COMMUNICATING IN THE REAL WORLD: 3D MIMO

XIANG CHENG, BO YU, LIUQING YANG, JIANHUA ZHANG,
GUANGYI LIU, YONG WU, AND LEI WAN

ABSTRACT

Spectrum efficiency has long been at the center of mobile communication research, development, and operation. Today it is even more so with the explosive popularity of the mobile Internet, social networks, and smart phones that are more powerful than our desktops used to be not long ago. The discovery of spatial multiplexing via multiple antennas in the mid-1990s has brought new hope to boosting data rates regardless of the limited bandwidth. To further realize the potential of spatial multiplexing, the next leap will be accounting for the three-dimensional real world in which electromagnetic waves propagate. In this article we discuss fundamentals and key technical issues in developing and realizing 3D multi-input multi-output technology for next generation mobile communications.

INTRODUCTION

"When you have a scarce resource, an industry run as an oligopoly and a population that can't get enough, you have all the ingredients for the first new resource crisis of the millennium."

No, not oil. This excerpt from a 2010 *Time Magazine* article is all about the wireless spectrum. With the explosive increase of data-hungry services including Facebook and Twitter, as well as always-connected smart mobile devices, this statement is edging ever closer to reality.

In the 1990s Foschini and Telatar first revealed that the channel capacity of multi-antenna systems increases linearly with the number of transmit/receive antennas, thus giving hope to meeting the unlimited data demand of the real world with the limited wireless spectrum (e.g. [1, 2] and references therein). Today it has become standard to equip base stations (BSs) with antenna arrays that facilitate various multi-input multi-output (MIMO) functionalities including beamforming, multiplexing, diversity, and interference coordination, just to name a few. In these existing cellular systems, however, the BS antenna array has remained passive and can only adjust the beam in the horizontal dimension with fixed downtilt angle, based on the horizontal channel information.

On the one hand the real-world channel features three-dimensional (3D) characteristics, rendering two-dimensional (2D) MIMO techniques suboptimum. On the other hand, the capability of tilting the transmit beam angle in the full 3D space will intuitively improve the overall system throughput and interference management, especially for scenarios where mobile users are distributed in a 3D space with distinguishable elevation such as modern urban environments. The latter case is becoming increasingly important with the prevalence of the small cell concept, in which the horizontal scale becomes more comparable with the vertical scale.

Not surprisingly the 3D MIMO concept is embraced by various mainstream communications systems (long term evolution (LTE), LTE-advanced and beyond) thanks to its potential to boost system capacity and alleviate interference, both of which consist of the most important system development objectives. One core enabling technology for 3D MIMO is the so called active antenna system (AAS). The employment of AAS at BSs was recently approved by the 3rd Generation Partnership Project (3GPP) at TSG RAN #53 in September 2011. AAS technology integrates radio frequency components (power amplifiers and transceivers) with the antenna elements. In this manner the phase and amplitude of the signals from each antenna element can be electronically controlled, thus facilitating more flexible and intelligent beamforming, resulting in increased capacity and coverage. With a 2D or 3D AAS array at the BS, the antenna radiation pattern can be dynamically controlled in both horizontal and vertical dimensions, thus enabling 3D MIMO as opposed to the conventional 2D MIMO. The AAS-enabled 3D MIMO is attracting significant attention from academic researchers as well as industrial developers and operators. In this article we provide the overview and perspective of 3D MIMO technology. We will start from fundamentals and application scenarios, followed by discussions on 3D MIMO channels and an overview of key technological issues. We conclude the article with opportunities and challenges in 3D MIMO research and development.

FUNDAMENTALS AND APPLICATION SCENARIOS

At conventional BSs linear (1D) antenna arrays with fixed radiation patterns in the vertical domain are used. The transmitted beamwidth in

Xiang Cheng is with Peking University.

Bo Yu and Liuqing Yang is with Colorado State University

Jianhua Zhang is with Beijing University of Posts and Telecommunications

Guangyi Liu is with China Mobile Communications Corporation

Yong Wu and Lei Wan are with Huawei Technologies Company Ltd.

 1536-1284/14/$25.00 © 2014 IEEE

the vertical dimension and the antenna downtilt are usually fixed. Occasional adjustment of the downtilt angle can be achieved physically by, for example, Remote Electrical Tilt (RET) devices to direct the main lobe of the antenna response toward the ground. As a result the spatial freedom only lies in the azimuth dimension essentially in terms of the horizontal radiation beam pattern and width. With the deployment of 2D or 3D AAS at the BS, the elevation and azimuth steering angles, the beamwidth, and the radiation pattern can all be dynamically controlled in full dimensions by adaptively weighting the elements in the antenna array, potentially for each individual user equipment (UE), thus facilitating the so called 3D MIMO technology.

Fully utilizing both the horizontal and vertical dimensions, 3D MIMO is particularly suitable for scenarios with vertical user location distributions. One example is the dense urban area (including both residential areas and central business districts) with many high-rise buildings. There is usually a huge demand for mobile data capacity in these areas. Furthermore, the indoor users in these areas are usually located on different floors of high-rise buildings and the vertical user distribution is evident. Transmissions from outdoor BSs to users located on different floors can be better separated in their elevation angles. Hence, significant gain in system performance can be expected with 3D MIMO. Another important scenario is the dense population area where a huge number of users are closely located with each other and connected to one BS in a limited area. Examples include transportation stations, shopping malls, stadiums, and so on. In this scenario a great amount of traffic will be generated simultaneously and the data rate of each user will be degraded. 3D MIMO will provide a good solution for this problem. For suburban and rural scenarios, elevation beamforming can also be beneficial in terms of the cell range expansion achieved by vertical sectorization.

To date 3D beamforming is by far the most studied 3D MIMO technique, thanks to its relative simplicity, flexibility, and effectiveness. An example is shown in Fig. 1, where a single wide beam covering the entire cell with a fixed downtilt angle is replaced by multiple simultaneous narrower beams sectoring the cell with dynamic downtilt angles. Essentially a kind of physical beamforming technique without any channel state information (CSI), 3D beamforming comes at low complexity. The granularity of the vertical sectorization enabled by 3D beamforming can be theoretically adjusted to different levels from very coarse (two to three sectors in the radial direction) to very fine UE-specific (e.g. [3]), leading to maximized UE signal strength as well as highly flexible interference management.

