Toward Green and Soft: A 5G Perspective

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ABSTRACT

As the deployment and commercial operation of 4G systems are speeding up, technologists worldwide have begun searching for next generation wireless solutions to meet the anticipated demands in the 2020 era given the explosive growth of mobile Internet. This article presents our perspective of the 5G technologies with two major themes: green and soft. By rethinking the Shannon theorem and traditional cell-centric design, network capacity can be significantly increased while network power consumption is decreased. The feasibility of the combination of green and soft is investigated through five interconnected areas of research: energy efficiency and spectral efficiency co-design, no more cells, rethinking signaling/control, invisible base stations, and full duplex radio.

INTRODUCTION

With the maturing of fourth generation (4G) standardization and the ongoing worldwide deployment of 4G cellular networks, research activities on 5G communication technologies have emerged in both the academic and industrial communities. Various organizations from different countries and regions have taken initiatives and launched programs aimed at potential key technologies of 5G: 5GNOW and METIS launched under the European Telecommunications Standards Institute's (ETSI's) Framework 7 study new waveforms and the fundamentals of 5G to meet the requirements in 2020; the 5G Research Center was established in the United Kingdom to develop a world-class testbed of 5G technologies; the Third Generation Partnership Project (3GPP) has drawn up its draft evolution roadmap to 2020; and China has kicked off its IMT-2020 Forum to start the study of user demands, spectrum characteristics, and technology trends [1]. There is a broad consensus that 5G requirements include higher spectral efficiency (SE) and energy efficiency (EE), lower end-to-end latency, and more connection nodes. From the perspective of China Mobile, 5G should reflect two major themes: green and soft.

As global carbon emissions increase and sea levels rise, global weather and air pollution in many large cities across the world is becoming more severe [2]. Consequently, energy saving has been recognized as an urgent issue worldwide. Information and communications technologies (ICT) take up a considerable proportion of total energy consumption. In 2012, the annual average power consumption by ICT industries was over 200 GW, of which telecoms infrastructure and devices accounted for 25 percent [3]. In the 5G era, it is expected that millions more base stations (BSs) with higher functionality and billions more smart phones and devices with much higher data rates will be connected. The largest mobile network in the world consumed over 14 billion kWh of energy in 2012 in its network of 1.1 million BSs. If green communications technologies are universally deployed across this network, significant energy savings can be realized, enabling larger infrastructure deployments for 4G and 5G capacity upgrades without requiring significant increase in average revenue per user (ARPU). Dramatic improvements in EE will be needed; consequently, new tools for jointly optimizing network SE and EE will be essential.

Several research groups and consortia have been investigating EE of cellular networks, including Mobile VCE, EARTH, and Green-Touch. Mobile VCE has focused on the BS hardware, architecture, and operation, realizing energy saving gains of 75–92 percent in simulations [4]. EARTH has devised an array of new technologies including low-loss antennas, micro direct transmission (DTX), antenna muting, and adaptive sectorization according to traffic fluctuations, resulting in energy savings of 60–70 percent with less than 5 percent throughput degradation [5]. GreenTouch has set up a much more ambitious goal of improving EE 1000 times by 2020 [6]. Several operators have been actively developing and deploying green technologies, including green BSs powered solely by renewable energies, and green access infrastructure such as cloud/collaborative/clean radio access network (C-RAN) [7].

Carrier grade networks are complex and composed of special-purpose nodes and hardware. New standards and features often require a variety of equipment to be developed and integrated, thus leading to very long launch cycles. In order to accommodate the explosive mobile

Internet traffic growth and a large number of new applications/services demanding much shorter times to market, much faster turnaround of new network capabilities is required. Dynamic RAN reconfiguration can handle both temporal and spatial domain variation of mobile traffic without overprovisioning homogeneously. Soft technologies are the key to resolve these issues.

By separating software and hardware, control plane and data plane, building software over general-purpose processors (GPPs) via programming interfaces and virtualization technology, it is possible to achieve lower cost and higher efficiency using software defined networks (SDNs) and network functions virtualization (NFV) [8]. The OpenRoad project at Stanford University introduced Open-flow, FlowVisor, and SNMPVisor to wireless networks to enhance the control plane. Base station virtualization from NEC concentrated on slicing radio resources at the medium access control (MAC) layer. CloudEPC from Ericsson modified Long Term Evolution (LTE) control plane to control open-flow switches. CellSDN from Alcatel-Lucent considered a logically centralized control plane, and scalable distributed enforcement of quality of service (QoS) and firewall policies in the data plane. C-RAN implements a soft and virtualized BS with multiple baseband units (BBUs) integrated as virtual machines on the same server, supporting multiple radio access technologies (RATs). A soft end-to-end solution from the core network to the RAN can enable the 5G goals of spectral and energy efficiency.

