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Investigation on Key Technologies in Large-Scale MIMO

Xin Su[1] (粟　欣), *Member, IEEE*, Jie Zeng[1,*] (曾　捷), *Member, IEEE*, Li-Ping Rong[1,2] (容丽萍) and Yu-Jun Kuang[2] (邝育军), *Member, IEEE*

[1] *Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing 100084, China*

[2] *College of Communication and Information Engineering, University of Electronic Science and Technology of China Chengdu 611731, China*

E-mail: {suxin, zengjie}@tsinghua.edu.cn; imkongjian@163.com; kyj@uestc.edu.cn

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Abstract Large-scale MIMO (multiple-input multiple-output) systems with numerous low-power antennas can provide better performance in terms of spectrum efficiency, power saving and link reliability than conventional MIMO. For large-scale MIMO, there are several technical issues that need to be practically addressed (e.g., pilot pattern design and low-power transmission design) and theoretically addressed (e.g., capacity bound, channel estimation, and power allocation strategies). In this paper, we analyze the sum rate upper bound of large-scale MIMO, investigate its key technologies including channel estimation, downlink precoding, and uplink detection. We also present some perspectives concerning new channel modeling approaches, advanced user scheduling algorithms, etc.

Keywords large-scale multiple-input multiple-output, channel estimation, downlink precoding, uplink detection

1 Introduction

The explosive growth of wireless data service calls for more new spectrum resources, while the available spectrum for further wireless communication systems is expensive and limited. As we all know, MIMO (multiple-input multiple-output) systems with multiple antennas at the transmitter and receiver promise high capacity and link reliability by spatial multiplexing and diversity[1]. MIMO technology is becoming mature, and has been applied to 4 G and Beyond 4 G systems combining with orthogonal frequency division multiplexing (OFDM)[2] or orthogonal frequency and code division multiplexing (OFCDM)[3-4] technology. Since the capacity of an MIMO system greatly increases with the minimum number of antennas at the transmitter and receiver sides under rich scattering environments[5], the large-scale MIMO[6] shown in Fig.1 is one of the most important techniques to address the issue of exponential growth in wireless data service by using spatial multiplexing and interference mitigating. In terms of power efficiency, the large-scale MIMO system can transmit concentrated beams of signals selectively to particular users at once utilizing channel state information (CSI), improving the signal to noise ratio (SNR) and reducing the power any antenna needed to send a given amount of information. Large-scale MIMO also credibly addresses the sweet spot where the amount of data transmitted increases while the energy required for that transmission is reduced. Hence, the total transmission power can be reduced sharply, which is a valuable feature since energy efficiency is becoming more and more important in wireless communication. Due to the low power consumption and high spectrum efficiency, large-scale MIMO systems can offer excellent economic benefits.

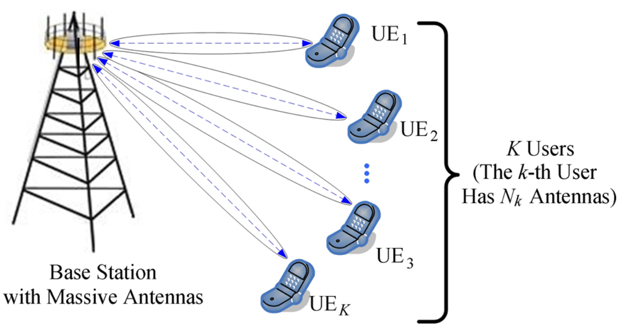

Fig.1. Large-scale MIMO system schematic.