Another potential technology is the extension of spatial multiplexing from 2D MIMO to the 3D MIMO regime. Different from 3D beamforming, spatial multiplexing requires instantaneous or statistical CSI at the Tx (CSIT), and is inherently UE-specific. Based on the CSIT, the spatial multiplexing gain is exploited to improve the system performance by optimizing each UE's specific precoding coefficients. There are two main categories of such designs, namely single-user (SU-)MIMO and multi-user (MU-)MIMO. For SU-MIMO, the optimal beam directions are simply the channel eigen-directions. However, MU-MIMO inherently accounts for multi-user interference and is thus more suitable for cellular applications.

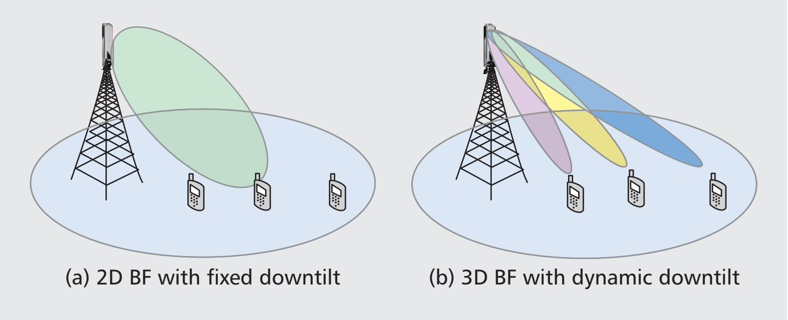

Figure 1. 2D vs 3D BF.

In addition to these multiplexing-oriented techniques, 3D MIMO also has the potential to facilitate enhanced spatial diversity via more sophisticated antenna deployment. However, it has been long understood that exploiting diversity gains implies sacrificing multiplexing gains. We will focus on multiplexing-oriented techniques in this article.

Interference coordination has been traditionally one main concern since the invention of the cellular concept in the last century. These various 3D MIMO techniques pose unprecedented opportunities as well as unique challenges to this long-standing problem, hence stimulating research and development innovations. Such efforts inevitably call for 3D MIMO channel measurements and modeling. These measurement-based channel models are not only indispensable for the development and verification of 3D MIMO technology, but also critical in justifying the benefit of 3D MIMO with respect to its 2D counterpart, because the propagation environment in the real world is inherently 3D, hence comparisons can only be fair using such channel models.

Channel Measurements and Modeling

The complete process of channel measurements and modeling includes the following steps:
1) Channel measurement
2) Raw data post-processing
3) Data analysis and channel modeling

These steps are intimately interlaced. For example, the last step consisting of data analysis and channel modeling may gain useful information in revising measurement campaigns in the first step. For raw data post-processing, spatial alternating generalized expectation-maximization (SAGE) has been widely adopted as one of the most popular channel estimation algorithms, thanks to its high accuracy, capability of estimating channel parameters, and applicability to almost every type of antenna array. In this section we will summarize and report some recent 3D MIMO channel measurement and modeling efforts.


(a) (b)

Item		Value	
Antenna type		UPA	ODA
Element number		32	56
Polarization		+–45 degree	+–45 degree
Spacing		0.5 wavelength	0.5 wavelength
Arrangement of elements		Planar	Cylinder
Angle range	Azimuth	–70°~70°	–180°~180°
	Elevation	–70°~70°	–55°~90°

Figure 2. Details of (a) UPA antenna and (b) ODA antenna.

Channel Measurements

Unlike the 2D MIMO, 3D MIMO channel measurement is still at a very early stage due to the elevated requirement on the measurement equipment. Currently only a few qualified channel sounders are available, for example, the PropSound channel sounder by Elektrobit and the RUSK MIMO channel sounder by Medav. More recently one of the leading mobile device manufacturers, Huawei, plans to design and produce their own channel sounder for 3D MIMO measurements. In the meantime several 3D MIMO measurement campaigns have been recently conducted and others are on the way to investigate the 3D MIMO propagation channels for various application scenarios (e.g. [4, 5] and the references therein). These mostly focus on the elevation related channel parameters, for example, elevation angles of departure (EAOD) and elevation angles of arrival (EAOA), whereas their impact on other important parameters, for example, polarization, Doppler, and power delay profile, have not yet received much attention.

These recent measurement campaigns use 2, 3.5, and 5 GHz as carrier frequencies, near-static scenarios including outdoor and outdoor-to-indoor (O2I) environments with both line-of-sight (LoS) and non-LoS conditions, and are typically wideband from 30 to 100 MHz. Recently, led by China Mobile Communications Corporation (CMCC) and Beijing University of Posts and Telecommunications (BUPT), a new 3D MIMO measurement campaign based on PropSound channel sounder at 3.5 GHz with 100 MHz bandwidth has been conducted for typical Urban Macro (UMa), Urban Micro (UMi), and O2I scenarios in Beijing, China [4]. To collect data with accurate 3D spatial information, specially designed Tx and Rx antennas are needed. In this measurement a uniform planner array (UPA) with 32 elements was used at the BS Tx, while a three dimensional omni-directional array (ODA) with 56 antennas was installed at the mobile terminals as the Rx, as depicted in Fig. 2. This measurement revealed that both EAOD and EAOA distributions can be well fitted by the Laplacian distribution [5].

Channel Modeling

Based on the understanding of 3D MIMO propagation characteristics via either theoretical analyses and/or channel measurements, one can develop accurate yet easy-to-use cannel models. We classify existing 3D MIMO channel models in terms of their respective modeling approaches. As summarized in Fig. 3 the two basic categories are deterministic versus stochastic models.

Deterministic channel models characterize 3D MIMO channel parameters in a purely deterministic manner. This category can be further classified into the geometry-based deterministic model (GBDM) and the finite-difference time-domain (FDTD) model. Both methods need an accurate database, high computation time, and use approximations of Maxwell's equation for their solution, while the former is in general based on ray-tracing, which exploits the high-frequency approximation of Maxwell's equation, and thus needs a detailed and time-consuming description of the site-specific propagation scenarios. Therefore the deterministic channel model typically has high complexity and cannot be easily generalized.

Stochastic channel models determine the physical parameters in a stochastic manner with or without presuming any underlying geometry and thus can be easily used to deal with various scenarios. These models can be further classified into the correlation-based model (CBM), the geometry-based stochastic model (GBSM), and the measurement-based pseudo-geometric model (MBPGM). The CBM characterizes the 3D MIMO channel matrix statistically in terms of the correlation among the matrix elements. Therefore the CBM aims at obtaining the spatial channel correlation function and then generates the channel response or some statistical properties of the channel based on such correlation function. It is an analytical model and thus comes with low complexity and could be readily used in theoretical analysis as well as systematic design of the 3D MIMO technology.