In the following sections, this article will elaborate on a green and soft 5G vision. In addition to the traditional emphasis on maximizing SE, EE must be positioned side by side for joint optimization. We present an EE and SE co-design framework. The concept of no more cells is highlighted later with user-centric design and C-RAN as key elements of a soft cell infrastructure. The rationale for a fundamental rethinking of signaling and control design in 5G is provided. This article further discusses the idea of invisible BSs incorporating line-side answer supervision (LSAS) technology. Finally, the fundamental interference management issues in networks based on full duplex technologies and potential solutions are identified; we then summarize this article.

RETHINK SHANNON: EE AND SE CO-DESIGN

Given limited spectrum and ever increasing capacity demand, SE has been pursued for decades as the top design priority of all major wireless standards, ranging from cellular networks to local and personal area networks. The cellular data rate has been improved from kilobits per second in 2G to gigabits per second in 4G. SE-oriented designs, however, have overlooked the issues of infrastructure power consumption. Currently, RANs consume 70 percent of the total power. In contrast to the exponential growth of traffic volume on mobile Internet, both the associated revenue growth and the network EE improvement lag by orders of magnitude. A sustainable future wireless network must therefore be not only spectral efficient but also energy efficient. Therefore EE and SE joint optimization is a critical part of 5G research.

Looking at traditional cellular systems, there are many opportunities to become greener, from equipment level such as more efficient power amplifiers using envelop tracking, to network level such as dynamic operation in line with traffic variations both in time and space. For fundamental principles of EE and SE co-design, one must first revisit the classic Shannon theory and reformulate it in terms of EE and SE.

In classic Shannon theory, the channel capacity is a function of the log of the transmit power (P_t), noise power spectral density (N_0), and system bandwidth (W). The total system power consumption is a sum of P_t and the circuit power P_c, that is,

$$P_{tot} = \frac{P_t}{\rho} + P_c,$$

where ρ is power amplifier (PA) efficiency defined as the ratio of the input of the PA to the output of the PA. From the definition of EE [9], EE is equal to the channel capacity normalized by the system power consumption. SE is the channel capacity normalized by system bandwidth. The relationship of EE and SE can be shown as a function of PA efficiency and P_c in Fig. 1a. From Fig. 1a, it can be observed that when P_c is zero, there is a monotonic trade-off between η_{EE} and η_{SE} as predicted by the classic Shannon theory. For nonzero P_c, however, η_{EE} increases in the low SE region and decreases in the high SE region with η_{SE} (for a given η_{EE}, there are two values of η_{SE}). As P_c increases, the EE-SE curve appears flatter. Furthermore, when taking the derivative of η_{EE} over η_{SE}, the maximum EE (η_{EE}^*) and its corresponding SE (η_{SE}^*) then satisfy the following: $\log_2 \eta_{EE}^* = \log_2 \rho/(N_0 \ln 2) - \eta_{SE}^*$. This means there is a linear relationship between $\log_2 \eta_{EE}^*$ and η_{SE}^*, and the EE-SE relationship at the EE optimal points is independent of P_c. This observation implies that as P_c decreases, an exponential EE gain may be obtained at the cost of linear SE loss.

Figure 1b compares the EE-SE performance of current Global System for Mobile Communications (GSM) and LTE BSs. LTE performs better than GSM in terms of both SE and EE; both, however, are working in a low SE region, indicating room for improvement.

Antenna muting is proposed in EARTH to improve EE, while LSAS stipulates EE improvement by increasing the number of antennas. The seemingly contradicting conclusions are actually consistent with the analysis presented above where the difference is that the former operates in a low SE region, whereas the latter operates in a high SE region.

