Cooperative MIMO Channel Models: A Survey

Cheng-Xiang Wang and Xuemin Hong, Heriot-Watt University
Xiaohu Ge, Huazhong University of Science and Technology
Xiang Cheng, Heriot-Watt University
Gong Zhang, Huawei Technologies Company Ltd.
John Thompson, The University of Edinburgh

ABSTRACT

Cooperative multiple-input multiple-output technology allows a wireless network to coordinate among distributed antennas and achieve considerable performance gains similar to those provided by conventional MIMO systems. It promises significant improvements in spectral efficiency and network coverage and is a major candidate technology in various standard proposals for the fourth-generation wireless communication systems. For the design and accurate performance assessment of cooperative MIMO systems, realistic cooperative MIMO channel models are indispensable. This article provides an overview of the state of the art in cooperative MIMO channel modeling. We show that although the existing standardized point-to-point MIMO channel models can be applied to a certain extent to model cooperative MIMO channels, many new challenges remain in cooperative MIMO channel modeling, such as how to model mobile-to-mobile channels, and how to characterize the heterogeneity and correlation of multiple links at the system level appropriately.

INTRODUCTION

Multiple-input multiple-output (MIMO) is an advanced technology that can effectively exploit the spatial domain of mobile fading channels to bring significant performance improvements to wireless communication systems. Conventional MIMO systems, known as point-to-point MIMO or collocated MIMO, require both the transmitter and receiver of a communication link to be equipped with multiple antennas. In practice, however, many wireless devices may not be able to support multiple antennas due to size, cost, and/or hardware limitations. Cooperative MIMO [1], also known as virtual or distributed MIMO, aims to utilize distributed antennas on multiple radio devices to achieve some benefits similar to those provided by conventional MIMO systems. The basic idea of cooperative MIMO is to group multiple devices into virtual antenna arrays (VAAs) to emulate MIMO communications. A cooperative MIMO transmission involves multiple point-to-point radio links, including links within a VAA and links between possibly different VAAs. For relay-based cooperative MIMO communications, there are three main cooperative strategies: amplify-and-forward, decode-and-forward, and compress-and-forward techniques.

Previous theoretical studies have revealed the pros and cons of cooperative MIMO compared to point-to-point MIMO systems [1]. The disadvantages of cooperative MIMO come from the increased system complexity and the large signaling overhead required for supporting device cooperation. The advantages of cooperative MIMO, on the other hand, are due to its capability to improve the capacity, cell edge throughput, coverage, and group mobility of a wireless network in a cost-effective manner. These advantages hinge on the usage of distributed antennas, which can increase the system capacity by decorrelating the MIMO channels and allow the system to exploit the benefits of macro-diversity in addition to micro-diversity. In many practical applications, such as cellular mobile and wireless ad hoc networks, the advantages of deploying cooperative MIMO technology usually outweigh the disadvantages [2, 3]. Over recent years, cooperative MIMO technologies have been gradually adopted into the mainstream of wireless communication standards.

In this article we focus on cooperative MIMO in the context of cellular mobile systems. Three types of cooperative MIMO schemes have been proposed for cellular systems: coordinated multipoint transmission (CoMP) [2], fixed relay [3], and mobile relay [3]. Simple illustrations of these cooperative MIMO schemes are shown in Fig. 1a–c. As the most mature cooperative MIMO technology, fixed relays have been incorporated into the IEEE 802.16j WiMAX standard. Meanwhile, the Third Generation Partnership Project (3GPP) is currently evaluating cooperative MIMO technologies for its fourth-generation (4G) cellular communication standard, Long Term Evolution-Advanced (LTE-Advanced).

 0163-6804/10/$25.00 © 2010 IEEE

To accurately evaluate and compare the performance of different transmission technologies for cooperative MIMO cellular systems, realistic cooperative MIMO channel models are indispensable. Earlier theoretical research on cooperative MIMO systems utilized simple narrowband fading channel models such as Rayleigh, Rician, or Nakagami channel models [1]. These analytical channel models are oversimplified and clearly inappropriate for system-level performance simulations. The existing standardized MIMO channel models, such as the 3GPP spatial channel model (SCM) [4], the WINNER II channel model [5], and the IEEE 802.16j channel model [6], can be used to simulate individual point-to-point channels. However, since cooperative MIMO involves multiple point-to-point links, its channel model should consider not only the properties of the individual links, but also the system-level variations (or heterogeneity) and correlation of multiple links in a multicell environment. Also, for cooperative MIMO using mobile relays, realistic mobile-to-mobile (M2M) channel models should be developed for channels between mobile users.

This article provides an overview of the existing cooperative MIMO channel models. Different types of cooperative MIMO schemes in cellular systems are presented in the next section. We then review and compare major standardized MIMO channel models applicable to cooperative MIMO systems. Future challenges in cooperative MIMO channel modeling are subsequently identified. The final section concludes the article.