The GBSM is derived from some predefined stochastic distribution of the scatterers/clusters by applying the fundamental laws of wave propagation [6]. Such models can be easily adapted to diverse scenarios by modifying the stochastic distribution and properties of scatterers/clusters and the shape of the scattering region. GBSMs can be further classified into regular-shaped GBSMs (RS-GBSMs) and irregular-shaped GBSMs (IS-GBSMs) depending on whether scatterers/clusters are placed on regular shapes, for example, two-sphere and two-cylinder, or irregular shapes, as illustrated in Fig. 3. Its direct involvement of scatterers/clusters renders GBSM one of the most promising candidates for 3D MIMO channel modeling.

The MBPGM is entirely based on channel measurements. Examples of MBPGM include the widely used SCM and WINNER models [7], though both are often mistakenly referred to as

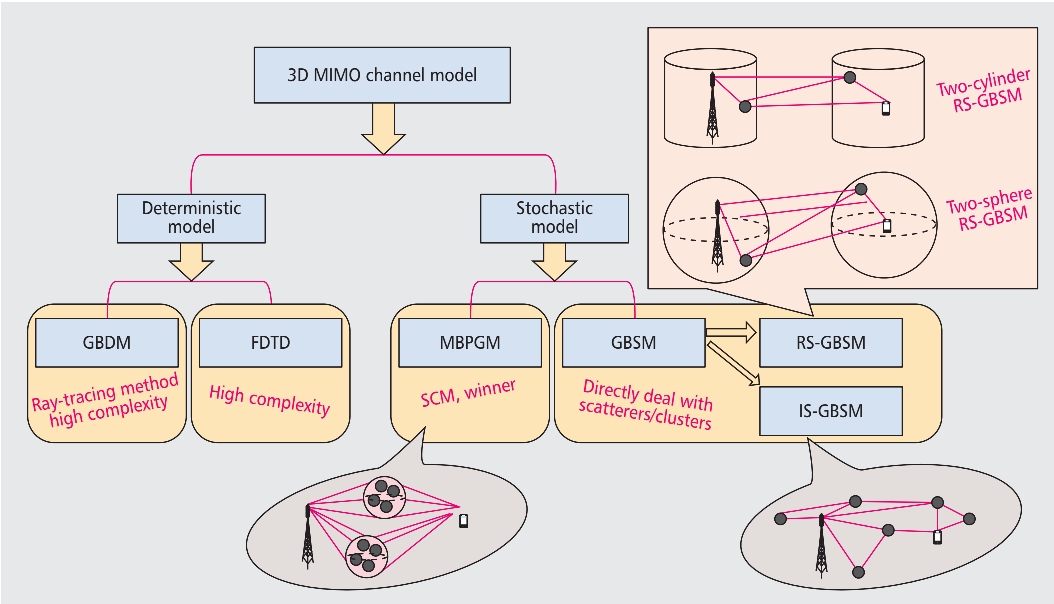

Figure 3. Classification of 3D MIMO channel models.

Unlike the 2D case, 3D MIMO channel measurement is still at a very early stage due to the elevated requirement on the measurement equipment. Currently, only a few qualified channel sounders are available, for example, the PropSound channel sounder by Elektrobit and the RUSK MIMO channel sounder by MEDAV.

GBSM. Such misunderstanding is largely due to the fact that the main channel parameters are all related to scatterers/clusters, for example, angle of arrival/departure and angle spread, as depicted in Fig. 3. However, notice that all these scatterer/cluster-related parameters are actually obtained solely based on measurements, instead of predefined stochastic distributions of the scatterers/clusters. Therefore, both SCM and WINNER models are more properly classified as MBPGM, and should be distinguished from GBSM.

So far MBPGMs, for example, SCM and WINNER models, are the most popular models for 3D MIMO channels. After the elevation-related parameters are obtained from measurements, for example, the Laplacian distribution parameters of the elevation angle, 2D the SCM and WINNER models can be readily extended to 3D models as discussed in [7]. The extended 3D SCM model is used for beamforming simulations in the following section using Huawei's system-level simulator. Two-cylinder RS-GBSM is used to show the impact of some important parameters on 3D MIMO channel capacity. In these simulations we use a 5.25 GHz carrier frequency, 91 Hz maximum Doppler frequency, 10^4 Hz sampling rate, two receive and two transmit antenna elements with antenna element spacing of half wavelength, consider SNR = 3 dB, and uniformly distributed azimuth angle of arrival (AAOA) and azimuth angle of departure (AAOD), and both EAOA and EAOD follow Laplacian distributions with variance 1. As shown in Fig. 4 this model involves an LoS component with Ricean factor K, single- and double-bounce components with energy-related parameters η_S and η_D that specify how much the single- and double-bounced rays contribute to the total scattered power and thus $\eta_S + \eta_D = 1$. From Fig. 4 it is clear that the increase of elevation angle spread results in an increase of the channel capacity, which agrees with our intuition. Figure 4 also demonstrates that the increase of η_D results in an increase of 3D MIMO channel capacity. This is because a larger η_D value implies richer scatterers in the 3D environment, and thus smaller spatial correlation. Moreover, the channel capacity decreases with the increase of K, which is because larger K values also lead to smaller spatial correlation. We believe these results will provide guidance for future channel measurement campaigns.

Key 3D MIMO Technologies

In this section we give an overview of the key 3D MIMO technologies as briefly mentioned above, namely the CSI-independent 3D beamforming, CSI-dependent spatial multiplexing including SU-MIMO and MU-MIMO techniques, as well as interference coordination techniques.