While some progress has been made in EE and SE co-design investigation, there is still a long way to go to develop a unified framework and comprehensive understanding in this area. Ideally, the EE-SE curve in future systems should achieve the following criteria:
• The EE value should be improved for each SE operation point.
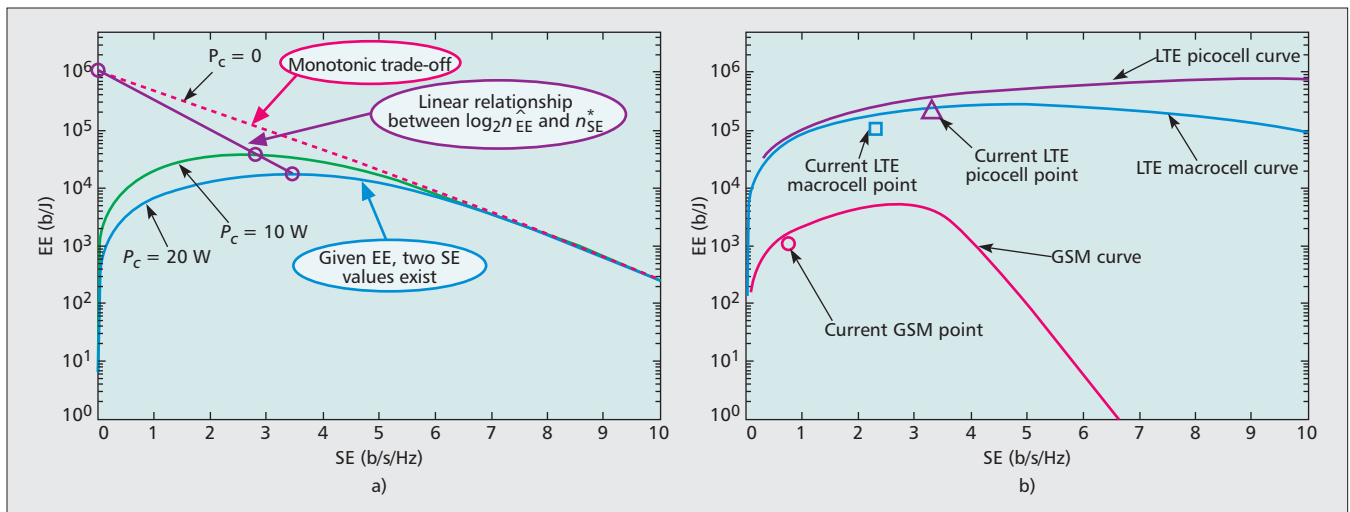
Figure 1. *SE and EE relationship for different circuit powers and current networks.*

- The EE-SE win-win region should be enlarged and the EE-SE trade-off region should be reduced.
- The slope of the EE-SE curve in the trade-off region should be reduced.

RETHINK RING AND YOUNG: NO MORE CELLS

The concept of cellular systems was proposed in 1947 by two researchers from Bell Labs, Douglas H. Ring and W. Rae Young. Since the first generation of cellular standards, this cell-centric design has been maintained through every new generation of standards including 4G.

The nature of a homogeneous cell-centric design is that cell planning and optimization, mobility handling, resource management, signaling and control, coverage, and signal processing are all assumed to be done either for or by each BS uniformly. In practical deployment, it is clear this system does not match with traffic variations and diverse environments. Relay, coordinated multipoint (CoMP), distributed antenna systems (DASs), and heterogeneous networks (HetNets) have been implemented as short-term solutions to amend these issues. Recently, Beyond Cellular Green Generation (BCG2), liquid cells, soft cells, and phantom cells have surfaced as potential radio access architectures. These paradigms all lead to the principle of no more cells. 5G design should start with such a paradigm shift, departing from cell-based coverage, resource management, and signal processing, and leaning toward user-centric coverage facilitated by a C-RAN architecture.

USER-CENTRIC DESIGN

The concept of no more cells is user-centric with amorphous cells, decoupled signaling and data, and decoupled downlink (DL) and uplink (UL). For example, a macro BS would become a signaling BS while small cells would be data-only BSs. In a HetNet scenario, the small cell is within the coverage of a macro cell. Even if the small cell has no traffic, it cannot be turned off in the traditional cell paradigm. But with a control and data decoupling scheme, the macro cell is responsible for control and the small cell only for data. Thus, when there is no data traffic in the small cell, it can be completely turned off to save energy. New users can access the macro cell, and then the macro cell can coordinate with the small cell for possible data transmission.

