Since traditional multiuser MIMO beamforming algorithms cannot be directly applied to mmWave MIMO system, Li et al. [93] suggested a robust hybrid beamforming algorithm with low computational complexity for the uplink multiuser scenario to reduced inter-user interference for both analog beamforming and digital beamforming. Given a perfect channel state information (CSI) and round robin scheduling, hybrid beamforming-enabled multi-user (MU) MIMO achieves better coverage and data rate performance than single-user spatial multiplexing (SM) or single-user analog beamforming (SU-BF) in mmWave cellular networks. In order to determine the minimum allowable efficiency of MU-MIMO that will deliver higher data rates than SM or SU-BF, the overhead due to channel acquisition and computational complexity must be appropriately considered [94].

Three-dimensional beamforming equipped with two-dimensional antenna arrays enables both vertical and horizontal sectorization within a cell by making a beamforming zone for the corresponding sector. However, farther beamforming zone area will likely support more users than nearer beamforming zone. Carrier aggregation from additional base stations can be utilized to solve the considerable inequality among areas of beamforming zone, thereby efficiently improving cell throughput of mmWave cellular networks. Simpler additional base station which offers only a few beamformings can effectively improve the equality of UE's radio resource occupation [95]. The position information from the train control system can be leveraged to develop an efficient beam alignment through beam switching for millimeter wave communication to support high speed trains [96]. Adaptive beamforming applied to both transmitter and receiver in [97] achieved highest signal-to-interference-noise ratio in mmWave beamforming based high speed train communication system.

Pilot contamination introduced by the limitation of coherence time in the use of non-orthogonal pilot schemes proposed for channel estimation in multi-cell TDD networks, hardware impairment and non-reciprocal transceivers reduces the spectrum efficiency and energy efficiency of massive MIMO systems [98, 99]. Pilot contamination occurs in single-cell massive MIMO systems when the number of active users is greater than the pilot sequence length [100]. Also, unavoidable reuse of pilot sequence from User Equipment (UEs) in different cells introduces pilot contamination which in turn limits the performance of massive MIMO systems. When the terminals are fully loaded, the interference from terminals in neighboring cells using the same pilots as in the home cell (inter-cell pilot contamination) impairs the system performance. Although inter-cell contamination can be avoided when the terminals are intermittently active by pre-allocation of pilots while same-cell terminals utilize random access to select the allocated pilot sequences, this also results in intra-cell pilot contamination. Figure 5 shows pilot contamination in massive MIMO system of multiple cells.

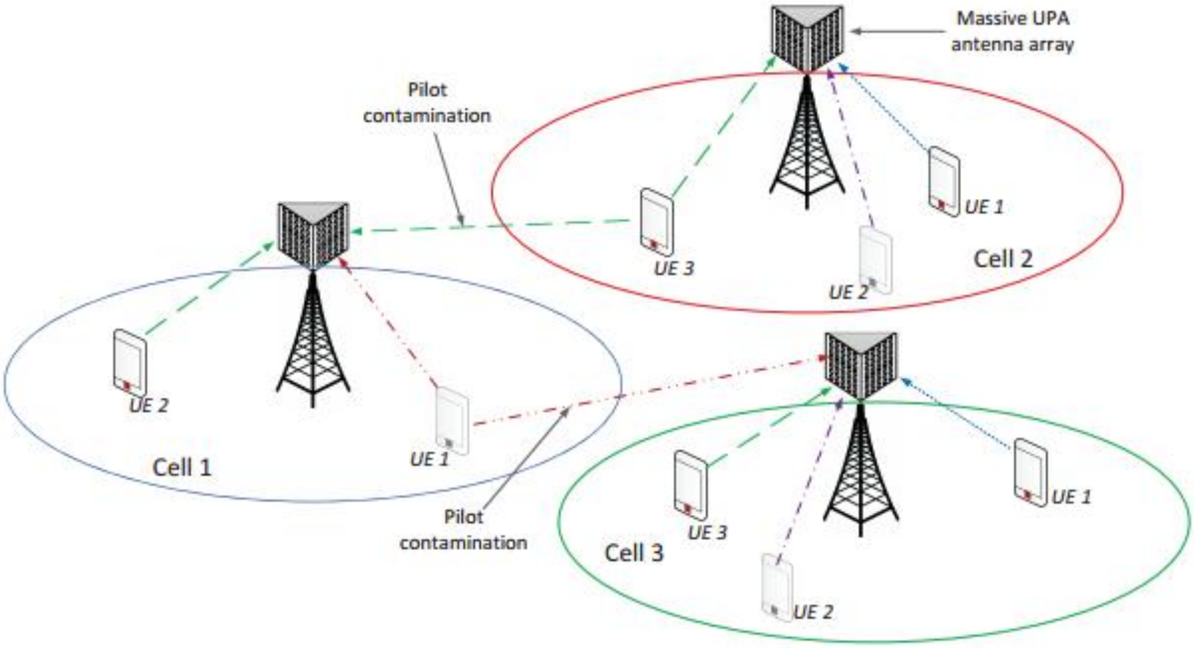

Figure 5: Multi-cell massive MIMO system [101]

In time division duplexing (TDD) massive MIMO systems, pilot contamination saturates the signal-to-interference-plus-noise ratio (SINR) and reduces the maximum number of users whose SINR targets can be achieved in downlink massive MIMO. In cases of large number of antennas, time-shifted pilot scheme mitigates pilot contamination effectively in massive MIMO zero-forcing (ZF) systems using conjugate beamforming [102]. Zhu et al. [103] utilized weighted graph coloring to develop pilot decontamination technique based on classical graph coloring algorithms by denoting each color as a pilot and each vertex as a user in an edge-weighted interference graph (EWIG), which is able to eliminate pilot contamination by assigning different pilots to connected users with a large weight in a greedy way with insufficient pilot resource. The generalized Welch bound equality sequences can be exploited to develop techniques for achieving the user capacity (uplink pilot training sequences and downlink power allocation) that satisfies the SINR requirement of each user and deliver energy-efficient transmission in the large-antenna-size (LAS) regime. Here, the power allocated to each user is proportional to its SINR target [104]. Carvalho et al. [105] considered intra-cell pilot collisions, intermittent terminal activity, and interference while developing a random access framework that can be employed in massive MIMO networks. In addition, the terminal activation probability and pilot length can be optimized with the newly derived uplink sum rate expressions.

From a system level point of view, the pilot assignment problem can be modeled using game-theoretic methods where the adaptation processes following best and better response dynamics converge to a Nash equilibrium [106]. Given that the total number of users in the system is less than the uplink duration, superimposed pilots enable each user to be assigned a unique pilot sequence, thereby allowing for a significant reduction in pilot contamination [107]. Unlike conventional pilot reuse protocols that limit the pilot length to be an integer multiple of the number of users, a pilot design algorithm based on alternating minimization with an arbitrary length can be employed for flexible pilot sequence to maximize spectral efficiency [108]. Considering that typical wideband massive MIMO channel is correlated in both space and frequency domains, Discrete Fourier Transform (DFT), whose basis can be determined without channel statistics and that is more viable for practical use, can be employed to exploit channel sparsity. Since the subspaces of the desired and interference channels are approximately orthogonal, even when the number of antennas is not so large, a pilot assignment policy can be designed to identify the subspace of the desired channel, and a desired channel subspace aware least square channel estimator can be derived to remove the pilot contamination [109].

In cases where both macro-cell base station and small cell access points are equipped with a very large number of antennas, it is assumed that mobile users may be biased to connect to small cell access points rather than the macro-cell base station. Therefore, efficient resource allocation techniques must be employed to find the optimal bias that maximizes the total system capacity while keeping the transmitted power from the macro-cell base station and small cell access points within a certain limit [110]. Considering the heterogeneity of transmitter powers, huge number of antennas, diversity of multiplexing gain capabilities, and highly irregular user density of future heterogeneous networks, efficient user-cell association techniques are highly essential to properly manage the available wireless infrastructure. For simplicity and system social optimum performance, the user-cell association may be decentralized and user-centric, allowing each user to connect individually and selfishly to the base station with the potential of delivering the highest peak data rate, and make local association decisions in a probabilistic manner [111].