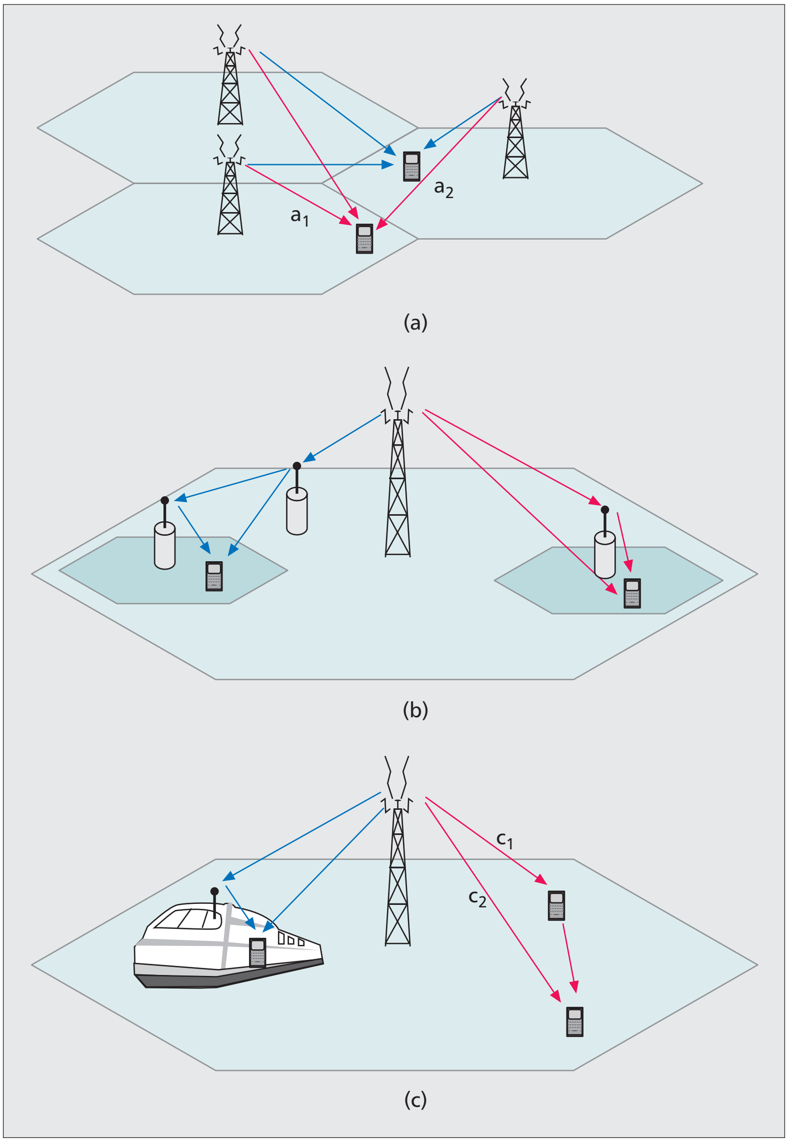

Figure 1. *Three types of cooperative MIMO schemes in cellular systems: a) CoMP; b) fixed relay; c) mobile relay.*

Cooperative MIMO in Cellular Systems

CoMP

CoMP [2] is an emerging technique to combat intercell interference and improve cell edge performance. The system architecture is illustrated in Fig. 1a. The idea is to share data and channel state information (CSI) among neighboring base stations (BSs) to coordinate their transmissions in the downlink and jointly process the received signals in the uplink. CoMP techniques can effectively turn otherwise harmful intercell interference into useful signals, allowing significant power gain, channel rank advantage, and/or diversity gains to be exploited. The promised advantages of CoMP rely on a high-speed backbone enabling the exchange of information (e.g., data, control information, and CSI) between the BSs.

CoMP has been studied intensively in both academia and industry over recent years, and is a very strong candidate technology for 4G standards. CoMP systems are only concerned with the BS to mobile station (MS) channels, which are fixed-to-mobile (F2M) channels.

Fixed Relays

As illustrated in Fig. 1b, fixed relays are low-cost and fixed radio infrastructures without wired backhaul connections. They store data received from the BS and forward to the MSs, and vice versa. Fixed relay stations (RSs) typically have smaller transmission powers and coverage areas than a BS. They can be deployed strategically and cost effectively in cellular networks to extend coverage, reduce total transmission power, enhance the capacity of a specific region with high traffic demands, and/or improve signal reception. By combining the signals from the relays and possibly the source signal from the BS, the MS is able to exploit the inherent diversity of the relay channel. The disadvantages of fixed relays are first the additional delays introduced in the relaying process, and second the potentially increased levels of interference due to frequency reuse at the RSs.

As the most mature cooperative MIMO technology, fixed relay has attracted significant support in major cellular communication standards. The IEEE 802.16j specification has incorporated fixed relays to enhance WiMAX performance. Fixed relay is also a very strong candidate technology for 4G, with possible mesh extensions in a later standard release. As shown in Fig. 1b, fixed relay systems involve different types of links, including BS-MS, BS-RS, RS-RS, and RS-MS links. The BS-RS and RS-RS channels are fixed-to-fixed (F2F) channels, while the BS-MS and RS-MS channels are F2M channels.