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*Corresponding Author

Large-scale MIMO can provide a huge increase in capacity along with obvious energy saving, but requires tremendous changes in the way networks are provided since something particular appears when additional numerous antennas are installed[7]. Firstly, random things (e.g., channel characteristics) tend to be deterministic, and the high-dimensional matrices whose spatial dimensions enlarge by using a large number of transmit/receive antennas tend to be well conditioned as the antenna array grows large. Some matrix operations (e.g., inversions) become simple and can be completed fast by using a series of extension techniques[8]. Secondly, the bigger the aperture of the antenna array, the more resolutions of the antenna array. When the antenna array grows large, the communication performance of the array depends on the actual statistics of the propagation channel rather than the aggregated properties of the propagation such as asymptotic orthogonality. Finally, several conclusions of large-scale MIMO systems were drawn in [9]. Theoretically, the effects of fast fading and uncorrelated noise in multi-cell multi-user MIMO systems with an infinite number of base station (BS) antennas vanish. The number of users and throughput per cell would have no relation with the size of the cell. The system performance is only limited by inter-cell interference caused by the reuse of the pilot sequences in adjacent cells (pilot contamination)[10-11]. Moreover, the required transmitted energy per bit becomes arbitrarily small, and the simplest forms of precoders/detectors become optimal[12].

The advantages and features above have motivated entirely new theoretical research of large-scale MIMO. The first advocacy of the use of pretty large antenna arrays is in [9], and then caused widespread concern and great research interest[13-14]. Especially, the large antenna array has mostly attracted pure academic interest when the number of receive and transmit antennas grows without bound. Some asymptotic capacity scaling laws were obtained under ideal situations. Recently, the research of large-scale MIMO gradually turns to practical system aspects from pure theoretical study. Paper [9] displays a system with unlimited number of transmit antennas but under realistic assumptions. A time division multiplexing (TDM) cellular system with the bandwidth of 20 MHz but without cooperation among the BSs may contain more than 40 single-antenna users. The net average throughput of users is 17Mbps both on the uplink and downlink. The system exploits the CSI acquired by uplink pilot measurements to achieve a throughput of 3.6Mbps with 95% probability. Besides, the problem that how many antennas are needed by large-scale MIMO systems attracts extensive concern and is fully investigated in [8].

In this paper, we focus on the analysis of the sum rate upper bound, the research status of key technologies, and the discussion of research hotspots of large-scale MIMO. The rest of the paper is organized as follows. In Section 2 we start with the overall system to analyze the sum rate upper bound of a large-scale MIMO system. In Section 3, the key technologies to approach this upper bound, including channel estimation, downlink precoding, and uplink detection, are introduced. We focus on their technical features and research status. Based on our investigation and analysis, some future research hotspots are listed in Section 4. Section 5 concludes this paper.

2 Sum Rate Upper Bound

It is known that the capacity of an MIMO system increases linearly with the minimum number of antennas at the transmitter and receiver sides. In essence, the more antennas the transmitter/receiver is equipped with, and the more degrees of freedom the propagation channel can provide, the better system performance in terms of link reliability or data rate the system can obtain. However, the number of antennas in a physical and practical system cannot be arbitrarily large subjected to physical constraints, energy consumption for the signal processing, increasing complexity of hardware and computation[15]. Besides, if the number of receive and transmit antennas tends to be infinite, the mathematical models for the physical reality will collapse. For example, the aggregated received power at some points would surpass the transmitted power, and then without any physical significance. There is even a great amount of engineering difficulties that do not appear until the physical models break down. Thus, the problem that how many BS antennas are needed in a large-scale MIMO system is urgent to be solved. Some theory analysis considers the large-scale MIMO systems installed antenna arrays with an order of magnitude more elements than that in the existing systems, say a hundred antennas or even more. Paper [6] considers large-scale MIMO systems with at least a hundred but perhaps less than a thousand of BS antennas. In addition, many studies of large-scale MIMO consider the systems whose number of transmit and receive antennas with the order of tens to hundreds[16-17].

More intuitively, [14] analyzes the sum rate of a system comprised of four cells, with 10 single-antenna users each. It shows that at low SNR, the achievable rate is significantly improved by installing numerous additional BS antennas. The sum rate tends to be stable when the number of BS antennas is more than one hundred, approaches the lower bound on the achievable uplink rate with an unlimited number of BS antennas, and becomes independent on the SNR. The sum rate basically keeps constant when the number of BS antennas continues to grow.