3D Beamforming

To demonstrate the benefit of dynamic 3D beamforming let us start with a simple simulation. We consider a snapshot in the LTE small cell network scenario, in which the small cells are independently deployed following a uniform distribution, while the UEs are deployed non-uniformly in different hotspots. We consider three different antenna tilting schemes: 2D beamforming with fixed tilting at 6°, cell-specific 3D beamforming, and UE-specific 3D beamforming. For cell-specific beamforming the antenna tilt angle for each BS is adjusted adaptively according to the specific cell coverage area, while for UE-specific beamforming the main lobe of the antenna beam is steered directly to the scheduled user location for each BS in each sub-frame. Note that in the majority of literature on this subject the weighting vectors used to achieve the desirable beamforming angles are obtained based on only the location of the UEs and no CSI is used (e.g. [3, 8].) The BS can determine the UE location by estimating the direction of arrival (DoA) of the received uplink signal with some specialized algorithms. The signal-to-interference-and-noise ratio

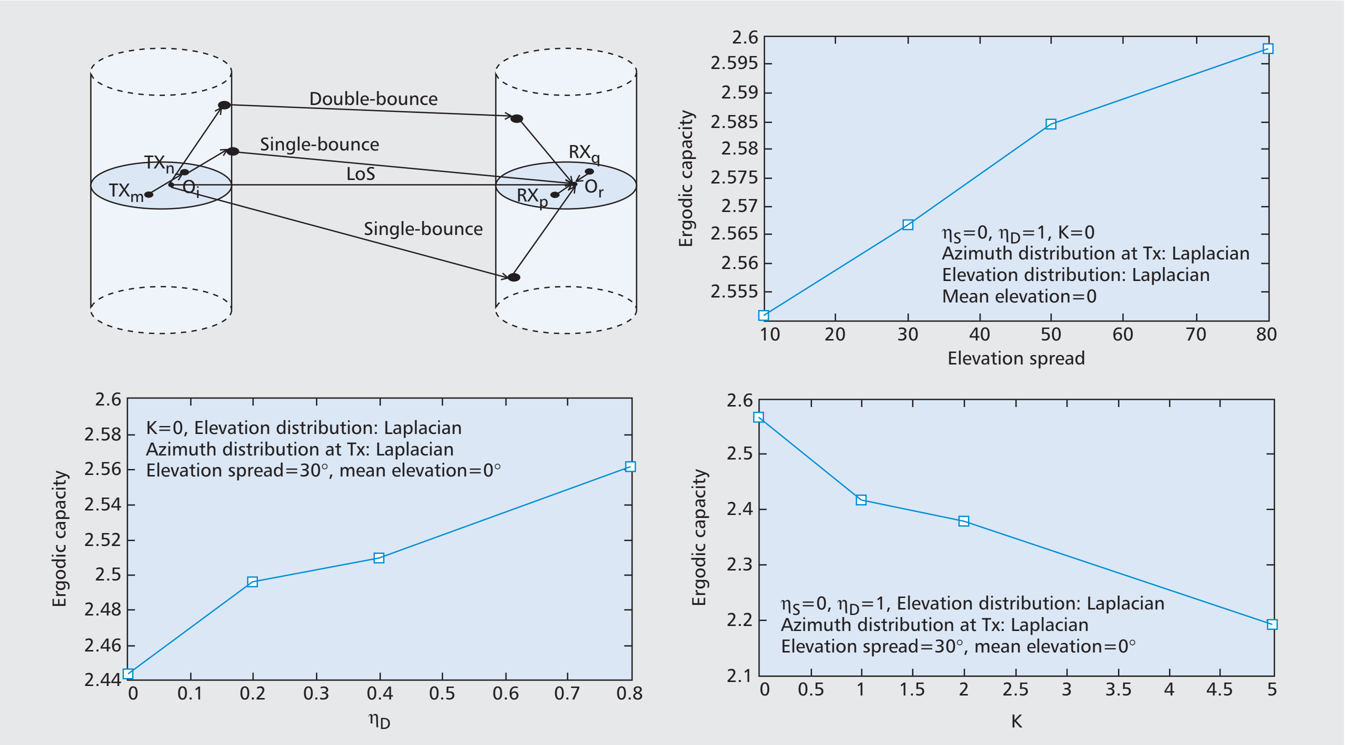

Figure 4. Two-cylinder RS-GBSM and simulation results of the impact of key channel parameters on 3D MIMO channel capacity.

(SINR) and user throughput comparisons are shown in Figs. 5a and 5b, respectively. It is observed that UE-specific 3D beamforming tilting provides the best performance in terms of both metrics.

With the capability of dynamic vertical beam adaptation, different kinds of 3D beamforming can be realized to exploit the added degree of freedom, in contrast to the conventional 2D counterpart where the beamforming is done only in the horizontal plane. Generally the vertical beam adaptation schemes can be classified into two categories: one is cell splitting with vertical sectorization, the other is UE-specific antenna downtilt adaptation. An example of vertical sectorization is that a single cell can be split into two cells by generating two separated vertical beams with different downtilts and beam width. Each cell will be served by a vertical beam separately. The simulation results in [9] show that 3 × 2 sectorization (three horizontal sectors, two vertical sectors per horizontal sector) can provide significant capacity gain.

For UE-specific antenna downtilt adaptation, more complicated processing is required since the antenna downtilt is adjusted for each UE such that the main lobe of the vertical beam is steered directly to the specific UE. In this case the received signal power at the scheduled UE is maximized. However the interference generated depends on the location of the UE and the beamwidth. The field trial in [10] considers a simple scenario with two BSs and five UEs. The downtilts are adjusted according to the location of each UE, while the vertical half-power beamwidth (HPBW) for the two BSs are 6.2° and 7.5°, respectively. The measurement results show that the UE-specific downtilt adaptation can increase the signal-to-interference ratio (SIR) at different UE locations by about 5-10 dB compared to a system with fixed downtilt at the BSs. A thorough comparison among various vertical sectorization schemes and the UE-specific downtilt adaptation scheme has been conducted in [3]. The results show that cell edge throughput benefits from vertical sectorization due to reduced interference at the cell edge, whereas UE-specific downtilt adaptation with limitation of minimum downtilt boosts spectral efficiency since the signal power at the scheduled UE is always maximized.

It is worth noting that for the added vertical-dimension beamforming the adjustment range of the vertical beam pattern is usually much less than in the horizontal direction, and the vertical beamwidth is also much narrower than the horizontal beamwidth. For example, in a typical macro cell scenario (according to 3GPP case 1) the antenna downtilt is 15° and the vertical half-power beamwidth (HPBW) is 10°, while the horizontal HPBW is 70°. This means that much finer and more accurate control of the vertical beam pattern is highly preferred in order to improve vertical beam separation and achieve fine granularity UE-specific vertical beam adaptation. The fine granularity beamforming can be realized by employing an active 2D or 3D antenna array with a large number of radiation elements.