Although a standardized cooperative MIMO channel model is not yet available, it can be constructed with a reasonable accuracy based on the existing standardized point-to-point MIMO channel models and recently developed models for some scenarios.

MOBILE RELAYS

Mobile relays differ from fixed relays in the sense that the RSs are mobile and are not deployed as the infrastructure of a network. Mobile relays are therefore more flexible in accommodating varying traffic patterns and adapting to different propagation environments. For example, when a target MS temporarily suffers from bad channel conditions or requires relatively high-rate service, its neighboring MSs can help to provide multihop coverage or increase the data rate by relaying information to the target MS. Moreover, mobile relays enable faster and lower-cost network rollout. Similar to fixed relays, mobile relays can enlarge the coverage area, reduce the overall transmit power, and/or increase the capacity at cell edges. On the other hand, due to their opportunistic nature, mobile relays are less reliable than fixed relays since the network topology is highly dynamic and unstable.

As shown in Fig. 1c, two types of mobile relay systems can be distinguished: moving networks and mobile user relays. The moving network employs dedicated RSs on moving vehicles (e.g., trains) to receive data from the BS and forward to the user MSs onboard, and vice versa. The purpose of the moving network is to improve coverage on the vehicle. The mobile user relay enables distributed MSs to self-organize into a wireless ad hoc network, which complements the cellular network infrastructure using multihop transmissions. Theoretical studies have shown that mobile user relays have a fundamental advantage in that the total network capacity, measured as the sum of the throughputs of the users, can scale linearly with the number of users given sufficient infrastructure supports. Mobile user relays are therefore a desirable enhancement to future cellular systems. However, mobile user relays also face huge challenges in routing, radio resource management, and interference management. The major disadvantage of mobile user relays is that MS batteries can be used up by relay transmissions even if the user does not use them. Mobile user relays also complicate the billing problem (i.e., who shall pay the bill when a user helps other users as a relay).

Currently, moving networks are supported by the IEEE 802.16j WiMAX standard. A number of advanced mobile relays concepts are being evaluated for the 4G standard. Moving networks involve the BS-MS, BS-RS, and RS-MS links, where the BS-MS and BS-RS channels are F2M channels, while the RS-MS channels are F2F or F2M channels. Mobile user relays involve BS-MS and MS-MS links, where the BS-MS channels are F2M channels, while the MS-MS channels are M2M channels.

COOPERATIVE MIMO CHANNEL MODELS

To allow accurate assessments and fair comparisons of different cooperative MIMO technologies, realistic cooperative MIMO channel models are indispensable. Although a standardized cooperative MIMO channel model is not yet available, it can be constructed with reasonable accuracy based on the existing standardized point-to-point MIMO channel models and recently developed models for some scenarios (e.g., M2M models). This section aims to review the existing standardized MIMO channel models, compare their pros and cons, and discuss how they can be extended and applied to cooperative MIMO systems.

Standardized channel models are developed for different purposes, based on which we can classify them into two types: system simulation models and calibration models. System simulation models are intended for accurate performance assessments of different algorithms and systems. They seek to represent the real-world channels as realistically as possible, with reasonable computational complexity. Calibration channel models, on the other hand, are simplified channel models developed for conformance testing of different products and technologies. Conformance testing specifies a required level of system performance when using the calibration channel model and indicates whether a tested system fulfills this requirement. In this article we concentrate on system simulation models.

Prominent standardized MIMO channel models include the COST 259/273 channel model, the 3GPP SCM, the SCM-Extended model, the WINNER II channel model, the IEEE 802.11n channel model, the Stanford University interim (SUI) channel model, and the IEEE 802.16 channel model [7]. Although these models are developed by different research bodies and projects, they are closely related. In the following we focus on the three most representative MIMO channel models:

- The SCM [4], which is a cellular MIMO channel model developed by the 3GPP in 2003 for the evaluation of different MIMO schemes in high-speed downlink Packet Access (HSDPA) systems. The SCM supports a center frequency of 2 GHz and a system bandwidth of 5 MHz.
- The WINNER II model [5], which was developed by the IST-WINNER II project in 2007 and represents the state of the art in wireless channel modeling. It supports a center frequency range from 2 to 6 GHz and a system bandwidth up to 100 MHz.
- The IEEE 802.16j channel model [6], which is based on the SUI model and was extended in 2007 to cover relay scenarios in IEEE 802.16j WiMAX systems. It supports a center frequency of 5 GHz and a maximum system bandwidth of 20 MHz.

GENERAL FEATURES

All three models employ a tapped-delay-line structure to construct the wideband channel impulse response, with each tap representing a resolvable path or a cluster of scatterers with a different delay. The numbers of taps used by the SCM and IEEE 802.16j channel model are fixed to 6 and 3, respectively, while the numbers of taps in the WINNER II channel model can vary between 4 and 24. Intracluster delay spread is further introduced in the WINNER II channel model to account for better delay resolution and consequently broader bandwidths.