Based on the channel conditions, service types, and BS traffic loads, the DL and UL can be decoupled to facilitate better resource allocation between cells. This can be illustrated in the following example: Consider two cells where cell 1 is heavily loaded in the downlink and cell 2 loaded in the uplink. In the traditional cell concept, if one user equipment (UE) device is located at the cell boundary with symmetric DL and UL data requirements, and the serving cell is cell 1, its DL requirement may not be satisfied. If the UE device's serving cell is cell 2, its UL requirement may not be satisfied. If there is a user-centric network design, the UE device's DL can be from cell 2 and UL to cell 1, meeting the UE device's data requirement for symmetric DL and UL.

C-RAN

Building on the architecture of distributed BSs where radio units are placed outdoors closer to the antenna and baseband units (BBUs) are placed indoors at cell sites, C-RAN goes one step further by bringing BBUs from multiple BSs to a central pool location (Fig. 2). The GPP servers perform baseband processing using virtual machines running on real-time Linux. The centralization of the baseband processing leads to more energy-efficient cooling, making the C-RAN network architecture an essential part of the design of energy-efficient networks. Energy savings of 70 percent in the OPEX of the BS infrastructure have been realized in 2G and 3G trials inside China. By virtualizing the baseband processing, new features can be added to the network within months, as opposed to years in the traditional infrastructure. The centralized baseband processing allows for soft technologies such as CoMP processing, multi-RAT virtualiza-

tion, as well as soft and dynamic cell reconfiguration [7]. C-RAN is a revolutionary new type of radio access architecture and another essential element of 5G.

RETHINK SIGNALING AND CONTROL

Existing mobile networks are designed more specifically for conventional and streaming applications such as voice and video. As mobile data traffic grows exponentially, more diversified traffic profiles have emerged. They have brought new challenges to mobile networks, especially small-sized persistent bursty traffic types, such as instant messaging (IM) traffic, that contain frequent texts, photos, and periodic pings. These mobile applications would cause frequent transitions between Connected and Idle states. As a consequence, these transitions not only increase device battery drainage, but also cause excessive signaling overhead in mobile networks. Table 1 summarizes the traffic profiles for both the conventional cellular applications and bursty IM applications based on data from China Mobile's network.

As illustrated in Fig. 3, there is a large gap between different traffic profiles in terms of data to signaling/control ratio (DSR). While video streaming achieves DSR larger than 1000 (i.e., signaling overhead less than 0.1 percent of useful data transmission), and voice over IP (VoIP) has a DSR between 50–150, the DSR of IM is less than 6. While mobility may have significant impact on long period streaming, it does not adversely affect short IM bursts.

In current networks, only one kind of signaling/control mechanism is designed for all types of traffic with a variety of different profiles such as traffic rate, traffic interarrival time, and tolerable delay. The current signaling/control over the air is connection oriented, thus resulting in relatively high overhead for bursty traffic. Each connection over the air requires several signaling and data bearer connections, and involves more than 10 times the interaction. In addition, in a connection-oriented system, the network needs to maintain connections during connected state and update these connections when moving between cells.

Proposals raised in 3GPP Release-11 and previous releases for increasing the traffic efficiency of small packet transmission include fast transition to Idle in order to combat the tail effect due to the radio resource connection (RRC) InactivityTimer, and always connected with adaptive DRX switching to reduce UE battery consumption and signaling overhead [10]. These methods, however, result in either a ping-ponging effect between RRC states or large signaling overhead in the case of high-mobility users. It has also been proposed in 3GPP Release-12 to use the RRC channel to transmit small packets for machine-to-machine (M2M) infrequent small packets, thereby avoiding excessive signaling overhead.