For the systems with different antenna arrays, we give some simulation results of sum rate performance in Fig.2. It is shown that the sum rate first improves as the number of BS antennas M increases for a given number of multiplexing layers K (which is equal to the number of single-antenna users severed simultaneously), and then tends to be stable when the number of BS antennas grows up to a certain value. When K is larger than 8, the sum rate does not slow the growth rate down until the number of BS antennas grows greater than 128. While if K is small (e.g., $K = 1, 2, 4$), when the number of BS antennas grows approximately to 64, the sum rate improves slowly and even tends to be stable. It means that it makes no sense to keep huge additional BS antennas to improve the system capacity.

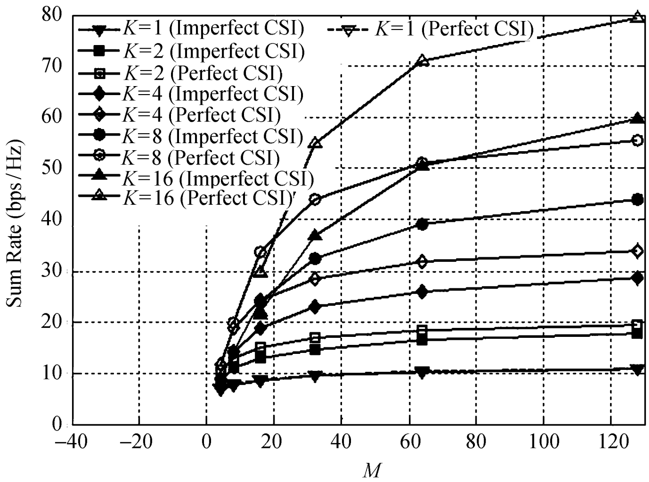

Fig.2. Capacity analysis (independent and identically distributed, $CN(0,1), \lambda = 0.1$), $SNR = 15\,\text{dB}$.

In summary, the number of BS antennas needed in a large-scale MIMO system depends on the precise circumstances. It may be set to 64 when the number of multiplexing layers is no larger than 4, and be set to 128 when that of multiplexing layers is larger than 8.

3 Key Technologies

3.1 Channel Estimation

Accurate CSI at the transmitters/receivers is required for uplink detection and downlink precoding. Hence, accurate channel estimation is of great importance. Meanwhile, channel estimation is a challenge in wireless system due to the inherent and highly dynamic feature of the radio channel. The MIMO broadcast channel based on user scheduling and precoding which uses the CSI acquired by channel estimation is shown in Fig.3.

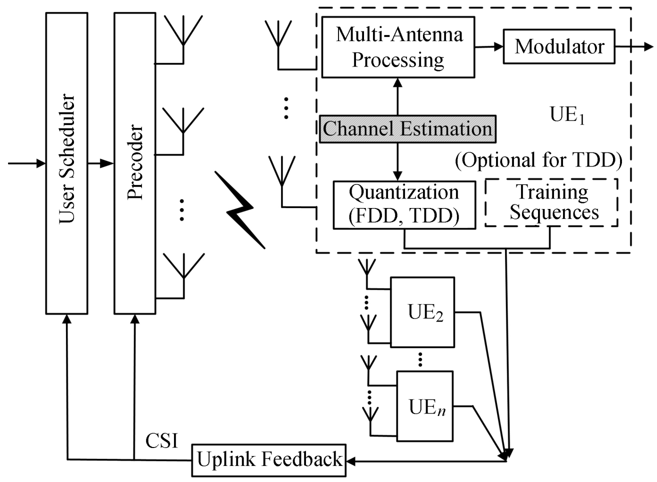

Fig.3. MIMO broadcast channel.