Based on the modeling methodology, standardized MIMO channel models can be roughly classified into geometry-based stochastic models

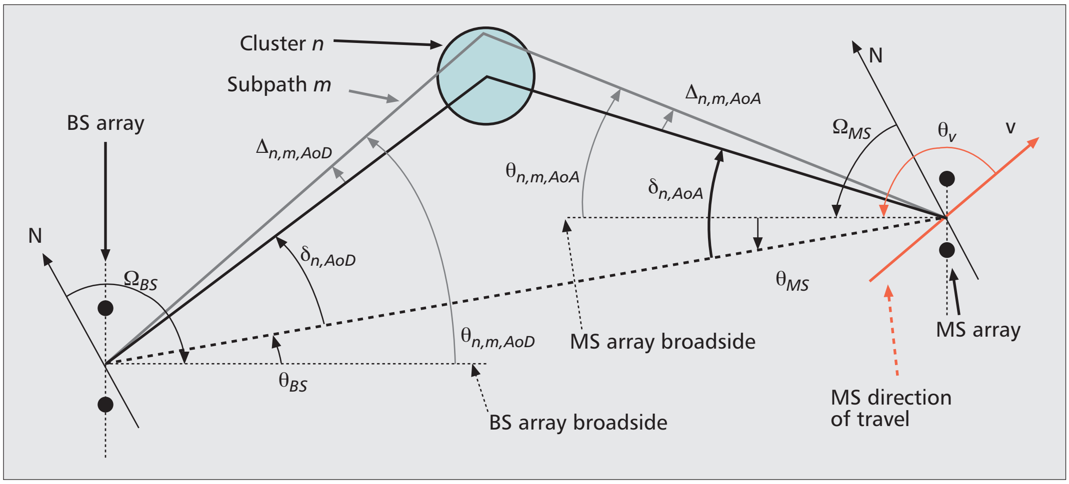

Figure 2. *BS and MS angle parameters in the 3GPP SCM with one cluster of scatterers [4, 8].*

The SCM, WINNER II, and IEEE 802.16j channel models all support multiple scenarios to reflect significantly varying channel properties across typical environments.

(GBSMs) and correlation-based stochastic models (CBSMs). The SCM and Winner II channel models are GBSMs, while the IEEE 802.16j channel model is a CBSM. Both modeling approaches have pros and cons. GBSMs simulate the geometrical propagation of multipaths using a large number of random variables as model parameters. A simplified plot of the SCM is given in Fig. 2, where only one cluster of scatterers is shown as an example with corresponding random angle parameters associated with the BS and MS. The detailed explanations of the angle parameters can be found in [4, 8] and are neglected here for simplicity. A cluster/tap or resolvable path further consists of multiple subpaths (i.e., irresolvable rays) with different amplitudes, phases, angles of arrival, and angles of departure. The sum-of-sinusoids method is used to sum up the irresolvable rays and generate taps. With proper parameterization, GBSMs are usually accurate and flexible for describing different scenarios. However, they are complex and computationally inefficient. Besides, the spatial-temporal correlation properties are not explicitly specified in the model and need to be further derived from other parameters [8]. This means that theoretic performance studies of MIMO systems cannot be directly linked to the underlying spatial-temporal correlation properties. On the other hand, CBSMs assume Rayleigh or Ricean fading for each tap, and then carefully introduce autocorrelation and cross-correlation into the MIMO channel matrix via Doppler filtering and spatial filtering. CBSMs are relatively simple and computationally efficient. They also explicitly address the correlation properties of MIMO channel matrices, providing a useful reference for system designers. The drawback of CBSMs comes from the oversimplification and consequently an unrealistic representation of link variations in system-level simulations. In general, GBSMs tend to be better system simulation models, while CBSMs tend to be better calibration models [8].

Heterogeneity of Multiple Links

Conventional cellular systems and CoMP are only concerned with the BS-MS links. In fixed and mobile relay cooperative MIMO systems, more links need to be considered: BS-RS, RS-RS, RS-MS, and MS-MS links. Because the BSs, RSs, and MSs have different heights, densities, moving speeds, and transmission ranges, different links in a cooperative MIMO system can have distinct statistical properties in terms of the path loss, shadowing standard deviation, delay spread, Doppler spread, line-of-sight (LoS) probability, and so on. In other words, a high degree of link heterogeneity is expected in cooperative MIMO systems.

The SCM, WINNER II, and IEEE 802.16j channel models all support multiple scenarios to reflect significantly varying channel properties across typical environments. Some scenarios further differentiate LoS and non-LoS (NLoS) conditions, leading to the received signal often following Rayleigh and Rice distributions, respectively. The resulting channel models can be used to characterize the link heterogeneity in cooperative MIMO systems.