These sets of solutions in 3GPP are incremental improvements. To fundamentally resolve the problems of excessive radio signaling overhead, more aggressive changes are needed. For the 5G radio signaling/control design, significant savings in the
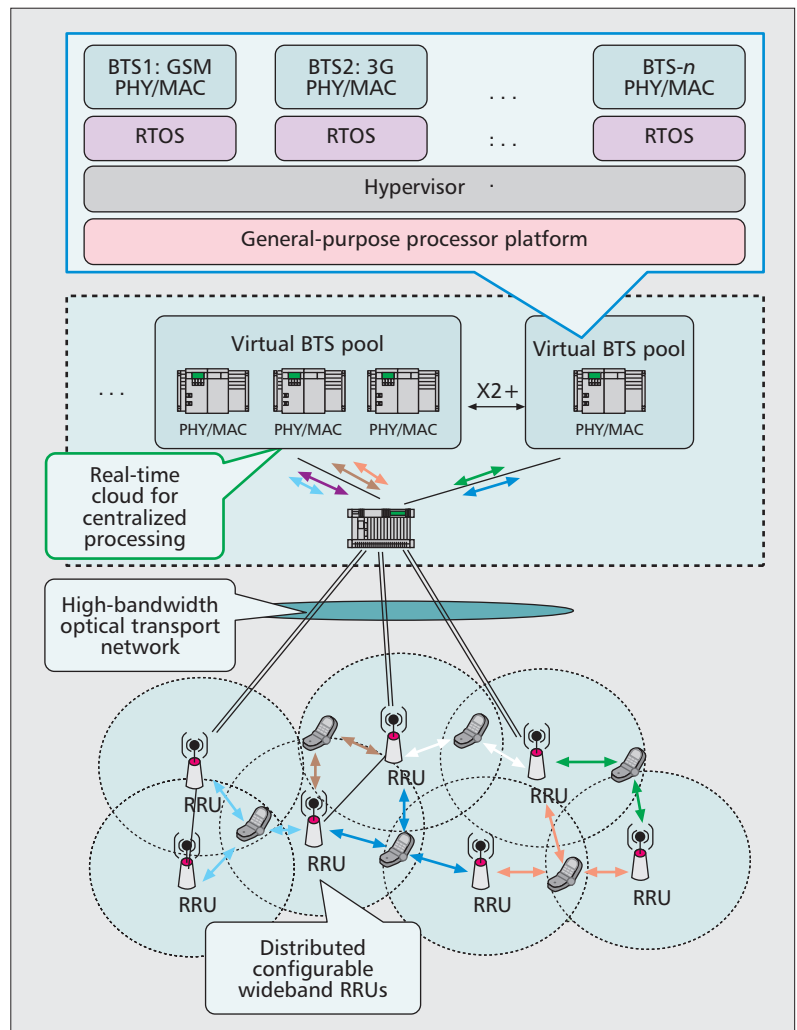

Figure 2. *C-RAN architecture.*

radio connection/release might be achieved by moving away from a pure connection-oriented mechanism. Instead, adaptive signaling/control combining both connection-oriented and connectionless mechanisms should be devised. Depending on traffic types and network loading, an appropriate mechanism would be dynamically applied.

Two modifications to the radio signaling mechanism of Release-11 are introduced to test an appropriate dynamically applied mechanism. The first is a lightweight RRC state without maintenance overhead for handover and channel status feedback. The second is a slim radio signaling interaction (e.g., without establishing a data radio bearer and with contention-based access). As shown in Fig. 3, the DSR of IM applications has improved significantly with the new design from 5.2 to 30.4. In addition, other dimensions such as quality of experience (QoE) can also be considered to further optimize radio signaling. For example, periodic keep-alive messages have much looser requirements than text messages for IM applications regarding delay and reliability. Thus, the radio signaling procedures such as the retransmission mechanism can be specifically designed for keep-alive and text messages to achieve greater signaling saving.

Type	Session (%)	Session rate (kbytes/s)	Session length (s)	Msg size (kbytes)	Session inter-arrival time (s)	Msg inter-arrival (s)
Video streaming						
Video		200	60		3600	
VoIP						
Voice		13.3	60		2400	
Instant message (IM)						
Voice	35			10		50
Text	60			0.1		50
Photo	4			150		2000
Video	1	200	60	1500		20000
Stand-by				0.6		300

Table 1. *Traffic models of cellular applications.*

INVISIBLE BASE STATIONS WITH IRREGULAR ANTENNA ARRAYS

Massive multiple-input multiple-output (MIMO) or LSAS [11] has been a research focus since Marzetta'a seminal paper [12]. The premise of LSAS is that the number of BS antennas with complete transceiver chains L is much larger than the number of single-antenna UE terminals K, where L is assumed to be hundreds to thousands of antennas. Given perfect channel state information (CSI), the total radiated power is inversely proportional to L, allowing the use of low-power PAs [12]. For a fixed L/K, SE increases linearly with L using multi-user beamforming. Near optimal performance can be achieved with low-complexity Tx/Rx algorithms such as matched filters. CSI in a time-division duplex (TDD) system can be acquired using natural reciprocity, thereby allowing L to increase without increasing signaling overhead.