Several channel estimation techniques, including blind[18], semi-blind[19], and pilot-based channel estimation[13,20], are adopted to exploit radio channel statistics. Considering the computational complexity and convergence, large-scale MIMO prefers to adopt the pilot-based channel estimation. In LTE Rel-10, the reference signals are specified for the channel quality indicator (CQI) measurement of frequency division duplex (FDD) systems with up to 8 antennas. However, the number of BS antennas in a large-scale MIMO system is far more than 8. Since the number of reference signals increases linearly with the number of BS antennas, there will be no resource elements for data transmission when the number of BS antennas grows large. Thus, we may achieve data transmission at the cost of the accuracy of channel estimation by reducing the overhead of reference signals in FDD systems. And more efficient pilot pattern should be designed. While for a time division duplex (TDD) system, the different phases in a coherence interval are shown in Fig.4. Channel reciprocity can be adopted to train on the uplink and estimate channels to obtain an accurate CSI at the transmitters (CSIT)[21]. However, the pilot contamination should be addressed. So far, the study of channel estimation through TDD pilots relying on channel reciprocity has just started, and the detailed investigation of it is still a question for future research.

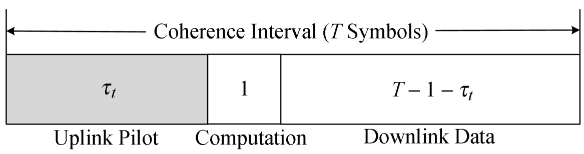

Fig.4. Different phases in a coherence interval.

Besides, varieties of criteria have been proposed for channel estimation. Without any knowledge of channel statistics, least squares (LS) is simple and adequate at high SNR, but suffers from high mean square error (MSE). Minimum mean square error (MMSE) can employ the second order statistics of the channel condition to minimize the MSE, but with high complexity, which grows exponentially with the observation samples and makes the system even more complex. Paper [22] proposed new scaled LS (SLS) and relaxed MMSE techniques which require less knowledge of the channel second order statistics and/or obtain better performance than the conventional LS and MMSE. Besides, a new method was proposed by using evolutionary programming (EP) to combine LS and MMSE channel estimators in [23], and achieved a good performance over the existing methods.

3.2 Downlink Precoding

On the MIMO downlink[24], the best performance will be achieved in an interference free (IF)[25] system without any inter-user interference. For the practical systems, we can adopt precoding at transmitters to mitigate the inter-user interference and reduce the burden of the receivers by signal processing.

We focus on the TDD system with channel reciprocity here. Considering a single-cell large-scale MIMO system consisting of M BS antennas and K single-antenna users, M and K are assumed to be large, but with a fixed ratio α =M/K. When M is not much larger than K, that is, α is small, the nonlinear precoding methods, such as the Tomlinson-Harashima precoding (THP)[26] and vector perturbation (VP)[27-28], are important techniques, which can well approximate to the capacity limit in a multi-antenna broadcast channel. Paper [6] discusses different precoding methods and gives their SNR and SINR expressions shown in Table 1.

Table 1. SNR and SINR Expressions

Precoding	Perfect CSI	Imperfect CSI
IF	$\rho_f\alpha$	—
VP	$\frac{\rho_f\alpha\pi}{6}(1-\frac{1}{\alpha})^{(1-\alpha)}$	N/A
MF	$\frac{\rho_f\alpha}{\rho_f+1}$	$\frac{\varepsilon^2\rho_f\alpha}{\rho_f+1}$
ZF	$\rho_f(\alpha-1)$	$\frac{\varepsilon^2\rho_f(\alpha-1)}{(1-\varepsilon^2)\rho_f+1}$

It shows that the performance gap of zero forcing (ZF) precoding to IF is significant, and there is room for improvement by VP (as a representative of nonlinear methods) when $M \approx K$. When M is twice as many as K, the gap of ZF precoding to an IF system is only 3 dB. VP will close to IF when $\alpha \approx 1.79$, but cannot surpass it, which makes the expression meaningless. Since the number of users served simultaneously is limited, the number of BS antennas is generally much larger than that of user antennas in a practical large-scale MIMO system. Thus, there is not much gain by using nonlinear methods, while linear methods are virtually optimal and available in large-scale MIMO systems.