Multiple Scenarios — The SCM [4] was dedicated to outdoor propagation and defined three main propagation scenarios: suburban macrocell, urban macrocell, and urban microcell. The urban microcell scenario supports both LoS and NLoS conditions. Additionally, it is possible to modify the urban macrocell scenario by applying a far-scattering cluster or an urban canyon option.

The WINNER II channel model [5] is the most comprehensive channel model and includes 13 scenarios:

- A1: indoor (small office/residential), A2: indoor to outdoor
- B1: urban microcell, B2: bad urban microcell, B3: indoor hotspot, B4: outdoor to indoor, B5: stationary feeder
- C1: suburban macrocell, C2: urban macrocell, C3: bad urban macrocell, C4: urban macrocell outdoor to indoor
- D1: rural macrocell, D2: moving networks

All 13 scenarios can distinguish LoS and NLoS conditions. It is worth noting that the B5 scenario in WINNER II corresponds to fixed relays (i.e., stationary feeders). Because fixed relays can be deployed above the rooftop (ART), below the rooftop (BRT), or at street level, the B5 scenario is further divided into five sub-scenarios: B5a (LoS, ART to ART), B5b (LoS, street level to street level), B5c (LoS, BRT to street level), B5d (NLoS, ART to street level), *The probability that LoS or NLoS links occur in a system depends on various environment factors, e.g., terrain features and distance. Probabilistic models are employed by the SCM, WINNER II, and IEEE 802.16j channel models to describe the LoS probability.*

Cooperative MIMO scheme	Link type	Description	Recommended scenario
CoMP	BS-MS	MS indoor	C2 (NLoS)
		MS outdoor	C2 (LoS)
Fixed relay	BS-MS	Indoor or outdoor	C2
	BS-RS	Various RS locations	B5 (LoS/NLoS)
	RS-RS	Various RS locations	B5 (LoS/NLoS)
	RS-MS	Indoor-to-indoor	A1 (LoS/NLoS)
		Indoor-to-outdoor	A2 (NLoS)
		Outdoor-to-outdoor	B1 (LoS/NLoS)
Moving network	BS-MS	Indoor	C2 (NLoS)
	BS-RS	LoS for RS	C2 (LoS)
	RS-MS	Indoor	B3 (LoS/NLoS)
Mobile user relay	BS-MS	Indoor or outdoor	C2
	MS-MS	LoS	B5b (*not aN M2M scenario*)

Table 1. *A cooperative MIMO channel model based on the WINNER II channel model.*

and B5f (LoS/NLoS, ART to ART/BRT). Moreover, the D2 channel corresponds to the moving network scenario in mobile relay networks.

IEEE 802.16j presents nine types of channel models, Types A–H and Type J [6], commonly experienced in WiMAX multihop relay networks. Similar to the B5 sub-scenarios in WINNER II, the IEEE 802.16j distinguishes two different locations of BSs and RSs: ART and BRT. Three terrain features are defined by IEEE 802.16j: hilly terrain with moderate to heavy tree densities, intermediate path loss condition, and flat terrain with light tree densities. Types A, B, C, F, and G support both LoS and NLoS conditions, Types D and H support only the LoS condition, while Types E and J support only the NLoS condition.

The different scenarios described above can be adopted to simulate most of the links in cooperative MIMO systems. In [6] four relay usage models or application scenarios are defined: fixed infrastructure, in-building coverage, temporary coverage, and coverage on a mobile vehicle. A mapping of the nine types of channel models to the four relay usage models was provided in [6]. By analogy, we can selectively apply the 13 scenarios defined in the WINNER II channel model to construct a cooperative MIMO channel model. An example is given in Table 1.

LoS Probability and Scenario Transition — The probability that LoS or NLoS links occur in a system depends on various environment factors (e.g., terrain features and distance). Probabilistic models are employed by the SCM, WINNER II, and IEEE 802.16j channel models to describe the LoS probability. In the SCM an LoS model is defined for the urban microcell scenario only and not for the suburban or urban macrocell cases due to low probabilities of LoS occurrence. The LoS probability in the microcell scenario decreases linearly with the propagation distance and reduces to 0 at a distance of 300 m [4]. The WINNER II channel model uses a set of scenario-dependent expressions for the LoS probability, given that neither the transmitter nor the receiver is inside a building. These expressions are simple functions of a few parameters, including the horizontal distance of the propagation path, BS height, MS height, as well as parameters that characterize the radio environment [5]. The IEEE 802.16j channel model defines two LoS models for Type F and Type G scenarios. The LoS probability is expressed as a nonlinear function of the transmitter-receiver distance with cutoff points [6].