EE-SE ANALYSIS OF N BY M ACTIVE ANTENNA STRUCTURE

Although the generic LSAS requires a complete transceiver chain for each antenna element, for practical considerations, a much smaller number of transceivers than that of antenna elements may be adopted. Unlike current BS RF structures, where each transceiver is connected to a column of antenna elements generating a fixed coverage beam, the LSAS system under investigation is an LSAS system of size $L = N \times M$, where N is the number of transceivers and M is the number of active antennas per transceiver. For a given L, it would be desirable to find the optimal N in terms of EE-SE performance.

In order to simplify the problem, it is assumed that there is perfect analog beamforming within each set of M active antennas with zero inter-beam interference. Zero beam interference is based on the assumption that the number of transmit antennas L is larger than the number of receive antennas M. Assuming normalized channel gain, the sum capacity of this structure can be expressed as the number of transceivers times the log of the transmit power, number of antennas, and PA efficiency (similar to the Shannon channel capacity discussed later). In this model, a simplified power model of the sum of the antenna transmit power and total circuit power is used. The EE-SE relationship can then be written as the system capacity normalized by the number of transceivers' transmit power plus the circuit power. As shown in Fig. 5, when the transceiver power P_0 dominates, smaller N yields better EE performance at lower SE, while the optimal N increases at higher SE (optimal M can then be calculated by the size of L where $M = L/N$). If the P_{common} (common circuit power
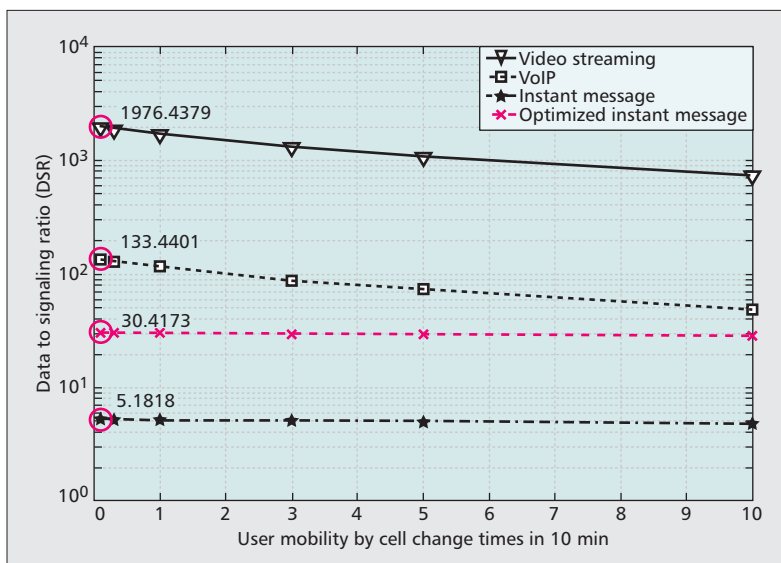

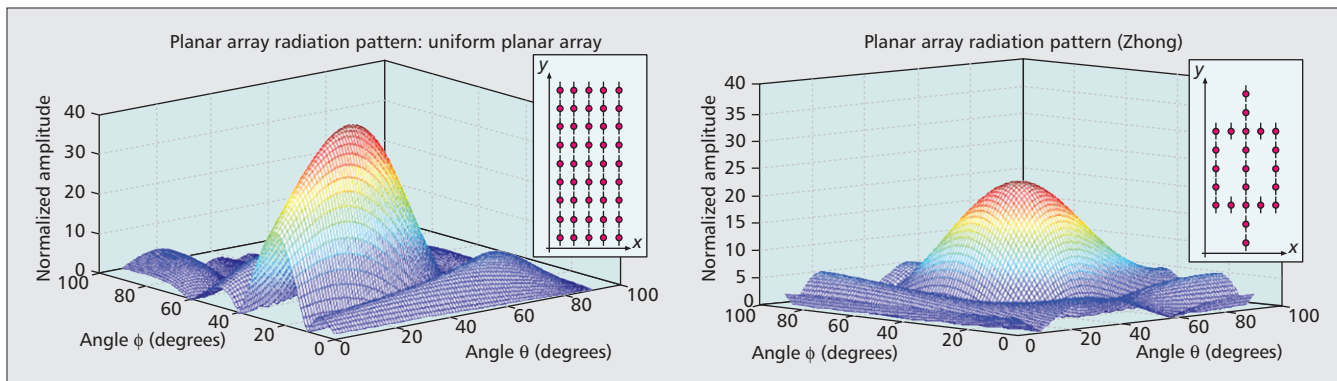**Figure 3.** *DSR comparisons between different traffic profiles and mobility.*