Let $\boldsymbol{G}$ denote the channel matrix, the precoding matrixes of different linear methods, including matched filtering (MF)[29], ZF[30], and regularized-ZF (RZF)[31], are given in Table 2. Paper [6] shows that MF is optimal when $M \to \infty$. But with finite transmit antennas, MF needs at least two orders of magnitude more BS antennas than ZF to gain the same capacity. ZF inverts the channel by means of the pseudo-inverse to assure its performance close to that of the IF system, but with a disadvantage that processing cannot be done distributedly by at each antenna separately. As a compromise between MF and ZF, RZF can achieve the performance of MF with the number of antennas reduced by one order of magnitude. Besides, the same conclusion in [31] shows that RZF can attain the same performance as that of beamforming (BF) with one order of magnitude fewer antennas in both uncorrected and correlated fading channels.

Table 2. Precoding Matrixes of Different Linear Precoding Methods

Precoding Method	Precoding Matrix
MF	$(\boldsymbol{G}^{\mathrm{T}})^{\mathrm{H}} = \boldsymbol{G}^{\dagger}$
ZF	$(\boldsymbol{G}^{\mathrm{T}})^{\dagger} = \boldsymbol{G}^{\mathrm{H}}(\boldsymbol{G}^{\mathrm{T}}\boldsymbol{G}^{\mathrm{H}})^{-1}$
RZF	$\boldsymbol{G}^{\mathrm{H}}(\boldsymbol{G}^{\mathrm{T}}\boldsymbol{G}^{\mathrm{H}} + \eta\boldsymbol{I}_K)^{-1}$

According to the different values of regularization factor η (seen in Table 2), we term the precoding methods in the cases with $\eta = 0$, $\eta = \frac{K}{\rho_f}$, and $\eta = \frac{K}{\rho_f} + \frac{K}{\rho_r+1}$ as ZF, RZF-MMSE (RZF with MMSE criterion), and RZF-MMSE-C, respectively. Consider a large-scale MIMO system with 128 BS antennas and different numbers of single-antenna users. The independent and identically distributed (i.i.d.) Rayleigh flat fading channels are assumed, QPSK modulation is applied, and channel coding is not employed. The noise is $AWGN \sim CN(0,\sigma^2)$. The downlink data transmitted power p_f is 5 dB higher than the uplink pilot transmitted power p_r. The simulation result in Fig.5 illustrates the relationship between the sum rate and the number of multiplexing users for ZF and RZF. It is obvious that as the number of users increases, the sum rate of ZF precoding grows at first, achieves the maximum points when the number of multiplexing single-antenna users reaches a certain value (we term it as the optimum number of multiplexing users for a given number of BS antennas), and decreases to zero. But for the RZF precoding, the sum rate grows as the number of multiplexing users increases at first, and keeps stable when the number of multiplexing users approximates to the optimum number of multiplexing users. It means that when the number of users is not so large, we should adopt ZF for the simplicity to achieve a good performance. But when the number of users grows large, RZF outperforms ZF due to its ability to inter-user interference mitigation and strong robustness to channel estimation error. Therefore, the threshold of the number of users served simultaneously for a given number of BS antennas is still a question for further research. We may combine the precoding methods with the user scheduling schemes.

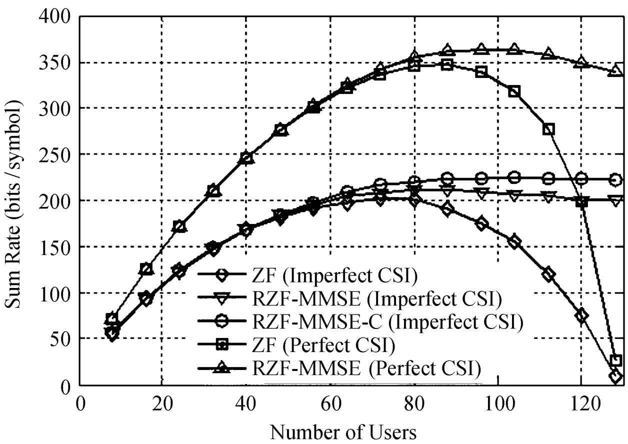

Fig.5. Relationship between sum rate and number of users. $M = 128$, $P/\sigma^2 = 15\,\text{dB}$, $P/\sigma^2 = 10\,\text{dB}$.