Users in different categories have varying data rate requirements and will choose to associate with the cell(s) that offer(s) the highest data rate. Therefore, the cells also have to allocate resources in terms of antennas to different classes of users to maximize their total revenue [112]. Since scheduled user rates can be predicted a priori with massive MIMO, simple admission control mechanisms and rudimentary BS schedulers can be employed for near-optimal user-BS association and resource allocation [86]. Particularly for improved cell-edge performance, Ye et al. [86] presented better approaches for harmonized operation of distributed and cellular massive MIMO in the downlink that optimize resource allocation at a coarser time scale across the network. At the network-level, optimal user-association for a densely and randomly deployed network of massive MIMO-enabled access nodes must account for both channel and load conditions. Such global optimal solution with reasonable complexity contribute significantly to the achieved rate levels compared to a baseline strategy and as well enable effective alternative network access element deployment strategies [113].

With a high possibility of ultra-dense cellular network deployment in future 5G, interference becomes a major source of obstacles to cell throughput improvement. In addition, cell edge users suffer more from co-channel interference, which may dominate end users' experiences [114]. Ye et al. [115] reduced the interference in the small cell downlink using joint transmission (JT) with local precoding (users are served simultaneously by multiple BSs without requiring channel state information exchanges among cooperating BSs), and resource blanking (some macro BS resources are left blank). In a typical macro/small-cell overlay scenarios, massive MIMO can be leveraged to shield small-cell user equipments (UEs) from macro-cell interference using spatial transmit processing [113]. Liu and Lau [116] reduced the number of pilot symbols required for CSI estimation in massive MIMO downlink with a hierarchical precoding structure where the inner precoder controls the intra-cell interference and the outer precoder controls the inter-cell interference. Channel time variation deteriorates the accuracy of the channel state information at the transmitter (CSIT) and causes inter-user interference (IUI) on multiuser MIMO downlink transmission. The excess degrees of freedom (DoFs) of the base station antenna array in massive MIMO can be exploited to perform additional null-steering which extend the null-space dimension and thus suppress the IUI caused by the time varying channel [117]. Shi et al. [118] presented an interference mitigation approach of massive MIMO based on antenna selection provided that both the base station and UE can acquire real-time channel state information. To achieve remarkable diversity and multiplexing gains for space division multiple access in no-line-of-sight mm-wave massive MIMO, the beamformer for multi-user frequency-selective indoor channels can be implemented with a pre-filter designed to minimize the inter-user interference present in conventional time-reversal (TR) [119].

Adhikary et al. [120] suppressed interference by exploiting the highly directional channel vectors of massive MIMO to concentrate transmission energy only in particular directions while creating transmission opportunities for the small cells in the other directions. In addition, low-complexity interference coordination is achieved by turning off small cells based on the amount of cross-tier interference received or caused to the scheduled macrocell hotspots; scheduling hotspots such that treating interference as noise is approximately optimal for the resulting Gaussian interference channel; and offloading some of the macrocell hotspots to nearby small cells to improve throughput fairness across all hotspots [120]. Due to the complexity and deployment consideration in practical scenarios at individual eNodeBs, cooperative massive MIMO (CM-MIMO) where multiple base stations cooperate together and form a distributed antenna array to serve multiple users simultaneously is an attractive way of mitigating inter-user interference. The cooperative transmission among neighbouring cells enables CM-MIMO to significantly improve the system performance of cell edge users even if the cell average performance is very slightly degraded or maintained caused by the power imbalance of received signal from different cooperative neighboring cells [121].

Accurate channel state information is essential for coherent detection in order to fully maximize the benefits of massive MIMO. However, exorbitant pilot overhead makes traditional pilot aided channel estimation methods unsuitable for massive MIMO systems due to large number of antennas at the base station. Wang et al. [122] improved sparse channel estimation with compressive sensing to reduce the pilot overhead in FDD multiuser massive MIMO systems. Gao et al. [123] leveraged the spatio-temporal common sparsity of delay-domain MIMO channels and temporal channel correlation to reduce pilot overhead and improve channel estimation accuracy [124]. In addition to the structured compressive sensing (SCS) based on spatio-temporal joint channel estimation, Dai et al. [125] further exploited the sparsity of channels to acquire accurate channel state information at the base station with reduced feedback overhead. For wideband massive MIMO systems that utilize orthogonal frequency division multiplexing, adjustable phase shift pilots (APSPs) can reduce the pilot overhead with substantial performance gains in terms of achievable spectral efficiency [126]. To avoid the huge orthogonal pilot overhead when serving a large number of UEs, Bayesian channel estimation can be used to estimate channel parameters in the statistical channel state information acquisition for the user scheduling in beam division multiple access transmission [127]. Separate channel estimation and channel feedback schemes may impair the channel state information at the transmitter (CSIT) acquisition performance resulting in unnecessary complex computation for users. Shen et al. [128] jointly considered downlink channel training and uplink channel feedback in structured-CS based differential CSIT acquisition technique for massive MIMO systems. If channel state information is required at the receiver, the differential operation and structured compressive sampling matching pursuit (S-CoSaMP) can also be used at users for better channel estimation performance [129, 130]. Gao et al. [131] suggested a block compressive channel estimation and feedback technique for FDD massive MIMO, which can significantly reduce the overhead for CSI acquisition.

D. Spectrum Sharing Networks and Dynamic Backhaul Sharing

Future wireless networks needs to give special focus in addressing the challenges of affordability and inclusion in wireless broadband internet services for emerging economy countries. This can be achieved through either system design in 5G/LTE technologies, regulatory intervention and innovative spectrum agility and dynamic spectrum access technologies being tested in several countries. The regulatory process and management of dynamic spectrum wireless broadband networks (DS-WBN) is a complex undertaking which will require research and capacity building of telecom regulatory frameworks in emerging economies. The recent surge in dynamic spectrum broadband networks based on TV white spaces experimental network trials has shown that, broadband innovation using dynamic spectrum networks is a viable option in emerging economies. A number of experimental trials have shown that spectrum sharing of TV band frequencies using white space spectrum databases (WSDB) to build dynamic spectrum wireless broadband networks is possible, without interfering with existing legacy networks [132-134]. This gives an opportunity for deploying DS-WBNs to complement mobile broadband networks based on LTE and future 5G developments. Spectrum sharing TVWS networks are now providing much needed broadband connectivity in remote underserved areas [135] to provide broadband ICT based services in sectors such as education, health, transportation, agriculture. Figure 6 shows a topology of a spectrum sharing TVWS network used in suburban Cape Town South Africa [136]. The Cape Town TV white space spectrum sharing network is now providing a much needed broadband internet services to 10 underserved schools in the Tygerberg area. TV band frequency channels, are managed through a white space spectrum database (WSDB): whitespaces.meraka.csir.co.za) [137] through a geo-location based dynamic spectrum allocation system. Non interfering channels are allocated to the three-sectored high tower TVWS base station antenna connected a fiber backhaul. The question now is how do we connect and/or complement DS-WBN to the emerging 5G network standards? Can the offloading techniques described in section above be extended to the DS-WBN networks?

New mechanisms are also needed for bringing resiliency without replicating all the links, especially in the backhaul. They can be achieved by dynamic backhaul sharing between operators in order to exchange capacity during network traffic surge or network failure, but this approach keeps the competition at radio access level.