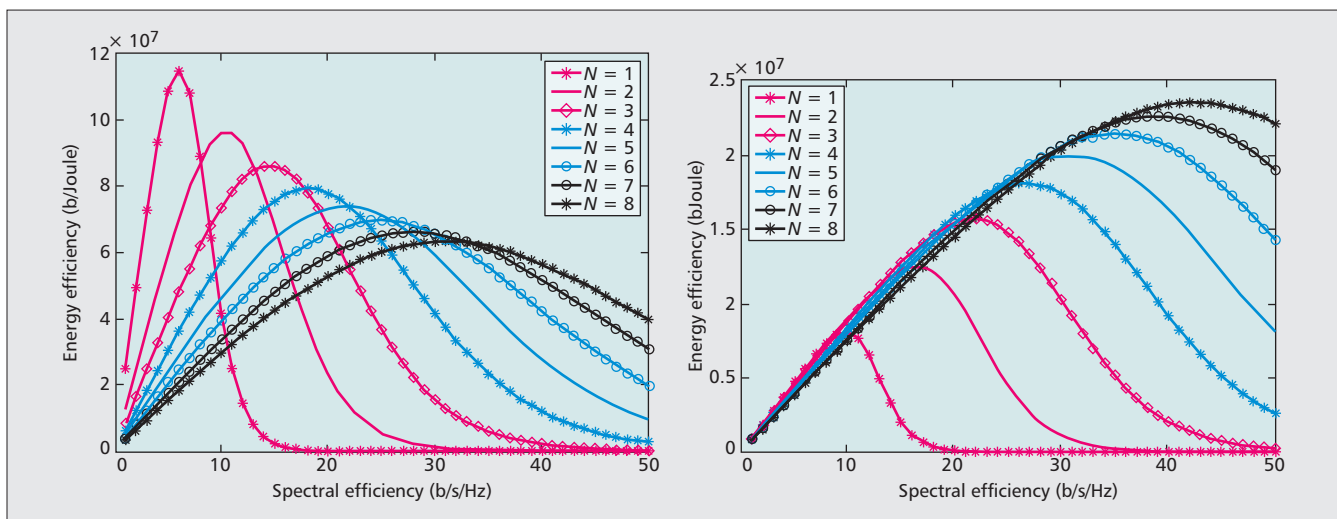**Figure 4.** *3D radiation patterns for uniform and irregular arrays.*

Figure 5. *EE-SE curves for N transceivers where P_0 = 4 W and P_{common} = 0 W for the left and P_{common} = 100 W for the right graph.*

independent of the number of transceivers) is dominant, with larger *N* there is better EE performance at almost all values of SE.

IRREGULAR ANTENNA ARRAYS

Although LSAS elegantly addresses the capacity and power consumption challenges, the physical size of an LSAS BS is of concern. Commercial deployment of BSs is already facing resistance from both the public and commercial property owners regarding the aesthetics and potential/perceived health issues due to exposure to electromagnetic waves. The much larger physical footprints of LSAS BSs will not only bring significant tower construction challenges but also lead to greater confrontation.

By integrating the antenna elements into the environment, the BSs can be made virtually invisible. Instead of constructing fake trees, which are often eyesores, multiple active elements can be built in the form of tiles. By separating the single LSAS panel into multiple tiles, the LSAS can be flexibly deployed in an irregular fashion as part of the building facade or signage, and thus blend into the environment.

Irregular antenna deployment in a practical environment requires different system design and adaptive signal processing algorithms. Figure 4 shows the 3D radiation patterns calculated

using array factors for half-wavelength dipoles arranged in a 5 × 9 uniform planar array with antenna separation of λ/2 and phase offsets of π/6 compared to an irregular 5 × 9 array in the shape of the Chinese character "Zhong." As predicted by sparse antenna array theory, the sidelobes of the sparse array have increased, and due to the smaller number of antennas, the main lobe peak has decreased. Advanced algorithms regarding subarrays, orthogonal placements, or parasitics can help optimize the beamforming performance of irregular arrays.