Spatial Multiplexing

With the degrees of freedom provided in the spatial dimension of the MIMO channel, multiple data streams can be spatially multiplexed onto the MIMO channel for simultaneous transmission, giving rise to the so called spatial multiplexing gain. MIMO precoding is a transmit

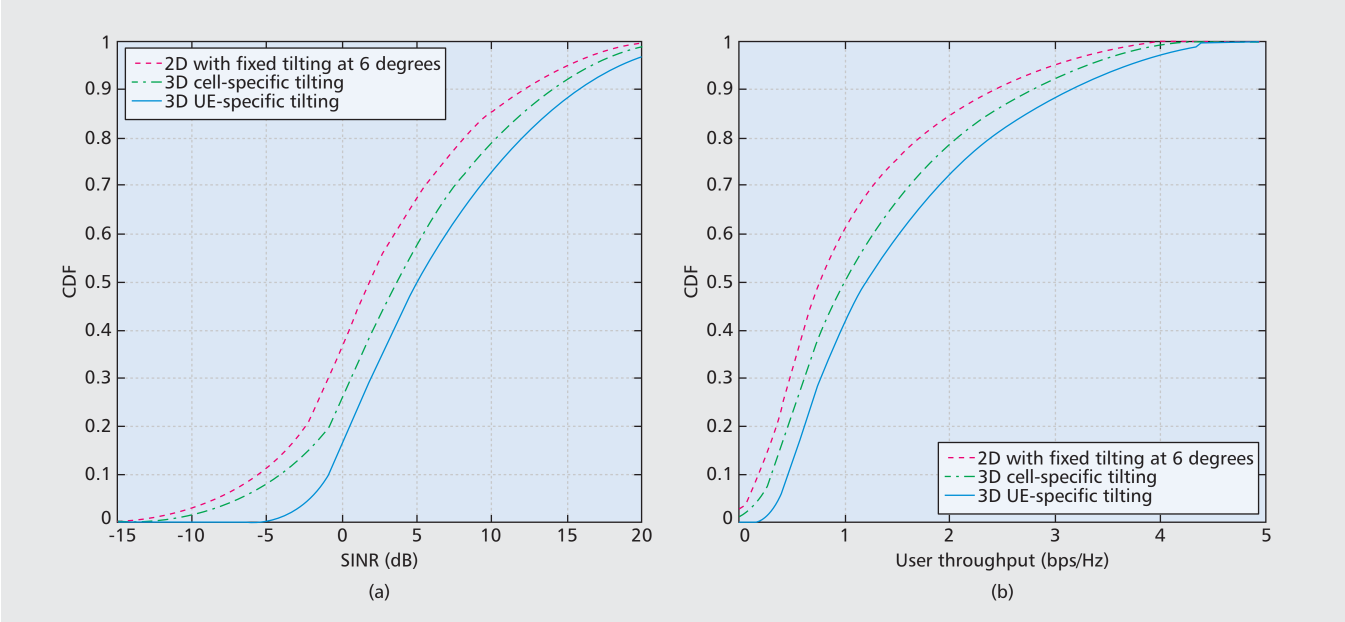

Figure 5. SINR and user throughput comparison between 2D vs 3D beamforming.

processing technique that utilizes CSIT to exploit the spatial multiplexing gain for improved system spectral efficiency. It can be regarded as a high resolution channel eigen-space beamforming to each UE, in contrast to the 3D physical beamforming discussed in the last section.

A proof-of-concept dynamic system-level simulation is conducted and the evaluation results are shown in Fig. 6. The scenario follows 3GPP case 1, where 19 cell sites (three sectors per cell site) are deployed in a hexagon grid with an average of 10 UEs per sector on the ground. The fast fading channel is generated using the 3GPP 2D SCM model, with the elevation dimension taken into consideration. The BS side vertical angle spread is 6°. A two-column ±45° linearly cross-polarized rectangular array is configured at the BSs with mechanical rotation of 15°. A cross-polarized two-element array with 0°/90° polarization is configured at the UEs. All antenna elements are separated by half wavelength. 2D MIMO and 3D MIMO are compared in both SU and MU scenarios. For the MU transmission, the maximum paired UE number is 4. For 2D MIMO only the linear four horizontal ports are active and the antenna downtilt is thus fixed and equal to the mechanical tilt. For 3D MIMO the 4 × 8 rectangular array is active and the antenna downtilt (as well as the shape of the array pattern) is adjusted for each UE according to the user channel condition. The comparison results for cell average spectral efficiency (SE) and cell edge SE are depicted in Figs. 6a and 6b, respectively. We can observe that for SU-MIMO a 12 percent gain is achieved for cell average SE, while the gain for cell edge SE is very limited. For MU-MIMO remarkable gains are achieved for both cell average SE (43 percent) and cell edge SE (41 percent).

Conventional 2D MIMO precoding has attracted much attention during the last decade and both linear and nonlinear precoding schemes based on different criteria have been proposed in the literature (e.g. [1, 11] and the references therein). In particular, linear precoding schemes provide a simple and efficient way to utilize CSIT and achieve desirable trade-offs between performance and complexity. Theoretically, for SU-MIMO it is well known that the optimal beam directions are the channel eigen-directions given the perfect CSIT. For MU-MIMO a number of precoding schemes have also been proposed in the literature (e.g. [11] and the references therein), including zero-forcing, block diagonalization, and so on. Most precoding schemes can achieve considerable spatial multiplexing gain even with imperfect CSIT, especially for MU-MIMO. A detailed description of the main features of MU-MIMO techniques adopted in LTE and LTE-A standards is provided in [12]. In the latest enhancement to MU-MIMO in LTE-A a maximum of eight transmit antennas are allowed to support simultaneous transmission of up to eight layers, and no more than four UEs can be co-scheduled considering the trade-off between performance and signaling overhead.

These conventional 2D MIMO precoding schemes may be readily applicable to the 3D MIMO scenario, at least in theory. However, unique features of 3D MIMO need to be taken into account when designing 3D MIMO precoding schemes for both optimality and complexity concerns. First, with an added dimension in vertical domain the 3D channel model is inherently different from the conventional 2D channel model, which may result in different precoding design principles. Second, the AAS-enabled 3D MIMO can potentially have very large size 2D or 3D antenna arrays at BSs, which will render signal processing on both Tx and Rx sides prohibitively complex.