The time evolution behavior of mobile fading channels, including transitions between different scenarios and LoS/NLoS conditions, may have a considerable impact on system performance. The SCM supports the time evolution feature based on a concept called *drops*. A drop corresponds to a local stationary interval, during which the channel undergoes fast fading but the large-scale parameters do not change significantly. A quasi-stationary framework is used which assumes that parameters in consecutive drops are independent [4]. The WINNER II channel model also uses a concept called *channel segments*, similar to the drops concept. A non-stationary framework is used to support smooth channel evolution. Transitions from an old segment to a new segment are carried out by linearly decreasing the powers of clusters in the old segment and increasing the powers of clusters in the new segment so that the old clusters are replaced one by

	SCM [4]	WINNER II [5]	IEEE 802.16j [6]
General model features			
Channel model type	GBSM	GBSM	CBSM
Maximum bandwidth	5 MHz	100 MHz	20 MHz
Carrier frequency	2 GHz	2–6 GHz	5 GHz
Number of taps	6	4–24	3
Intercluster delay spread	No	Yes	No
Heterogeneity of multiple links			
Number of scenarios	3	13	9
(i) Outdoor-to-indoor	No	Yes	Yes
(ii) Fixed relay	No	Yes	Yes
(iii) Moving network	No	Yes	Yes
(iv) Mobile user relay	No	No	No
LoS probability model	Urban microcell only	Scenario-dependent	Scenario-dependent
Scenario transition	Quasi-stationary	Non-stationary	No
Correlation of multiple links			
Intrasite SF correlation	0	Distance-dependent	Distance-dependent
Intersite SF correlation	0.5	0	Distance-and-angle-dependent
Correlation of other LSPs	Fixed values	Distance-dependent	Not considered

Table 2. *Major comparisons of the SCM, WINNER II, and IEEE 802.16j channel models.*

In the SCM and WINNER II channel models, the scenario transition and LoS/NLoS transition can be simulated by changing the scenarios and LoS/NLoS conditions in consecutive drops. The IEEE 802.16j model does not explicitly address the time evolution behavior of channels.

one by the new clusters [5]. In the SCM and WINNER II channel models, the scenario transition and LoS/NLoS transition can be simulated by changing the scenarios and LoS/NLoS conditions in consecutive drops. The IEEE 802.16j model does not explicitly address the time evolution behavior of channels.

Correlation of Multiple Links

Due to the environment similarity arising from common shadowing objects and scatterers contributing to different links, the parameters describing different links may exhibit certain dependence/correlation from the system point of view. The system-level correlation is closely related to the deployment assumptions such as the heights, densities, and distances of the transmitters and receivers. At the system level, two types of correlation can be identified: intrasite correlation and intersite correlation. A *site* is a highly elevated radio station, including all BSs and ART RSs. Intrasite correlation refers to the correlation between MSs connected to a site (e.g., the correlation between links c_1 and c_2 in Fig. 1c). Intersite correlation refers to the correlation of links from a single MS to multiple sites (e.g., the correlation between links a_1 and a_2 in Fig. 1a). Both intersite and intrasite correlations need to be considered properly in the cooperative MIMO channel model to allow accurate performance evaluation of cooperative MIMO systems.

The correlation of lognormal shadow fading (SF) is perhaps the most important system-level correlation because it directly influences the macro-diversity gain, which is a major benefit promised by cooperative MIMO systems. The SCM, WINNER II, and IEEE 802.16j models have all considered SF correlation. In the SCM the intrasite and intersite SF correlations are fixed to 0 and 0.5, respectively. In the WINNER II model the intrasite SF correlation is a cut-off exponential decaying function of the distance between the two MSs, while the intersite SF correlation is fixed to 0. The IEEE 802.16j model uses a distance-dependent exponential decaying function to describe the intrasite SF correlation (called autocorrelation in [6]), and a distance-and-angle-dependent function to describe the intersite SF correlation (called cross-correlation in [6]).

Besides the SF, other large-scale parameters (LSPs) such as delay spread (DS) and azimuth spread (AS) may also display intrasite correlation. The pair-wise intrasite correlations of SF, DS, and AS are determined by fixed values in the

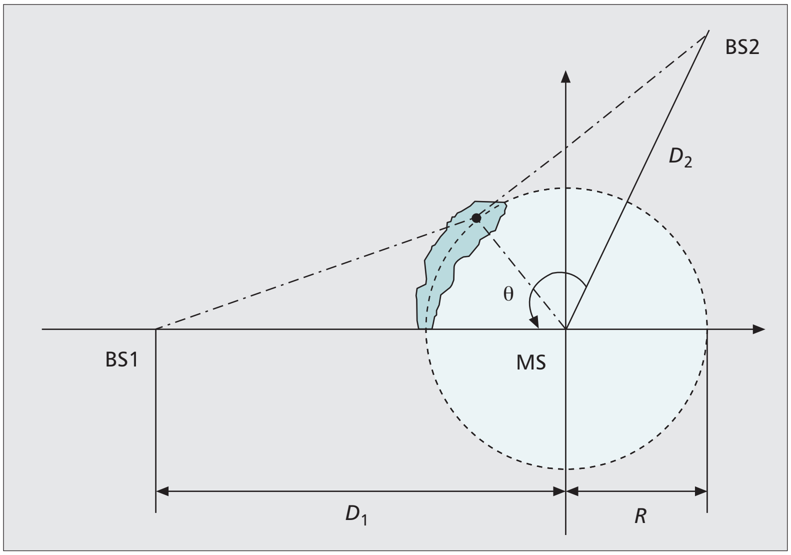

Figure 3. *A one-ring GBSM for a CoMP system.*

SCM and by distance-dependent functions in the WINNER II model. The correlation of DS and AS is not considered in the IEEE 802.16j model.