In addition to beamforming optimization, there are several other challenges for irregular antenna arrays. Synchronization, broadcast, and cell common reference signals in cellular systems are generally transmitted in an omnidirectional manner for better coverage, whereas LSAS panels can only create radiation patterns in front of the panel. Cell coverage will be more challenging since for a given antenna placement, there are many possible coverage scenarios. Another issue is channel modeling for irregular antenna deployment. 3D channel modeling is being investigated in 3GPP and various study groups like WINNER, where generally a regular antenna configuration is assumed. On top of the 2D channel model in WINNER or 3GPP, the elevation angle is added for each ray, where angle of

arrival/angle of departure (AoA/AoD) and large-scale fading with regard to different antennas are assumed to be the same due to the regular spacing in the traditional 2D array. With irregular antenna arrays, however, the spacing and relative position of each antenna may invalidate the above assumption where AoA /AoD and large-scale fading may be different for each ray with regard to different LSAS antennas; therefore, modification to the current channel modeling is needed.

FULL DUPLEX RADIO

Current cellular systems are either frequency-division duplex (FDD) or TDD. To double SE as well as improve EE, full duplex operation should be considered for 5G. A full duplex BS transmits to and receives from different terminals simultaneously using the same frequency resource. Self-interference cancellation is the key to the success of a full duplex system since high DL interference will make the receivers unable to detect the UL signal. Significant research progress has been made recently in self-interference cancellation technologies, including antenna placement, orthogonal polarizations, analog cancellation, and digital cancellation [13]. Most of the research, however, has been on either point-to-point relay or a single-cell BS scenario. There is also inter-user UL-to-DL interference in the single-cell full duplex system. To mitigate such interference, the inter-user interference channel must be measured and reported. The full duplex BS can then schedule proper UL and DL user pairs, possibly with joint power control.

In the case of a multi-cell full duplex network, interference management becomes significantly more complex. For current TDD or FDD systems, the DL-to-DL interference received at UE and UL-to-UL interference received at BSs have been studied extensively in literature and standardization bodies (e.g., CoMP in 3GPP LTE-Advanced and IEEE 802.16m). In a full duplex system, however, there are new interference situations. For example, if there are two BSs, there will be additional interference in the UL and DL between multiple UE mobile devices with the same frequency and time resources. In addition to intracell interference, there are inter-BS DL-to UL-interference and intercell inter-user UL-to-DL interference. These additional types of interference will adversely impact full duplex system performance. Traditional transmit or receive beamforming schemes can be applied to mitigate inter-BS DL-to-UL interference. The intracell interference mitigation can be extended to handle intercell inter-user UL-to-DL interference.

CONCLUSIONS

This article has presented five promising areas of research targeting a green and soft 5G system. The fundamental differences between classic Shannon theory and practical systems are first identified and then harmonized into a framework for EE-SE co-design. The characteristics of no more cells are described from the perspective of infrastructure and architecture variations with particular emphasis on C-RAN as a typical realization in order to enable various soft technologies. Rethinking signaling/control based on diverse traffic profiles and network loading is then explored, and initial redesign mechanisms and results are discussed. Virtually invisible base stations with irregular LSAS array are envisioned to provide much larger capacity at lower power in high-density areas when integrated into building signage. Optimal configuration of transceivers and active antennas is investigated in terms of EE-SE performance. Finally, new interference scenarios are identified in full duplex networks, and several candidate solutions are discussed. These five areas provide potential for fundamental breakthroughs, and together with achievements in other research areas, they will lead to a revolutionary new generation of standards suitable for 2020 5G deployment.

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BIOGRAPHIES

CHIH LIN I (icl@chinamobile.com) received her Ph.D. degree in electrical engineering from Stanford University and has almost 30 years experience in wireless communications. She has worked at various world-class companies and research institutes, including the Wireless Communication Fundamental Research Department of AT&T Bell Labs; the headquarters of AT&T, as director of Wireless Communications Infrastructure and Access Technology; ITRI of Taiwan, as director of Wireless Communication Technology; Hong Kong ASTRI, as vice president and founding group director of the Communications Technology Domain. She received the *IEEE Transactions on Communications* Stephen Rice Best Paper Award and is a winner of the CCCP National 1000 Talent program. Currently, she is China Mobile's chief scientist of wireless technologies in charge of advanced wireless communication R&D efforts of the China Mobile Research Institute. She established the Green Communications Research Center of China Mobile, spearheading major initiatives including 5G key technologies R&D; high energy efficiency system architecture, technologies, and devices;

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