An additional concern for frequency division duplex (FDD) systems is the excess feedback overhead in obtaining the CSIT for such large-scale antenna arrays. One approach to avoid the feedback overhead is to design a codebook con-

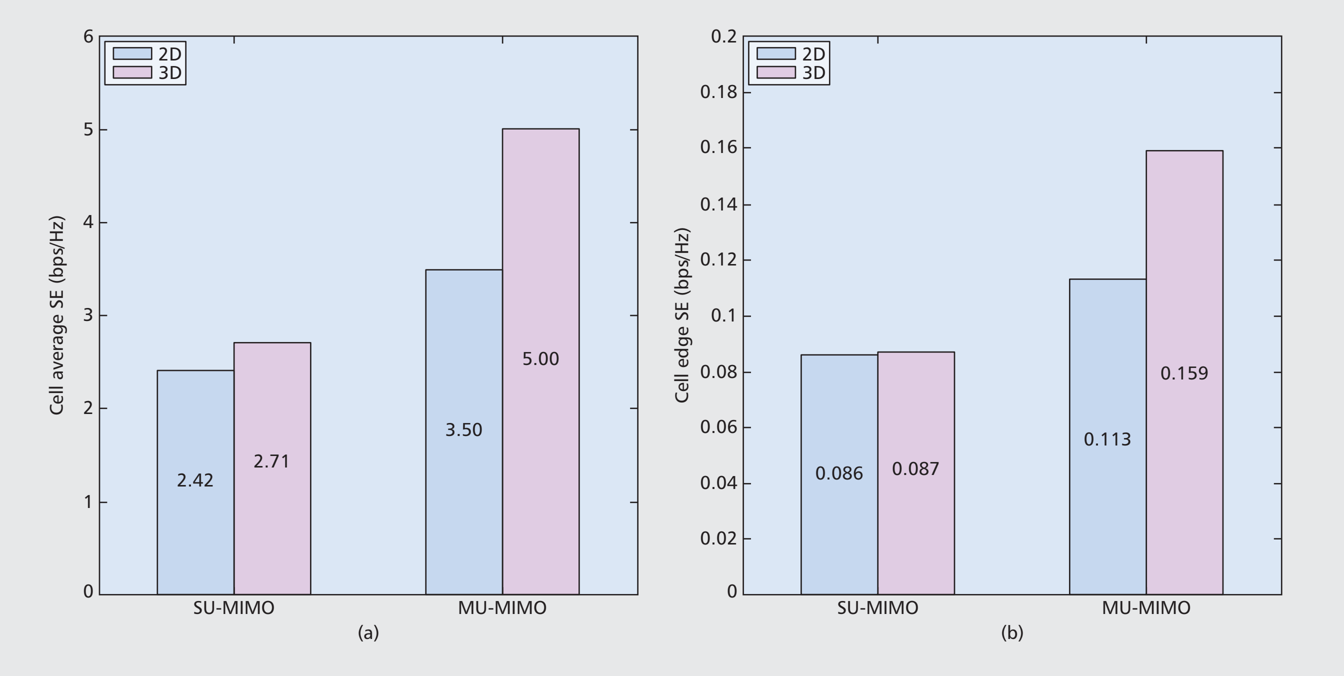

Figure 6. Cell average and cell edge SE comparison between 2D and 3D MIMO.

taining all possible quantized beamforming vectors. The codebook can be designed off-line and is known to both the Tx and Rx. The Rx can then choose the best beamforming vector from the codebook with different selection criteria based on the instantaneous channel knowledge and send the index back to the BS via a limited feedback channel. In this case the system performance depends heavily on the codebook quantization error, which is caused by the mismatch between the codebook space and the actual channel space. To a large extent the actual channel space depends on the antenna response of the antenna arrays. In the conventional 2D scenario the codebook that is designed based on linear antenna arrays thus cannot be directly adopted in the 3D scenario with 2D or 3D antenna arrays. In addition the large-scale antenna arrays may result in high dimensionality of the channel eigen-space, which in turn results in a large codebook size and further increases the feedback overhead.

On the other hand, for time division duplex (TDD) systems no feedback is needed since the CSIT can be obtained by channel reciprocity. However, the pilot contamination problem emerges and the effect is especially significant for 3D MIMO with the incorporation of large-scale 2D or 3D antenna arrays. Some suggest that pilot contamination is the limiting factor in the asymptotic sense as the number of antennas approaches infinity. The common understanding is that some level of coordination accounting for this problem is a necessity to ensure reasonable gain as the antenna array grows in size. For example, the optimal allocation and coordination of pilot sequences at the UE would be highly desirable. An insightful survey on several works proposed to deal with the pilot contamination problem can be found in [13].

Interference Coordination

Interference is always a major obstacle in achieving higher spectral efficiency. With 3D beamforming the situation becomes more complicated in comparison with 2D beamforming. With the latter the vertical beam direction cannot be dynamically adjusted to maximize the received signal power for each UE. However, this also confines most of the interference from leaking to the neighboring cells. On the other hand, with the capability of vertical beamsteering 3D beamforming can dynamically adjust the beam direction according to the location of each UE such that the received signal power for each UE can be maximized. However, the generated inter-cell interference can be very complicated. Therefore it is not straightforward whether the overall system performance (spectral efficiency as well as cell edge user throughput) can be improved.

In the existing literature there is a lack of solid analytical study on this problem. The simulated study in [3] shows that 3D beamforming with direct steering of the vertical beam toward the UE without any downtilt limitation performs better than fixed downtilt beamforming in terms of cell edge user throughput, but worse in terms of the overall spectral efficiency. Hence a more thorough investigation is needed to exploit the additional degree of freedom provided by the vertical dimension in order to manage the interference more flexibly and effectively. For example, advanced beam coordination methods may be a good option. It is also possible to combine 3D beamforming with existing interference management schemes in the literature, such as various coordinated multipoint transmission/reception (CoMP) techniques [14] and inter-cell interference coordination (ICIC) methods [15]. For 3D MU-MIMO, coordination can even be achieved at the precoding stage across BSs.

Opportunities and Challenges

Still at the launching stage, 3D MIMO research and development are not short of challenges and opportunities. Next we will discuss some of these open issues from various perspectives.

Measurements and Channel Modeling

So far 3D MIMO channel measurements are mainly conducted for UMa, UMi, and O2I scenarios; more measurement campaigns are needed for indoor hotspot scenarios. Furthermore, more comprehensive 3D MIMO channel measurement campaigns are needed to investigate the impact of 3D spatial environments on a wide range of key channel characteristics, for example time variation, stationarity, polarization, and so on, for various scenarios.