3.3 Uplink Detection

Detectors at the receivers must consequently recover the desired received signal from multiple transmit antennas simultaneously on the MIMO uplink. The design of receivers with reduced power consumption and low computational complexity is complicated but of great practical significance, especially when the number of antennas grows large. Hence, low-complexity detection algorithms with near-optimal performance have attracted a lot of attention recently.

For large-scale MIMO systems, two more advanced categories of detection algorithms, which include iterative linear filtering (which works by resolving the detection of the signaling vector by iterative linear filtering) and random step method[6], have been proposed. As an example of iterative linear filtering schemes, MMSE with successive interference cancelation (MMSE-SIC) has better performance but high complexity which is the third power of the number of BS antennas. Even though optimized, it is still too difficult to be achieved in large-scale MIMO systems. For the random step schemes, some algorithms derived from computational intelligence are shown to be pretty capable of achieving near optimum detection performance in large-scale MIMO systems with practical affordable complexities recently. In [32-33], the likelihood ascent search (LAS) algorithm based on local neighborhood search for large-scale MIMO detection was presented. LAS, which only permits transmissions to states with lower MSE and converges monotonically to a local minima in this way, can achieve a good performance close to maximum likelihood detection (MLD). Paper [34] presents an upper bound of bit error rate and a lower bound on asymptomatic multiuser efficiency. In order to improve the performance of the basic LAS, a more general version of LAS, termed as multistage LAS algorithm was proposed in [35]. When it encounters local minima, the multistage LAS algorithm carries out an escape mechanism by changing the definition of neighborhood. As opposed to the basic LAS with only coordinate in the basic neighborhood definition, the multistage LAS algorithm considers vectors which differ in two or more coordinates. Afterwards another local neighborhood search based algorithm, namely reactive tabu search (RTS), which outperformed the LAS algorithm by using a local minima exit strategy was proposed in [36-37]. It permits transmissions to the states with larger MSE to avoid local minima. More recently, in [38], belief propagation (BP) algorithm based on factor graph in large-scale MIMO systems was proposed. Paper [39] discusses these three low-complexity algorithms suitable for large-scale MIMO, and provides a comparison of them. Let m denote the order of the set of modulation constellation points, N_t and N_r be the number of transmit and receive antennas, respectively. Table 3 presents the complexity per-symbol of different detection algorithms. It is obvious that LAS, RTS and BP detection algorithms have lower complexities than maximum likelihood detection (MLD), and have the potential to be applied in the large-scale MIMO systems. To further improve the performance and reduce the computational complexity, more efficient and reasonable escape strategies from local minima should be adopted to design low-complexity detection algorithms.

Table 3. Computational Complexity

Detection Algorithm	Complexity
MLD	$O(m^{N_t})$
LAS	$O(N_tN_r)$
RTS	$O(N_tN_r)$
BP	$O(N_t)$

4 Future Research Issues

In addition to the above researches, several hot issues of large-scale MIMO systems still need to be studied in depth.

Capacity Analysis in Practical Systems. So far, the capacity analysis focuses on the asymptotic capacity for ideal systems with an infinite number of antennas[9,40]. However, in a practical system, the number of antennas cannot grow without limit. The research on capacity bound of ideal situation has little significance for the practical application. Therefore, we should further study the capacity in practical systems with a finite number of antennas and/or under more realistic assumptions.

Channel Model. Any wireless communication system needs to specify a channel model as a basis for performance evaluation and comparison. The existing classical channel models, such as 3GPP/3GPP2 spatial channel model (SCM)①, SCM-Extension (SCME)[41], WINNER I models②, and WINNER II models③~④, should be modified to meet the need of the large-scale MIMO systems due to the different antenna deployments. Considering the constrained array aperture and aesthetic factor, the uniform linear array (ULA) adopted in conventional MIMO systems is not suitable for a large antenna array. Therefore, a two-dimensional or even three-dimensional array structure may be developed for large-scale MIMO. For the channel models of two-dimensional or even three-dimensional array structure, the elevation angle to paths generated by SCM should be associated, the elevation statistics with other large-scale fading parameters, and the old statistics and procedure in SCM should be reused.