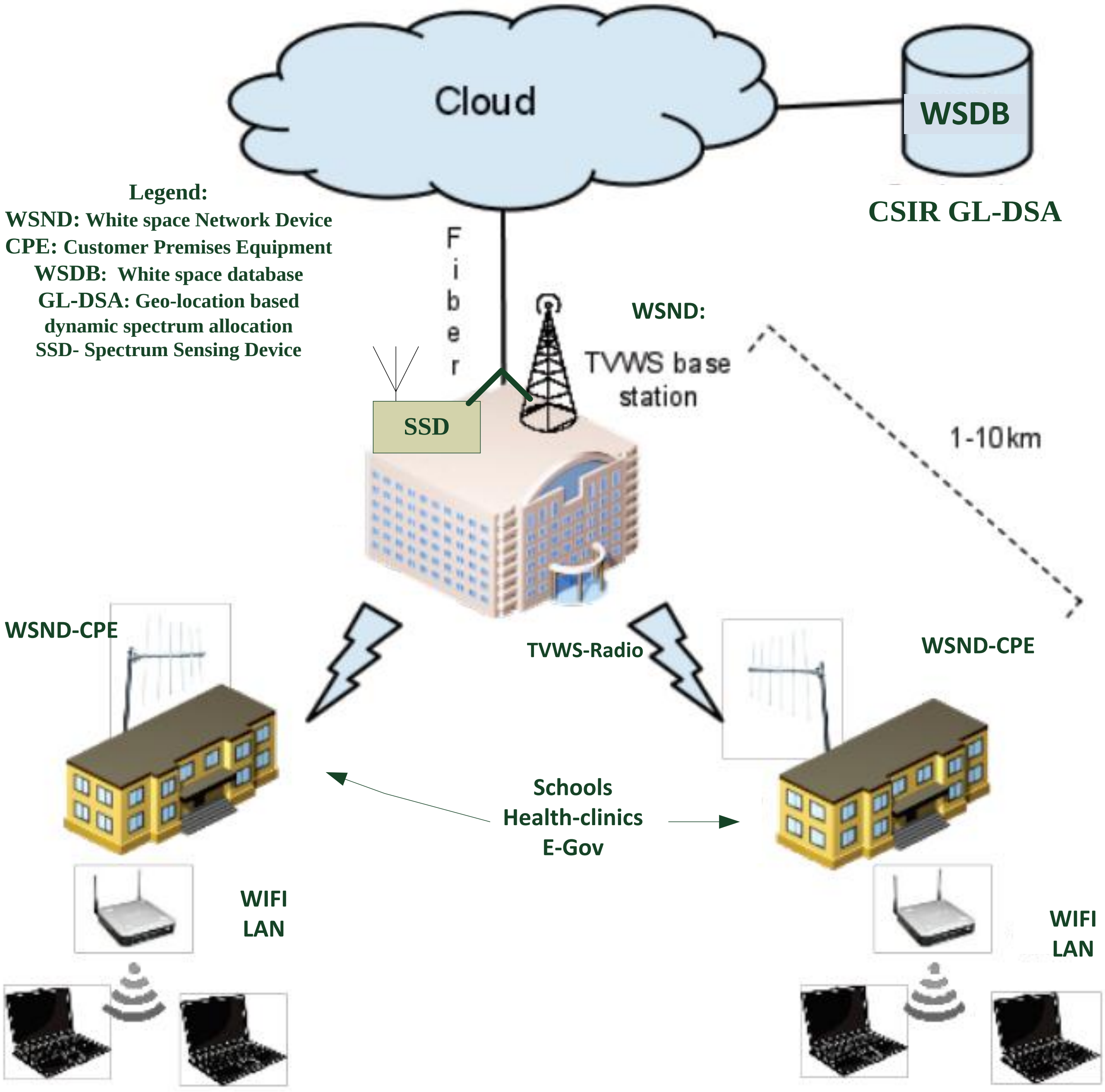

Figure 6: A Spectrum Sharing Network based on TVWSs [136]

IMPLEMENTATION CHALLENGES AND RESEARCH DIRECTIONS

Wireless network vendors and operators will encounter a wide range of difficulties while executing the disruptive changes that the fifth generation technologies introduce to wireless communication systems, especially in emerging markets. The implementation of the new architectures, technologies, and techniques to meet 5G network performance requirements, which demands additional cost and increases energy consumption, must be further optimized with adequate cost and energy control measures.

Beyond individual physical layer and transmission link power optimization, it is necessary to consider the reduction of large volume of fossil fuel consumption and exorbitant energy costs, which may likely constitute a major challenge for mobile network operators during practical deployment of future cellular networks in emerging economies. To address this challenge, more research should be done in order to further exploit the potentials of base station on/off switching strategy; optimized energy procurement from the smart electricity grid [138-144]; base station energy sharing [145-149]; and green networking collaboration between competitive mobile network operators [150-154]. Energy consumed by the base stations can be optimized under different use cases and constraints considered in the design of advanced sleeping strategy algorithms. Mobile network operators are encouraged to deploy renewable energy generators for operations at the base stations; and interact with energy retailers in smart grid to put downward pressure on energy prices as well as optimizing the use of renewable energy sources. To eliminate dependency on electricity grid, base stations with energy surplus can supply energy to deficient base stations through efficient energy sharing techniques [155].

As the deployment of future networks becomes more dense and heterogeneous, the capacity of the wireless systems is expected to be more flexible and scalable enough to accommodate many mobile users demanding for diverse kinds of services at the same time [156, 157]. It is a great challenge to transmit wireless backhaul traffic of the order of 100 Gbps in ultra-dense heterogeneous small cell networks with guaranteed QoS and affordable energy consumption in a sustainable way. On the other hand, rapid development of modern semiconductor technologies has dramatically increased the computation power of hardware, thereby drastically reducing computational complexity in practical applications. However, complexity of algorithms developed for solving optimum MIMO detection problem exponentially increases with the number of decision variables [158, 159]. To further minimize the complexity for sustainable implementation in emerging markets, high-performance sub-optimum MIMO detection algorithms are needed for practical MIMO applications [160].

Cloud Radio Access Network (C-RAN) is another candidate technology for emerging markets as it aim at solving the challenges related to densification and increased base station co-operation. It promises a centralized processing, collaborative radio, real-time cloud computing, and power efficient infrastructure where all base station computational resources are aggregated into a central pool. Radio frequency signals from geographically distributed antennas are collected by Remote Radio Heads (RRHs) and transmitted to the cloud platform through an optical transmission network. C-RAN architecture enables multiple mobile users in a large geographical area to share the processing capability of a base station. This technology conveniently adapt to typical time-geometry changes of network load of base stations in both residential and commercial areas, thereby saving a large amount of power. Also, mobile network operators can exploit the cloud computing infrastructure to achieve low-cost operation. This architecture promise to provide end-to-end mobile service with service elasticity at minimal cost [161] and also it is expected to reduce both CAPEX and OPEX from the operator's perspective, while the end users, would experience better Quality-of-Experience (QoE) via base station coordination and cooperation. This technology has the capability to replace 28 3G NodeBs with 195 RRUs with decrease in network power consumption by two-third [162]. This is excellent, as emerging markets already have power deficits. Although, the network would in practice eliminate the need for local backhaul since end user data traffic will be delivered to and from the centralized location. Still, it will require high speed fiber front haul connections to the small cells (i.e. RRH) and therefore, may not be cost effective for massive deployments.

In addition, the rigid regulatory frameworks currently adopted in most developing economies does not favour business neither does it encourage service innovations. Thus, available spectrum must be efficiently used to deliver required services. In view of this, state-of-the-art cellular networks utilize more advanced transmission techniques, exploit spectrum holes through dynamic spectrum access technologies, and deploy smaller cells to maximize the gains of frequency reuse. Nevertheless, network performance of these systems cannot guarantee reliable service delivery in the future because they are largely limited by interference and high capital and operating expenditures.

CONCLUSION

Digital transformation enabled by 5G technology has enormous potential for boosting the efforts of developing economies towards achieving envisioned 2030 Sustainable Development Goals (SDGs) through the delivery of essential infrastructure and services in form of E-governance, E-learning, E-health, smart energy, smart agriculture, smart cities, and financial inclusion among many others. Unfortunately, significant number of use cases and contextual attributes that underpin the initial 5G research and standardization are still strongly influenced by early adopters in developed economies. Whereas, emerging markets have some peculiar factors that can frustrate sustainable deployment of the transformational technology in the region, thereby further pushing the hope of attaining sustainable development to the far future. In order to address this challenge, it is expedient to consider the key disruptive techniques and methods that can make future generation network design and deployment reasonably affordable, energy-efficient and eco-friendly, spectral-efficient, and more flexible for easy adaptation to rapidly changing business models and service innovations.