Currently MBPGM has been widely used for analyzing and evaluating 3D MIMO technologies both in academia and industry. For example, the 3D SCM model extended from the standardized 2D SCM model. However, current MBPGMs only take the elevation-related parameters into consideration. While the impacts of elevation angle on other important channel parameters, for example Doppler, non-stationarity, polarization, and so on, have not been considered. Based on further channel measurements, these impacts should be modeled for future MBPGMs.

On the other hand, considering that 3D MIMO technology will fully explore the 3D spatial environments that consist of scatterers, GBSMs should be used for accurate modeling and thus facilitating improved designs of 3D MIMO technology. Based on dedicated channel measurements and analysis, placing scatterers/clusters with certain distributions around the Tx and Rx in the 3D environments, setting their properties, and collecting all the received rays from greatly-simplified ray tracing to build real 3D MIMO GBSMs will be a future research direction for accurate 3D MIMO channel modeling. In addition, CBMs will be useful to bring us insight on how the different spatial correlation characteristics between 3D MIMO and 2D MIMO channels can be used for optimum design of 3D MIMO precoding schemes.

Key 3D MIMO Technologies

So far the effects of the 3D beamforming techniques have been studied mainly by system-level simulations and field trial evaluations in very simple scenarios. There is an urgent need for analytical study of the 3D beamforming design, in terms of how to optimally determine the cell border for cell splitting, what would be the optimal beam pattern and downtilt for each cell, and so on. More rigorous formulation of the optimization problem, together with careful analysis of the complexity-granularity trade-off, will significantly assist the massive deployment of 3D MIMO technology.

For 3D beamforming, in order to realize more fine granularity beamforming in the vertical domain, the number of antenna elements required can be very large, which will pose great challenges. First, the number of active antenna array elements that can be equipped at a BS is usually limited by the BS form factor. As a result, small-scale and more cost-efficient hardware design becomes challenging, especially for the electromagnetic elements, such as duplexers and filters, which are very difficult to be miniaturized due to the physical constraints, including wavelength, current densities, conductivity, and so on. In addition, with the potential large size antenna arrays, signal processing complexity becomes very high. The BS power consumption could also be a major concern taking into account the cost of heavy baseband signal processing. Therefore optimized (real-time and low-complexity) distributed signal processing algorithms need to be carefully designed and implemented. Furthermore, the synchronization of different transceiver and antenna element chains becomes complicated and is of great importance for the overall system performance. Note that the number of antennas at the UE does not need to be increased beyond what is defined in LTE/LTE-Advanced.

For cooperative 3D MIMO operations, where multiple BSs are clustered together to form a distributed antenna array and perform MU-MIMO operations, the overhead can be prohibitive. First, the CSI acquisition overhead is very high, considering the large size of the antenna arrays. The effect of errors in CSI estimation, quantization, and feedback to the system performance also need to be investigated thoroughly. In addition, in order to facilitate cooperation among multiple BSs the backhaul is also a non-negligible challenge.

At the same time, as the granularity of 3D beamforming continues to be refined it is expected that the number of BS antenna elements will approach the level that is considered massive MIMO (e.g. [13] and the references therein). Though 3D MIMO with finite antenna elements can be considered as an intermediate stage toward massive MIMO, the latter boasts drastically different (and likely simplified) signal processing from conventional precoding. On both the theoretical side and the operational side, it is worth investigating when and whether such a transition will take place and how the 3D MIMO community should prepare for that.

Conclusions

In this article we introduced the fundamentals and application scenarios of the emerging 3D MIMO technology and identified several key issues critical to the research and development of this technology. In terms of the channel measurements and modeling, we reported the recent measurement campaign conducted by CMCC and BUPT. In addition we are the first to comprehensively classify prevalent 3D MIMO channel models. In terms of the key 3D MIMO technologies, we used proof-of-concept simulations based on the system-level simulator provided by Huawei. We then summarized existing work in terms of 3D beamforming, SU- and MU-MIMO, as well as interference coordination. Last but not least, we delineated the opportunities and challenges on all these aspects, and laid out research issues together with possible directions of the next-phase 3D MIMO research and development.

the synchronization of different transceiver and antenna element chains becomes complicated and is of great importance for the overall system performance. Note that the number of antennas at UE does not need to be increased beyond what is defined in LTE/LTE-Advanced.

Though 3D MIMO with finite antenna elements can be considered as an intermediate stage toward massive MIMO, the latter boasts drastically different (and likely simplified) signal processing from conventional precoding. On both the theoretical side and the operational side, it is worth investigating when and whether such a transition will take place and how the 3D MIMO community should prepare for that.

Acknowledgment

This work was jointly supported by the National Science Foundation (Grant No. 5388740), the National Natural Science Foundation of China (Grant No. 61172105, 61101079 and 61322110), the National 863 Project (Grant No. 2014AA01A706), the Important National Science & Technology Specific Project of China (Grant No. 2013ZX03003006), the Science Foundation for the Youth Scholar of Ministry of Education of China (Grant No. 20110001120129), and the State Key Laboratory of Rail Traffic Control and Safety (RCS2014K008), Beijing Jiaotong University.

References

[1] G. B. Giannakis *et al*., *Space-Time Coding for Broadband Wireless Communications*, John Wiley & Sons, Inc., Jan. 2007.

[2] X. Ma, L. Yang, and G. Giannakis, "Optimal Training for MIMO Frequency-Selective Fading Channels," *IEEE Trans. Wireless Commun*., vol. 4, no. 2, 2005, pp. 453–66.

[3] H. Halbauer *et al*., "Interference Avoidance with Dynamic Vertical Beamsteering in Real Deployments," *Proc. IEEE Wireless Communications and Networking Conf. Workshop on 4G Mobile Radio Access Networks*, Paris, France, April 1–4, 2012, pp. 294–99.

[4] 3GPP R1-132543, "UMa Channel Measurements Results on Elevation Related Parameters," *China Mobile*, April 2013.

[5] J. Zhang *et al.*, "Three-Dimension Fading Channel Models: A Survey of Elevation Angle Research," *IEEE Commun. Mag*., accepted, 2013, http://wireless.pku.edu.cn/home/chengx/CMag_2013.pdf.

[6] X. Cheng *et al*., "An Adaptive Geometry-Based Stochastic Model for Non-Isotropic MIMO Mobile-to-Mobile Channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 9, 2009, pp. 4824–35.

[7] Y.-H. Nam *et al.*, "Full-Dimension MIMO (FD-MIMO) for Next Generation Cellular Technology," *IEEE Commun. Mag*., vol. 51, no. 6, 2013, pp. 172–79.