Scheduling Schemes for Much More Users Pairing. Currently, the existing scheduling schemes concentrate on the pairing of two or four single-antenna users. To take the advantage of the freedom of the large-scale MIMO channel, much more users should be scheduled and served simultaneously to form a high-order virtual MIMO array for better system performance (e.g., higher capacity). A probabilistic scheduling scheme proposed in [40] offers a novel direction.

Large-Scale MIMO Systems with TDD Model. The interest in TDD systems has grown in recent years. Some operations (e.g., channel estimation) in large-scale MIMO systems would be completed simply based on the TDD reciprocity[42]. Although TDD and FDD seem like inter-changeable architectures for cellular systems, there are some fundamental differences and issues that need to be studied in detail, for example, the pilot contamination and the in-depth study of precoding performance with channel estimation.

5 Conclusions

In this paper, we focused on several technical issues of large-scale MIMO. Study results show that sum rate improves as the number of BS antennas grows initially, and tends to be stable or decreases when the number of BS antennas continues to grow. We then introduced the key technologies. In terms of channel estimation, more efficient pilot pattern needs to be designed and the pilot overhead should be considered for FDD large-scale MIMO systems. And for TDD systems, we prefer to adopt the channel reciprocity to train on the uplink and estimate channels for CSIT. Linear precoding methods are effective and adequate, but the pilot contamination should be addressed. And the practical feasibility of low-complexity detectors (e.g., LAS, TRS) with more efficient escape strategies could be a potential trigger to create wider interest in the theory and implementation of large-scale MIMO systems. Finally, some research hotspot issues were discussed for the in-depth study in the future.

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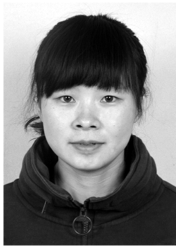
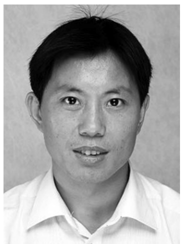
Xin Su received his M.S. degree in communications and electronic systems and Ph.D. degree in circuits and systems from the University of Electronic Science and Technology of China (UESTC) in 1996 and 1999 respectively. He is now with the School of Information Science and Technology at Tsinghua University and Tsinghua National Laboratory for Information Science and Technology (TNList), and is also the vice director of the Wireless and Mobile Communications Technology R&D Center of Tsinghua University, chairman of IMT-Advanced Technology Work Group in MIIT (Ministry of Industry and Information Technology of People's Republic of China) and vice chairman of the Innovative Wireless Technology Work Group of CCSA (China Communications Standards Association). His research interests include broadband wireless access, wireless and mobile network architecture, self organizing network, software defined radio, and cooperative communications. Dr. Su has published over 80 papers in the core journals and important conferences, applied for more than 40 patents and obtained more than 20 pieces of patent right.

Jie Zeng received the B.S. and M.S. degrees in electronic engineering from Tsinghua University in 2006 and 2009, respectively. He is now an assistant researcher in the Research Institute of Information Technology at Tsinghua University and TNList. His research interests include broadband wireless access, software defined radio, 4 G/B4 G technology and standardization, etc.



Li-Ping Rong is studying at the School of Communication and Information Engineering at UESTC for the M.S. degree. She received her B.S. degree in communication engineering from China Jiliang University in 2010. Since October 2011 she has been with the Tsinghua National Laboratory for Information Science and Technology and her research interests include wireless communication, cooperative communication, massive MIMO, etc.



Yu-Jun Kuang is with the University of Electronic Science and Technology of China (UESTC). He received his B.S. degree in communication engineering from Beijing University of Posts and Telecommunications (BUPT), M.S. degree in signal and information processing from UESTC, and Ph.D. degree in communication and information systems from BUPT. Presently his research interests include signal processing in wireless communication, cooperative communication, mobility management, V2V (vehicle to vehicle) communications and intelligent traffic control system, etc.