The major comparisons of the SCM, WINNER II, and IEEE 802.16j channel models are summarized in Table 2.

Challenges in Cooperative MIMO Channel Modeling

While many issues in cooperative MIMO channel modeling have been covered by the existing standardized point-to-point MIMO channel models, there are still some challenges that remain to be addressed.

The first challenge is how to implement a channel model that can run multiple scenarios simultaneously. As shown in Table 2, cooperative MIMO channels should rely on different scenarios to characterize different links. Providing a pool of 13 scenarios, the WINNER II channel model is obviously the best existing channel model to use. However, the current implementation of the WINNER II channel model does not allow simultaneous simulation of multiple links in different scenarios. Instead, to evaluate the performance of a network containing different scenarios, multiple drops should be run, one for each scenario, and merged afterward. This approach can be justified for conventional point-to-point MIMO systems, where an end-to-end transmission involves only one link. However, this approach cannot be used in cooperative MIMO systems, where an end-to-end transmission involves multiple heterogeneous links simultaneously.

Another important issue to address is the correlation model for multiple links at the system level. Table 2 has summarized the correlation models for LSPs used in standardized MIMO channel models. We can see that these correlation models are not consistent and even contradict each other. For example, the SCM treats the intrasite SF correlation as negligible and the intersite SF correlation as significant, while the WINNER II channel model considers the opposite. It is therefore desirable to develop a unified correlation model for LSPs, incorporating a new realistic SF correlation model, such as the one in [9]. Besides the LSP correlation, the small-scale fading of multiple links in cooperative MIMO systems may also be correlated, even with largely separated antennas. A simple GBSM can be used to gauge the extent of small-scale fading correlation. As illustrated in Fig. 3, two links are established from an MS to BS1 and BS2 in a CoMP system. Based on the classic one-ring model, scatterers are assumed to be distributed on a circle of radius R centered at the MS, following the well-known von-Mises distribution. This cluster of scatterers contributes to a *tap* in the channel impulse response. Without loss of generality, we assume that the carrier frequency is 5 GHz, the cluster mean angle of arrival is 90° and the cluster azimuth spread at arrival is 22°, corresponding to the urban micro-cell scenario with the NLoS condition in the WINNER II channel model [5]. The MS-BS1 and MS-BS2 distances are denoted D_1 and D_2, respectively. The angle between the two links is denoted θ. Assuming $D_1 = 500$ m and $R = 30$ m, the small-scale fading correlation of the two links is calculated numerically as a function of D_2 and θ. The absolute values of the resulting correlation coefficient are shown in Fig. 4. We can see that although the two BSs are far apart, high correlations between the two links can occur at certain distances and certain values of θ (e.g., when θ is small). Such small-scale fading correlation should not be neglected, and new small-scale fading correlation models for cooperative MIMO systems are needed.

The existing scenarios defined in the standardized MIMO channel models need to be expanded to include the M2M scenario. As shown in Fig. 1c, the M2M channel is an important type of channel in mobile user relay systems. In M2M systems both the transmitter and receiver are MSs in motion, often equipped with low-elevation antennas. M2M channels therefore differ significantly from conventional F2M channels, where only the MS is moving while the BS is fixed, often with high-elevation antennas. For example, the Doppler power spectrum density in M2M channels may exhibit different shapes, the density of mobile users has a great impact on the underlying M2M channel statistics, and M2M channels are in most cases statistically non-stationary, since the stationarity conditions pertain to a much shorter time period than in F2M channels [10]. For the state of the art and future challenges in M2M channel modeling and measurements, we refer the interested readers to [10, references therein]. Currently, none of the existing standardized point-to-point MIMO channel models includes M2M scenarios.

Conclusions

This article provides a brief survey of cooperative MIMO channel models applicable to cellular mobile networks. First, we have briefly introduced three different cooperative MIMO schemes and illustrated the corresponding propagation scenarios. We have then reviewed the existing standardized point-to-point MIMO channel models, compared their pros and cons, and discussed how they can be extended and applied to cooperative MIMO systems. New challenges in cooperative MIMO channel modeling have been identified and discussed, such as how to develop realistic M2M channel models and how to characterize heterogeneity and correlation of multiple links in multi-cell environments. Our discussions will hopefully inspire future efforts to develop standardized and more realistic cooperative MIMO channel models.