Ultra-densification of future base stations enhances self-organizing networks, minimizes cost, and reduces power consumption through the use of multiple radio access technologies in a multi-tier heterogeneous environment. It consequently improves the overall capacity of future wireless systems. Mobile data traffic offloading reduces the burden on macro base stations by shedding augmented data traffic demand to deliver higher data rates, improved network capacity, and better QoS user performance. In addition, millimeter wave communications offer potential solutions to the anticipated high capacity requirements of future 5G cellular networks owing to the large available spectrum in the millimeter wave frequency range and recent advances in hardware and electronic components. Massive MIMO technology supports both dynamic and static power allocation by employing more effective and efficient resource allocation algorithms for power minimization without compromising QOS performance requirement. Furthermore, recent surge in dynamic spectrum broadband networks based on TV white spaces experimental network trials proved that broadband innovation using dynamic spectrum networks is a viable option in emerging economies. Spectrum sharing TVWS networks provides much needed broadband connectivity in remote underserved areas for broadband ICT based services in vital sectors such as education, health, transportation, agriculture.

Despite the current research efforts, wireless network vendors and operators are still more likely to encounter a wide range of difficulties while executing the disruptive changes of 5G technologies in emerging markets. Therefore, the implementation design of the new architectures, technologies, and techniques to meet 5G network performance requirements, which demands additional cost and increases energy consumption, must be further optimized with adequate cost and energy control measures, and more flexible regulatory policies that favour efficient spectrum allocation and utilization.

REFERENCES

[1] C. V. N. I. Cisco, "Global mobile data traffic forecast update, 2013–2018," *white paper*, 2014.

[2] Q. C. Li, H. Niu, A. T. Papathanassiou, and G. Wu, "5G network capacity: Key elements and technologies," *IEEE Vehicular Technology Magazine,* vol. 9, pp. 71-78, 2014.

[3] L.-C. Wang and S. Rangapillai, "A survey on green 5G cellular networks," in *Signal Processing and Communications (SPCOM), 2012 International Conference on*, 2012, pp. 1-5.

[4] T. Janevski, "5G mobile phone concept," in *Consumer Communications and Networking Conference, 2009. CCNC 2009. 6th IEEE*, 2009, pp. 1-2.

[5] V. C. Borges, K. V. Cardoso, E. Cerqueira, M. Nogueira, and A. Santos, "Aspirations, challenges, and open issues for software-based 5G networks in extremely dense and heterogeneous scenarios," *EURASIP Journal on Wireless Communications and Networking,* vol. 2015, p. 164, 2015.

[6] N. Panwar, S. Sharma, and A. K. Singh, "A survey on 5G: The next generation of mobile communication," *Physical Communication,* vol. 18, pp. 64-84, 2016.

[7] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, *et al.*, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Communications Magazine,* vol. 52, pp. 122-130, 2014.

[8] A. Osseiran, F. Boccardi, V. Braun, K. Kusume, P. Marsch, M. Maternia, *et al.*, "Scenarios for 5G mobile and wireless communications: the vision of the METIS project," *IEEE Communications Magazine,* vol. 52, pp. 26-35, 2014.

[9] G. Wu, S. Talwar, K. Johnsson, N. Himayat, and K. D. Johnson, "M2M: From mobile to embedded internet," *IEEE Communications Magazine,* vol. 49, 2011.

[10] F. Nino, "Sustainable Development Goals—United Nations," 2015.

[11] J. G. Kahn, J. S. Yang, and J. S. Kahn, "'Mobile'health needs and opportunities in developing countries," *Health Affairs,* vol. 29, pp. 252-258, 2010.

[12] J. A. Blaya, H. S. Fraser, and B. Holt, "E-health technologies show promise in developing countries," *Health Affairs,* vol. 29, pp. 244-251, 2010.

[13] T. R. Liyanagunawardena, A. A. Adams, and S. A. Williams, "MOOCs: A systematic study of the

published literature 2008-2012," *The International Review of Research in Open and Distributed Learning,* vol. 14, pp. 202-227, 2013.

[14] T. R. Liyanagunawardena, S. Williams, and A. A. Adams, "The impact and reach of MOOCs: A developing countries' perspective," *eLearning Papers,* pp. 38-46, 2014.

[15] Y. Liu, W. Han, Y. Zhang, L. Li, J. Wang, and L. Zheng, "An Internet-of-Things solution for food safety and quality control: A pilot project in China," *Journal of Industrial Information Integration,* vol. 3, pp. 1-7, 2016.

[16] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of things for smart cities," *IEEE Internet of Things journal,* vol. 1, pp. 22-32, 2014.

[17] S. Corner, "How 5G will be different," *Australian Journal of Telecommunications and the Digital Economy,* vol. 2, p. 28, 2014.

[18] B. Bangerter, S. Talwar, R. Arefi, and K. Stewart, "Networks and devices for the 5G era," *IEEE Communications Magazine,* vol. 52, pp. 90-96, 2014.

[19] M. Chen, S. Mao, and Y. Liu, "Big data: A survey," *Mobile Networks and Applications,* vol. 19, pp. 171-209, 2014.

[20] X. Ge, H. Cheng, M. Guizani, and T. Han, "5G wireless backhaul networks: Challenges and research advances," *IEEE Network,* vol. 28, pp. 6-11, 2014.

[21] H. Shajaiah, A. Abdel-Hadi, and C. Clancy, "Utility proportional fairness resource allocation with carrier aggregation in 4G-LTE," in *Military Communications Conference, MILCOM 2013-2013 IEEE,* 2013, pp. 412-417.

[22] R. Vidhya and P. Karthik, "Dynamic Carrier Aggregation in 5G network scenario," in *Computing and Network Communications (CoCoNet), 2015 International Conference on,* 2015, pp. 936-940.

[23] Y. Sambo, M. Shakir, K. Qaraqe, E. Serpedin, and M. Imran, "Expanding cellular coverage via cell-edge deployment in heterogeneous networks: Spectral efficiency and backhaul power consumption perspectives," *IEEE Communications Magazine,* vol. 52, pp. 140-149, 2014.

[24] Y. S. Soh, T. Q. Quek, M. Kountouris, and H. Shin, "Energy efficient heterogeneous cellular networks," *IEEE Journal on Selected Areas in Communications,* vol. 31, pp. 840-850, 2013.

[25] I. Allai, S.-M. Senouci, J. Penhoat, and Y. Gourhant, "A new sustainable mechanism to wake-up bast stations in mobile networks," in *Global Information Infrastructure and Networking Symposium (GIIS), 2016,* 2016, pp. 1-6.

[26] P. Masek, K. Zeman, J. Hosek, Z. Tinka, N. Makhlouf, A. Muthanna, *et al.*, "User performance gains by data offloading of LTE mobile traffic onto unlicensed IEEE 802.11 links," in *Telecommunications and Signal Processing (TSP), 2015 38th International Conference on,* 2015, pp. 117-121.

[27] Y. He, M. Chen, B. Ge, and M. Guizani, "On WiFi offloading in heterogeneous networks: Various incentives and trade-off strategies," *IEEE Communications Surveys & Tutorials,* vol. 18, pp. 2345-2385, 2016.

[28] X. Wang, G. Feng, S. Qin, and Q. Liu, "Energy-efficient dynamic traffic offloading in HetNets," 2015.

[29] T. M. Ho, N. H. Tran, C. T. Do, S. A. Kazmi, T. LeAnh, and C. S. Hong, "Data offloading in heterogeneous cellular networks: Stackelberg game based approach," in *Network Operations and Management Symposium (APNOMS), 2015 17th Asia-Pacific,* 2015, pp. 168-173.