[8] B. Yu *et al.*, "Load Balancing with Antenna Tilt Control in Enhanced Local Area Architecture," *Proc. IEEE 79th Vehicular Technology Conf. Spring* (VTC 2014-Spring), Seoul, Korea, May 18–21, 2014.

[9] O. Yilmaz, S. Hamalainen, and J. Hamalainen, "System Level Analysis of Vertical Sectorization for 3GPP LTE," *Proc. 6th International Symp. Wireless Communication Systems* (ISWCS), Siena-Tuscany, University of Siena, Italy, Sept. 7–10, 2009, pp. 453–57.

[10] M. Danneberg *et al*., "Field Trial Evaluation of UE Specific Antenna Downtilt in an LTE Downlink," *Proc. Int'l ITG Workshop on Smart Antennas* (WSA), Dresden, Germany, March 7-8, 2012, pp. 274–80.

[11] Q. Spencer, A. Swindlehurst, and M. Haardt, "Zero-Forcing Methods for Downlink Spatial Multiplexing in Multiuser MIMO Channels," *IEEE Trans. Signal Process*., vol. 52, no. 2, 2004, pp. 461–71.

[12] C. Lim *et al*., "Recent Trend of Multiuser MIMO in LTE-Advanced," *IEEE Commun. Mag.*, vol. 51, no. 3, 2013, pp. 127–35.

[13] E. G. Larsson *et al*., "Massive MIMO for Next Generation Wireless Systems," *IEEE Commun. Mag*., vol. 52, no. 2, 2014, pp. 186–95.

[14] J. Lee *et al.*, "Coordinated Multipoint Transmission and Reception in LTE-Advanced Systems," *IEEE Commun. Mag*., vol. 50, no. 11, 2012, pp. 44–50.

[15] G. Boudreau *et al.*, "Interference Coordination and Cancellation for 4G Networks," *IEEE Commun. Mag*., vol. 47, no. 4, 2009, pp. 74–81.

Biographies

XIANG CHENG [S'05-M'10-SM'13] received a Ph.D. degree from Heriot-Watt University and the University of Edinburgh, Edinburgh, U.K., in 2009, where he received the Postgraduate Research Thesis Prize. He has been with Peking University, Beijing, China, since 2010, first as a Lecturer, and then as an Associate Professor since 2012. His current research interests include mobile propagation channel modeling and simulation, next generation mobile cellular systems, intelligent transportation systems, and hardware prototype development. He has published more than 80 research papers in journals and conference proceedings. He received the best paper award from the IEEE International Conference on ITS Telecommunications (ITST 2012) and the IEEE International Conference on Communications in China (ICCC 2013). He received the "2009 Chinese National Award for Outstanding Overseas Ph.D. Student" for his academic excellence and outstanding performance. He has served as Symposium Leading-Chair, Co-Chair, and a Member of the Technical Program Committee for several international conferences. He is now an Associate Editor for *IEEE Transactions on Intelligent Transportation Systems*.

BO YU [S'08] received a B.S. degree in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2008, and an M.S. degree in electrical engineering from the University of Florida, Gainesville, in 2010. He is currently pursuing a Ph.D. degree with the Department of Electrical and Computer Engineering, Colorado State University, Fort Collins. His research interests include spectrum and energy efficiency in cellular networks.

LIUQING YANG [S'02-M'04-SM'06] received her Ph.D. degree from the University of Minnesota, Minneapolis, in 2004. She then joined the University of Florida, Gainesville, and became an Associate Professor in 2009. She is currently an Associate Professor with the Department of Electrical and Computer Engineering at Colorado State University. Her general interests are in the areas of communications and signal processing. She was the recipient of the ONR Young Investigator Program (YIP) award in 2007, and the NSF Faculty Early Career Development (CAREER) award in 2009. She is serving as an active reviewer for more than 10 journals, as TPC chair/member for a number of conferences, and has served on the editorial board for *IEEE Transactions on Communications*, *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Intelligent Transportation Systems*, and *Phycom: Physical Communication*.

JIANHUA ZHANG received her Ph.D. degree in circuit and system from Beijing University of Posts and Telecommunication (BUPT) in 2003. She was an associate professor from 2005 and is now professor of BUPT. She has published more than 100 articles in refereed journals and conferences. She was awarded "2008 Best Paper" of the *Journal of Communication and Network*. In 2007 and 2013 she received two national novelty awards for her contribution to the research and development of Beyond 3G TDD demo system with 100Mb/s@20MHz and 1Gb/s@100MHz respectively. In 2009 she received the "second prize for science novelty" from the Chinese Communication Standards Association for her contributions to ITU-R and 3GPP in IMT-Advanced channel model. Her current research interests include channel measurement and modeling for broadband multiple antenna system, transmission techniques for 4G and 5G systems, channel emulator, OTA test, and and so on.

GUANGYI LIU [M] received his B.S. in physics from Chinese Ocean University in 1997. He received his M.S. and Ph.D. degrees in circuits and systems from Beijing University of Posts and Telecommunications in 2000 and 2006, respectively. Since 2006 he has been working for the Research Institute of China Mobile Communication Corporations. He is now chief technical officer of the Wireless Department of the same institute. His research interests include LTE/LTE-Advanced/5G standardization and trial, system performance modeling and evaluation, channel measurement and modeling, and flexible spectrum usage.

YONG WU received the B.S. degree from Dalian University of Technology, Dalian, China in 2003, and a Ph.D. degree from Tsinghua University, Beijing, China in 2008, both in electronics engineering. He is currently working at Huawei Technologies, Beijing. His research interests include multiple antenna processing, interference suppression, and system-level modeling and evaluation of wireless communications.

LEI WAN is a senior expert of Wireless Research and Standards at Huawei, currently responsible of LTE-Advanced research and 3GPP RAN standardization work in Huawei. Her main focus areas are network topology and air-interface evolution. She is known as the expert on TDD and the system-level evaluation methodology in the industry, as the main driver of LTE TDD/FDD frame structure merging, CoMP, LTE-Hi (3GPP R12 small cell enhancement) and U-LTE (unlicensed LTE) research and standardization, and the

inventor of the physical layer MI quality model that is widely used in system-level simulation. She has long experience in the wireless communication industry, with the background of WCDMA, TD-SCDMA, LTE and LTE-Advanced. Her research interests cover FDD and TDD harmonization, network topology evolution as CoMP and HetNet, traffic adaptive system design, interference coordination and the evaluation methodology.