[30] H. Yang, A. Huang, and L. Xie, "Best-fit cell attachment for decoupling DL/UL to promote traffic offloading in HetNets," in *Communications (ICC), 2015 IEEE International Conference on,* 2015, pp. 3466-3471.

[31] J. B. Rao and A. O. Fapojuwo, "Analysis of spectrum efficiency and energy efficiency of heterogeneous wireless networks with intra-/inter-RAT offloading," *IEEE Transactions on Vehicular Technology,* vol. 64, pp. 3120-3139, 2015.

[32] S. Zhang, J. Gong, S. Zhou, and Z. Niu, "How many small cells can be turned off via vertical offloading under a separation architecture?," *IEEE Transactions on Wireless Communications,* vol. 14, pp. 5440-5453, 2015.

[33] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE communications magazine,* vol. 49, 2011.

[34] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, *et al.*, "Millimeter wave mobile communications for 5G cellular: It will work!," *IEEE access,* vol. 1, pp. 335-349, 2013.

[35] K. Zheng, L. Zhao, J. Mei, M. Dohler, W. Xiang, and Y. Peng, "10 Gb/s hetsnets with millimeter-wave communications: access and networking-challenges and protocols," *IEEE Communications Magazine,* vol. 53, pp. 222-231, 2015.

[36] W. Roh, J.-Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, *et al.*, "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results," *IEEE communications magazine*, vol. 52, pp. 106-113, 2014.

[37] T. S. Rappaport, F. Gutierrez, E. Ben-Dor, J. N. Murdock, Y. Qiao, and J. I. Tamir, "Broadband millimeter-wave propagation measurements and models using adaptive-beam antennas for outdoor urban cellular communications," *IEEE transactions on antennas and propagation*, vol. 61, pp. 1850-1859, 2013.

[38] Y. Kim, H.-Y. Lee, P. Hwang, R. K. Patro, J. Lee, W. Roh, *et al.*, "Feasibility of mobile cellular communications at millimeter wave frequency," *IEEE Journal of Selected Topics in Signal Processing*, vol. 10, pp. 589-599, 2016.

[39] Y. Oguma, T. Nishio, K. Yamamoto, and M. Morikura, "Implementation and evaluation of reactive base station selection for human blockage in mmWave communications," in *Communications (APCC), 2015 21st Asia-Pacific Conference on*, 2015, pp. 199-203.

[40] D. Steinmetzer, J. Chen, J. Classen, E. Knightly, and M. Hollick, "Eavesdropping with periscopes: Experimental security analysis of highly directional millimeter waves," in *Communications and Network Security (CNS), 2015 IEEE Conference on*, 2015, pp. 335-343.

[41] N. DoCoMo, "5G radio access: Requirements, concept and technologies," *White Paper, Jul*, 2014.

[42] M. Tesanovic and M. Nekovee, "mmWave-based mobile access for 5G: key challenges and projected standards and regulatory roadmap," in *Global Communications Conference (GLOBECOM), 2015 IEEE*, 2015, pp. 1-6.

[43] C. Mathias, "Fixing the cellular network: Backhaul is the key," *Network World.[Online]. Availabl e: http://www. networkworld. com/community/node/35920*, 2008.

[44] M. Coldrey, U. Engström, K. W. Helmersson, M. Hashemi, L. Manholm, and P. Wallentin, "Wireless backhaul in future heterogeneous networks," *Ericsson Review*, vol. 91, pp. 1-11, 2014.

[45] S. Chia, M. Gasparroni, and P. Brick, "The next challenge for cellular networks: Backhaul," *IEEE Microwave Magazine*, vol. 10, 2009.

[46] Y. LIU and X. FANG, "Joint User Association and Resource Allocation for Self-Backhaul Ultra-Dense Networks," *中国通信*, vol. 2, p. 002, 2016.

[47] Z. Peng, L. Li, M. Wang, Z. Zhang, Q. Liu, Y. Liu, *et al.*, "An Effective Coverage Scheme With Passive-Reflectors for Urban Millimeter-Wave Communication," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 398-401, 2016.

[48] B. Panzner, V. Pauli, L. Yu, and I. Viering, "System level modeling of in-band wireless backhaul for 5G mmW," in *Wireless Communication Systems (ISWCS), 2015 International Symposium on*, 2015, pp. 716-720.

[49] Z. Pi, J. Choi, and R. Heath, "Millimeter-wave gigabit broadband evolution toward 5G: fixed access and backhaul," *IEEE Communications Magazine*, vol. 54, pp. 138-144, 2016.

[50] Y. Niu, C. Gao, Y. Li, L. Su, D. Jin, and A. V. Vasilakos, "Exploiting device-to-device communications in joint scheduling of access and backhaul for mmWave small cells," *IEEE Journal on Selected Areas in Communications*, vol. 33, pp. 2052-2069, 2015.

[51] R. Taori and A. Sridharan, "Point-to-multipoint in-band mmwave backhaul for 5G networks," *IEEE Communications Magazine*, vol. 53, pp. 195-201, 2015.

[52] Z. Shi, Y. Wang, L. Huang, and T. Wang, "Dynamic resource allocation in mmWave unified access and backhaul network," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2015 IEEE 26th Annual International Symposium on*, 2015, pp. 2260-2264.

[53] J. Park, S.-L. Kim, and J. Zander, "Tractable resource management with uplink decoupled millimeter-wave overlay in ultra-dense cellular networks," *IEEE Transactions on Wireless Communications*, vol. 15, pp. 4362-4379, 2016.

[54] O. Semiari, W. Saad, Z. Daw, and M. Bennis, "Matching theory for backhaul management in small cell networks with mmWave capabilities," in *Communications (ICC), 2015 IEEE International Conference on*, 2015, pp. 3460-3465.

[55] T. S. Rappaport, J. N. Murdock, and F. Gutierrez, "State of the art in 60-GHz integrated circuits and systems for wireless communications," *Proceedings of the IEEE*, vol. 99, pp. 1390-1436, 2011.

[56] H. Zhang, S. Venkateswaran, and U. Madhow, "Analog multitone with interference suppression: Relieving the ADC bottleneck for wideband 60 GHz systems," in *Global Communications Conference (GLOBECOM), 2012 IEEE*, 2012, pp. 2305-2310.

[57] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in

millimeter wave MIMO systems," *IEEE transactions on wireless communications,* vol. 13, pp. 1499-1513, 2014.

[58] A. Alkhateeb, O. El Ayach, G. Leus, and R. W. Heath, "Channel estimation and hybrid precoding for millimeter wave cellular systems," *IEEE Journal of Selected Topics in Signal Processing,* vol. 8, pp. 831-846, 2014.

[59] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Millimeter Wave Beamforming for Wireless Backhaul and Access in Small Cell Networks," *IEEE Trans. Communications,* vol. 61, pp. 4391-4403, 2013.

[60] T. E. Bogale, L. B. Le, and A. Haghighat, "User scheduling for massive MIMO OFDMA systems with hybrid analog-digital beamforming," in *Communications (ICC), 2015 IEEE International Conference on*, 2015, pp. 1757-1762.

[61] T. E. Bogale and L. B. Le, "Beamforming for multiuser massive MIMO systems: Digital versus hybrid analog-digital," in *Global Communications Conference (GLOBECOM), 2014 IEEE*, 2014, pp. 4066-4071.

[62] C. Zhang, Z. Xiao, L. Su, L. Zeng, and D. Jin, "Iterative channel estimation and phase noise compensation for SC-FDE based mmWave systems," in *Communication Workshop (ICCW), 2015 IEEE International Conference on*, 2015, pp. 2133-2138.

[63] C. Rusu, R. Mendez-Rial, N. Gonzalez-Prelcic, and R. W. Heath, "Adaptive one-bit compressive sensing with application to low-precision receivers at mmWave," in *Global Communications Conference (GLOBECOM), 2015 IEEE*, 2015, pp. 1-6.

[64] Z. Guo, Y. Yılmaz, and X. Wang, "Transmitter-Centric Channel Estimation and Low-PAPR Precoding for Millimeter-Wave MIMO Systems," *IEEE Transactions on Communications,* vol. 64, pp. 2925-2938, 2016.

[65] R. Méndez-Rial, C. Rusu, A. Alkhateeb, N. González-Prelcic, and R. W. Heath, "Channel estimation and hybrid combining for mmWave: Phase shifters or switches?," in *Information Theory and Applications Workshop (ITA), 2015*, 2015, pp. 90-97.

[66] Y. Wang, Z. Tian, S. Feng, and P. Zhang, "Efficient channel statistics estimation for millimeter-wave MIMO systems," in *Acoustics, Speech and Signal Processing (ICASSP), 2016 IEEE International Conference on*, 2016, pp. 3411-3415.

[67] D. Maamari, N. Devroye, and D. Tuninetti, "Coverage in mmWave cellular networks with base station co-operation," *IEEE Transactions on Wireless Communications,* vol. 15, pp. 2981-2994, 2016.

[68] S.-M. Oh, S.-Y. Kang, K.-C. Go, J.-H. Kim, and A.-S. Park, "An Enhanced Handover Scheme to Provide the Robust and Efficient Inter-Beam Mobility," *IEEE Communications Letters,* vol. 19, pp. 739-742, 2015.

[69] J. S. Kim, W. J. Lee, and M. Y. Chung, "A multiple beam management scheme on 5G mobile communication systems for supporting high mobility," in *Information Networking (ICOIN), 2016 International Conference on*, 2016, pp. 260-264.

[70] A. Mesodiakaki, F. Adelantado, L. Alonso, M. Di Renzo, and C. Verikoukis, "Energy-and Spectrum-Efficient User Association in Millimeter-Wave Backhaul Small-Cell Networks," *IEEE Transactions on Vehicular Technology,* vol. 66, pp. 1810-1821, 2017.

[71] J. Qiao, X. S. Shen, J. W. Mark, and L. Lei, "Video quality provisioning for millimeter wave 5G cellular networks with link outage," *IEEE Transactions on Wireless Communications,* vol. 14, pp. 5692-5703, 2015.

[72] J. Shen, D. Zhu, B. Li, and P. Liang, "Repeater-enhanced millimeter-wave systems in multi-path environments," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2015 IEEE 26th Annual International Symposium on*, 2015, pp. 769-774.

[73] A. Paulraj, R. Nabar, and D. Gore, *Introduction to space-time wireless communications*: Cambridge university press, 2003.

[74] D. Gesbert, M. Kountouris, R. W. Heath Jr, C.-B. Chae, and T. Salzer, "Shifting the MIMO paradigm," *IEEE signal processing magazine,* vol. 24, pp. 36-46, 2007.

[75] J. Mietzner, R. Schober, L. Lampe, W. H. Gerstacker, and P. A. Hoeher, "Multiple-antenna techniques for wireless communications-a comprehensive literature survey," *IEEE communications surveys & tutorials,* vol. 11, 2009.

[76] D. Gesbert, S. Hanly, H. Huang, S. S. Shitz, O. Simeone, and W. Yu, "Multi-cell MIMO cooperative networks: A new look at interference," *IEEE Journal on Selected Areas in Communications,* vol. 28, pp. 1380-1408, 2010.

[77] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, *et al.*, "Scaling up MIMO: Opportunities and challenges with very large arrays," *IEEE Signal Processing Magazine,* vol. 30, pp. 40-60, 2013.

[78] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Communications Magazine*, vol. 52, pp. 186-195, 2014.

[79] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, "An overview of massive MIMO: Benefits and challenges," *IEEE journal of selected topics in signal processing*, vol. 8, pp. 742-758, 2014.

[80] C. Han, T. Harrold, S. Armour, I. Krikidis, S. Videv, P. M. Grant, *et al.*, "Green radio: radio techniques to enable energy-efficient wireless networks," *IEEE communications magazine*, vol. 49, 2011.

[81] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, "Energy and spectral efficiency of very large multiuser MIMO systems," *IEEE Transactions on Communications*, vol. 61, pp. 1436-1449, 2013.

[82] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized MIMO: Challenges, opportunities, and implementation," *Proceedings of the IEEE*, vol. 102, pp. 56-103, 2014.

[83] A. He, L. Wang, Y. Chen, M. Elkashlan, and K.-K. Wong, "Massive MIMO in K-tier heterogeneous cellular networks: Coverage and rate," in *Global Communications Conference (GLOBECOM), 2015 IEEE*, 2015, pp. 1-6.

[84] P. Rayi and M. Prasad, "Optimization of energy and spectral efficiency of massive MIMO-small cell system," in *Smart Technologies and Management for Computing, Communication, Controls, Energy and Materials (ICSTM), 2015 International Conference on*, 2015, pp. 233-238.

[85] A. He, L. Wang, M. Elkashlan, Y. Chen, and K.-K. Wong, "Spectrum and energy efficiency in massive MIMO enabled hetnets: A stochastic geometry approach," *IEEE Communications Letters*, vol. 19, pp. 2294-2297, 2015.

[86] Q. Ye, O. Y. Bursalioglu, and H. C. Papadopoulos, "Harmonized cellular and distributed massive MIMO: Load balancing and scheduling," in *Global Communications Conference (GLOBECOM), 2015 IEEE*, 2015, pp. 1-6.

[87] P. Patcharamaneepakorn, S. Wu, C.-X. Wang, M. M. Alwakeel, X. Ge, and M. Di Renzo, "Spectral, energy, and economic efficiency of 5G multicell massive MIMO systems with generalized spatial modulation," *IEEE Transactions on Vehicular Technology*, vol. 65, pp. 9715-9731, 2016.

[88] D. Zhang, K. Yu, Z. Zhou, and T. Sato, "Energy efficiency scheme with cellular partition zooming for massive mimo systems," in *Autonomous Decentralized Systems (ISADS), 2015 IEEE Twelfth International Symposium on*, 2015, pp. 266-271.

[89] F. Sohrabi and W. Yu, "Hybrid digital and analog beamforming design for large-scale antenna arrays," *IEEE Journal of Selected Topics in Signal Processing*, vol. 10, pp. 501-513, 2016.

[90] J. Zhang, A. Wiesel, and M. Haardt, "Low rank approximation based hybrid precoding schemes for multi-carrier single-user massive MIMO systems," in *Acoustics, Speech and Signal Processing (ICASSP), 2016 IEEE International Conference on*, 2016, pp. 3281-3285.

[91] N. Ishikawa, R. Rajashekar, S. Sugiura, and L. Hanzo, "Generalized-spatial-modulation-based reduced-RF-chain millimeter-wave communications," *IEEE Transactions on Vehicular Technology*, vol. 66, pp. 879-883, 2017.

[92] A. Alkhateeb and R. W. Heath, "Gram Schmidt based greedy hybrid precoding for frequency selective millimeter wave MIMO systems," in *Acoustics, Speech and Signal Processing (ICASSP), 2016 IEEE International Conference on*, 2016, pp. 3396-3400.

[93] J. Li, L. Xiao, X. Xu, and S. Zhou, "Robust and low complexity hybrid beamforming for uplink multiuser mmWave MIMO systems," *IEEE Communications Letters*, vol. 20, pp. 1140-1143, 2016.

[94] M. N. Kulkarni, A. Ghosh, and J. G. Andrews, "A comparison of MIMO techniques in downlink millimeter wave cellular networks with hybrid beamforming," *IEEE Transactions on Communications*, vol. 64, pp. 1952-1967, 2016.

[95] J.-w. Kim, G. Noh, J.-w. Moon, Y.-o. Park, and I. Kim, "Improving beam distribution evenness in 3-dimensional beamforming with carrier aggregation," in *Advanced Communication Technology (ICACT), 2016 18th International Conference on*, 2016, pp. 766-771.

[96] V. Va, X. Zhang, and R. W. Heath, "Beam switching for millimeter wave communication to support high speed trains," in *Vehicular Technology Conference (VTC Fall), 2015 IEEE 82nd*, 2015, pp. 1-5.

[97] J. Kim, H.-S. Chung, I. G. Kim, H. Lee, and M. S. Lee, "A study on millimeter-wave beamforming for high-speed train communication," in *Information and Communication Technology Convergence (ICTC), 2015 International Conference on*, 2015, pp. 1190-1193.

[98] O. Elijah, C. Y. Leow, T. A. Rahman, S. Nunoo, and S. Z. Iliya, "A comprehensive survey of pilot

contamination in massive MIMO—5G system," *IEEE Communications Surveys & Tutorials,* vol. 18, pp. 905-923, 2016.

[99] X. Fang, Y. Zhang, H. Cao, and N. Ying, "Spectral and energy efficiency analysis with massive MIMO systems," in *Communication Technology (ICCT), 2015 IEEE 16th International Conference on*, 2015, pp. 837-843.

[100] U. Amin, S. Anwar, W. Khan, and S. I. Khan, "Energy efficiency analysis of single-cell massive MIMO under pilot contamination," in *Applied Sciences and Technology (IBCAST), 2016 13th International Bhurban Conference on*, 2016, pp. 704-709.

[101] A. Zaib, M. Masood, A. Ali, W. Xu, and T. Y. Al-Naffouri, "Distributed Channel Estimation and Pilot Contamination Analysis for Massive MIMO-OFDM Systems," *IEEE Transactions on Communications,* vol. 64, pp. 4607-4621, 2016.

[102] S. Jin, X. Wang, Z. Li, K.-K. Wong, Y. Huang, and X. Tang, "On massive MIMO zero-forcing transceiver using time-shifted pilots," *IEEE Transactions on Vehicular Technology,* vol. 65, pp. 59-74, 2016.

[103] X. Zhu, L. Dai, Z. Wang, and X. Wang, "Weighted-Graph-Coloring-Based Pilot Decontamination for Multicell Massive MIMO Systems," *IEEE Transactions on Vehicular Technology,* vol. 66, pp. 2829-2834, 2017.

[104] J.-C. Shen, J. Zhang, and K. B. Letaief, "Downlink user capacity of massive MIMO under pilot contamination," *IEEE Transactions on Wireless Communications,* vol. 14, pp. 3183-3193, 2015.

[105] E. De Carvalho, E. Björnson, E. G. Larsson, and P. Popovski, "Random access for massive MIMO systems with intra-cell pilot contamination," in *Acoustics, Speech and Signal Processing (ICASSP), 2016 IEEE International Conference on*, 2016, pp. 3361-3365.

[106] H. Ahmadi, A. Farhang, N. Marchetti, and A. MacKenzie, "A game theoretic approach for pilot contamination avoidance in massive MIMO," *IEEE Wireless Communications Letters,* vol. 5, pp. 12-15, 2016.

[107] K. Upadhya, S. A. Vorobyov, and M. Vehkapera, "Superimposed pilots: An alternative pilot structure to mitigate pilot contamination in massive MIMO," in *Acoustics, Speech and Signal Processing (ICASSP), 2016 IEEE International Conference on*, 2016, pp. 3366-3370.

[108] Y. Han and J. Lee, "Uplink pilot design for multi-cell massive MIMO networks," *IEEE Communications Letters,* vol. 20, pp. 1619-1622, 2016.

[109] Z. Chen and C. Yang, "Pilot decontamination in wideband massive MIMO systems by exploiting channel sparsity," *IEEE Transactions on Wireless Communications,* vol. 15, pp. 5087-5100, 2016.

[110] R. Sultan, L. Song, K. G. Seddik, and Z. Han, "Users association in small cell networks with massive MIMO," in *Computing, Networking and Communications (ICNC), 2016 International Conference on,* 2016, pp. 1-5.

[111] D. Bethanabhotla, O. Y. Bursalioglu, H. C. Papadopoulos, and G. Caire, "Optimal user-cell association for massive MIMO wireless networks," *IEEE Transactions on Wireless Communications,* vol. 15, pp. 1835-1850, 2016.

[112] P. Wang, W. Song, D. Niyato, and Y. Xiao, "QoS-aware cell association in 5G heterogeneous networks with massive MIMO," *IEEE Network,* vol. 29, pp. 76-82, 2015.

[113] J. Dommel, P.-P. Knust, L. Thiele, and T. Haustein, "Massive MIMO for interference management in heterogeneous networks," in *Sensor Array and Multichannel Signal Processing Workshop (SAM), 2014 IEEE 8th,* 2014, pp. 289-292.

[114] W. Nam, D. Bai, J. Lee, and I. Kang, "Advanced interference management for 5G cellular networks," *IEEE Communications Magazine,* vol. 52, pp. 52-60, 2014.

[115] Q. Ye, O. Y. Bursalioglu, H. C. Papadopoulos, C. Caramanis, and J. G. Andrews, "User association and interference management in massive MIMO HetNets," *IEEE Transactions on Communications,* vol. 64, pp. 2049-2065, 2016.

[116] A. Liu and V. Lau, "Hierarchical interference mitigation for massive MIMO cellular networks," *IEEE Transactions on Signal Processing,* vol. 62, pp. 4786-4797, 2014.

[117] T. Iwakuni, K. Maruta, A. Ohta, Y. Shirato, T. Arai, and M. Iizuka, "Inter-user interference suppression in time varying channel with null-space expansion for multiuser massive MIMO," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2015 IEEE 26th Annual International Symposium on*, 2015, pp. 558-562.

[118] Z. Shi, X. Zhu, Y. Zhao, and L. Huang, "Interference alignment based on antenna selection for massive MIMO system," in *Computer Science & Education (ICCSE), 2015 10th International Conference on*, 2015, pp. 606-610.

[119] C. A. Viteri-Mera and F. L. Teixeira, "Interference-Nulling Time-Reversal Beamforming for mm-Wave Massive MIMO in Multi-User Frequency-Selective Indoor Channels," *arXiv preprint arXiv:1506.05143,* 2015.

[120] A. Adhikary, H. S. Dhillon, and G. Caire, "Massive-MIMO meets HetNet: Interference coordination through spatial blanking," *IEEE Journal on Selected Areas in Communications,* vol. 33, pp. 1171-1186, 2015.

[121] C. He and R. D. Gitlin, "System performance of cooperative massive MIMO downlink 5G cellular systems," in *Wireless and Microwave Technology Conference (WAMICON), 2016 IEEE 17th Annual*, 2016, pp. 1-5.

[122] A. Wang, Y. Wang, and L. Jiang, "Improved sparse channel estimation for multi-user massive MIMO systems with compressive sensing," in *Wireless Communications & Signal Processing (WCSP), 2015 International Conference on*, 2015, pp. 1-5.

[123] Z. Gao, L. Dai, W. Dai, B. Shim, and Z. Wang, "Structured compressive sensing-based spatio-temporal joint channel estimation for FDD massive MIMO," *IEEE Transactions on Communications,* vol. 64, pp. 601-617, 2016.

[124] J. W. Choi, B. Shim, and S.-H. Chang, "Downlink pilot reduction for massive MIMO systems via compressed sensing," *IEEE Communications Letters,* vol. 19, pp. 1889-1892, 2015.

[125] L. Dai, Z. Gao, and Z. Wang, "Joint channel estimation and feedback with low overhead for FDD massive MIMO systems," in *Communications in China (ICCC), 2015 IEEE/CIC International Conference on*, 2015, pp. 1-6.

[126] L. You, X. Gao, A. L. Swindlehurst, and W. Zhong, "Channel Acquisition for Massive MIMO-OFDM With Adjustable Phase Shift Pilots," *IEEE Trans. Signal Processing,* vol. 64, pp. 1461-1476, 2016.

[127] Z. Zheng, C. Zhu, B. Jiang, W. Zhong, and X. Gao, "Statistical channel state information acquisition for massive MIMO communications," in *Wireless Communications & Signal Processing (WCSP), 2015 International Conference on,* 2015, pp. 1-5.

[128] W. Shen, B. Wang, J. Feng, C. Gao, and J. Ma, "Differential CSIT acquisition based on compressive sensing for FDD massive MIMO systems," in *Vehicular Technology Conference (VTC Spring), 2015 IEEE 81st,* 2015, pp. 1-4.

[129] Z. Zhang, X. Chai, K. Long, A. V. Vasilakos, and L. Hanzo, "Full duplex techniques for 5G networks: self-interference cancellation, protocol design, and relay selection," *IEEE Communications Magazine,* vol. 53, pp. 128-137, 2015.

[130] W. Shen, L. Dai, Y. Shi, B. Shim, and Z. Wang, "Joint channel training and feedback for FDD massive MIMO systems," *IEEE Transactions on Vehicular Technology,* vol. 65, pp. 8762-8767, 2016.

[131] Z. Gao, L. Dai, W. Dai, and Z. Wang, "Block compressive channel estimation and feedback for FDD massive MIMO," in *Computer Communications Workshops (INFOCOM WKSHPS), 2015 IEEE Conference on*, 2015, pp. 49-50.

[132] O. Holland, A. Aijaz, S. Ping, S. Wong, J. Mack, L. Lam, *et al.*, "Aggregation in TV white space and assessment of an aggregation-capable IEEE 802.11 white space device," in *Communications (ICC), 2016 IEEE International Conference on*, 2016, pp. 1-5.

[133] A. Kumar, A. Karandikar, G. Naik, M. Khaturia, S. Saha, M. Arora, *et al.*, "Toward enabling broadband for a billion plus population with TV white spaces," *IEEE Communications Magazine,* vol. 54, pp. 28-34, 2016.

[134] N. Faruk, N. T. Surajudeen-Bakinde, O. Kolade, A. A. Ayeni, and Y. A. Adediran, "DTV protection regions for spectrum sharing," *The Journal of Engineering,* vol. 1, 2014.

[135] A. A. Lysko, M. T. Masonta, M. R. Mofolo, L. Mfupe, L. Montsi, D. L. Johnson, *et al.*, "First large TV white spaces trial in South Africa: A brief overview," in *Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2014 6th International Congress on*, 2014, pp. 407-414.

[136] D. K. Louis, I. Hanson, and M. T. Masonta, "TV white space usage in education: An overview of GTUC TV white space network in Accra, Ghana," in *IST-Africa Week Conference, 2016*, 2016, pp. 1-11.

[137] A. K. Mishra and D. L. Johnson, *White Space Communication: advances, developments and engineering challenges*: Springer, 2014.

[138] F. Sissine, "Energy Independence and Security Act of 2007: a summary of major provisions," 2007.

[139] S. Lakshminarayana, Y. Xu, H. V. Poor, and T. Q. Quek, "Cooperation of storage operation in a power network with renewable generation," *IEEE Transactions on Smart Grid,* vol. 7, pp. 2108-2122, 2016.

[140] E. Yaacoub, "RESCUE: Renewable energy small cells for utility enhancement in green LTE HetNets," *IEEE Systems Journal,* 2015.

[141] S. Bu and F. R. Yu, "A game-theoretical scheme in the smart grid with demand-side management:

Towards a smart cyber-physical power infrastructure," *IEEE Transactions on Emerging Topics in Computing*, vol. 1, pp. 22-32, 2013.

[142] D. Niyato, X. Lu, and P. Wang, "Adaptive power management for wireless base stations in a smart grid environment," *IEEE Wireless Communications*, vol. 19, 2012.

[143] S. Bu, F. R. Yu, Y. Cai, and X. P. Liu, "When the smart grid meets energy-efficient communications: Green wireless cellular networks powered by the smart grid," *IEEE Transactions on Wireless Communications*, vol. 11, pp. 3014-3024, 2012.

[144] H. Ghazzai, E. Yaacoub, M.-S. Alouini, and A. Abu-Dayya, "Optimized smart grid energy procurement for LTE networks using evolutionary algorithms," *IEEE Transactions on Vehicular Technology*, vol. 63, pp. 4508-4519, 2014.

[145] M. Brabec, E. Pelikán, P. Krč, K. Eben, and P. Musilek, "Statistical modeling of energy production by photovoltaic farms," in *Electric Power and Energy Conference (EPEC), 2010 IEEE*, 2010, pp. 1-6.

[146] X. Huang, T. Han, and N. Ansari, "Smart grid enabled mobile networks: Jointly optimizing BS operation and power distribution," *IEEE/ACM Transactions on Networking*, 2017.

[147] A. Kwasinski and A. Kwasinski, "Architecture for green mobile network powered from renewable energy in microgrid configuration," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, 2013, pp. 1273-1278.

[148] M. J. Farooq, H. Ghazzai, A. Kadri, H. ElSawy, and M.-S. Alouini, "Energy sharing framework for microgrid-powered cellular base stations," in *Global Communications Conference (GLOBECOM), 2016 IEEE*, 2016, pp. 1-7.

[149] J. Leithon, T. J. Lim, and S. Sun, "Energy exchange among base stations in a cellular network through the smart grid," in *Communications (ICC), 2014 IEEE International Conference on*, 2014, pp. 4036-4041.

[150] A. P. Bianzino, C. Chaudet, D. Rossi, and J.-L. Rougier, "A survey of green networking research," *IEEE Communications Surveys & Tutorials*, vol. 14, pp. 3-20, 2012.

[151] T. Han and N. Ansari, "On greening cellular networks via multicell cooperation," *IEEE Wireless Communications*, vol. 20, pp. 82-89, 2013.

[152] J. Xu, L. Duan, and R. Zhang, "Energy group buying with loading sharing for green cellular networks," *IEEE Journal on Selected Areas in Communications*, vol. 34, pp. 786-799, 2016.

[153] M. A. Marsan and M. Meo, "Energy efficient wireless Internet access with cooperative cellular networks," *Computer Networks*, vol. 55, pp. 386-398, 2011.

[154] D.-E. Meddour, T. Rasheed, and Y. Gourhant, "On the role of infrastructure sharing for mobile network operators in emerging markets," *Computer Networks*, vol. 55, pp. 1576-1591, 2011.

[155] H. Ghazzai, E. Yaacoub, A. Kadri, H. Yanikomeroglu, and M.-S. Alouini, "Next-generation environment-aware cellular networks: Modern green techniques and implementation challenges," *IEEE Access*, vol. 4, pp. 5010-5029, 2016.

[156] J. Liu, T. Zhao, S. Zhou, Y. Cheng, and Z. Niu, "CONCERT: a cloud-based architecture for next-generation cellular systems," *IEEE Wireless Communications*, vol. 21, pp. 14-22, 2014.

[157] V. Yazıcı, U. C. Kozat, and M. O. Sunay, "A new control plane for 5G network architecture with a case study on unified handoff, mobility, and routing management," *IEEE communications magazine*, vol. 52, pp. 76-85, 2014.

[158] S. Verdú, "Computational complexity of optimum multiuser detection," *Algorithmica*, vol. 4, pp. 303-312, 1989.

[159] D. Micciancio, "The hardness of the closest vector problem with preprocessing," *IEEE Transactions on Information Theory*, vol. 47, pp. 1212-1215, 2001.

[160] S. Yang and L. Hanzo, "Fifty years of MIMO detection: The road to large-scale MIMOs," *IEEE Communications Surveys & Tutorials*, vol. 17, pp. 1941-1988, 2015.

[161] T. Taleb, "Toward carrier cloud: Potential, challenges, and solutions," *IEEE Wireless Communications*, vol. 21, pp. 80-91, 2014.

[162] C. Mobile, "C-RAN: the road towards green RAN," *White Paper, ver*, vol. 2, 2011.