ACKNOWLEDGMENT

The authors acknowledge the support from the RCUK for the UK-China Science Bridges Project: R&D on (B)4G Wireless Mobile Communications. C.-X. Wang, X. Hong, X. Cheng, and J. S. Thompson acknowledge the support from the Scottish Funding Council for the Joint Research Institute in Signal and Image Processing between the University of Edinburgh and Heriot-Watt University, which is a part of the Edinburgh Research Partnership in Engineering and Mathematics (ERPem). X. Ge also acknowledges the support from the National Natural Science Foundation of China (NSFC) (contract/grant number 60872007) and National 863 High Technology Program of China (contract/grant number 2009AA01Z239).

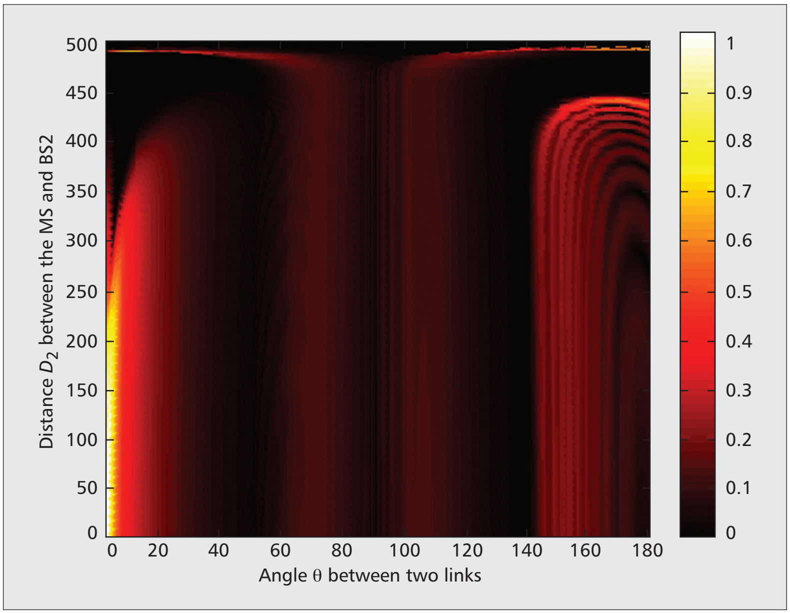

Figure 4. *Absolute values of small-scale fading correlation coefficients of the two links in a CoMP system as a function of* θ *and* D_2 (D_1 *= 500 m*, R *= 30 m*).

REFERENCES

[1] Y. Fan and J. S. Thompson, "MIMO Configurations for Relay Channels: Theory and Practice," *IEEE Trans. Wireless Commun.*, vol. 6, no. 5, May 2007, pp. 1774–86.

[2] M. K. Karakayali, G. J. Foschini, and R. A. Valenzuela, "Network Coordination for Spectrally Efficient Communications in Cellular Systems," *IEEE Commun. Mag.*, vol. 44, no. 8, Aug. 2006, pp. 56–61.

[3] D. Soldani and S. Dixit, "Wireless Relays for Broadband Access," *IEEE Commun. Mag.*, vol. 46, no. 3, Mar. 2008, pp. 58–66.

[4] 3GPP TR 25.996, "Spatial Channel Model for Multiple Input Multiple Output (MIMO) Simulations (Rel. 6)," Sept. 2003.

[5] P. Kyosti *et al.*, "WINNER II Channel Models," IST-WINNER II D1.1.2, Nov. 2007.

[6] G. Senarth *et al.*, "Multi-hop Relay System Evaluation Methodology (Channel Model and Performance Metric)," IEEE 802.16j-06/013r3, Feb. 2007.

[7] P. Almers *et al.*, "Survey of Channel and Radio Propagation Models for Wireless MIMO Systems," *EURASIP J. Wireless Commun. Net.*, vol. 2007, Article ID: 19070, 2009.

[8] C.-X. Wang *et al.*, "Spatial Temporal Correlation Properties of the 3GPP Spatial Channel Model and the Kronecker MIMO Channel Model," *EURASIP J. Wireless Commun. Net.*, vol. 2007, Article ID: 39871, 2007.

[9] P. Agrawal and N. Patwari, "Correlated Link Shadow Fading in Multihop Wireless Networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, Aug. 2009, pp. 4024–36.

[10] C.-X. Wang, X. Cheng, and D. I. Laurenson, "Vehicle-to-Vehicle Channel Modeling and Measurements: Recent Advances and Future Challenges," *IEEE Commun. Mag.*, vol. 47, no. 11, Nov. 2009, pp. 96–103.

BIOGRAPHIES

CHENG-XIANG WANG (cheng-xiang.wang@hw.ac.uk) received his Ph.D. degree from Aalborg University, Denmark, in 2004. He joined Heriot-Watt University, United Kingdom, as a lecturer in 2005 and became a reader in August 2009. His research interests include wireless channel modeling and simulation, cognitive radio networks, vehicular communication networks, cooperative communications, green communications, MIMO, and (beyond) 4G. He served or is serving as an editor or guest editor for several international journals including *IEEE Transactions on Wireless Communications*. He has published one book chapter and over 120 papers in journals and conferences.

XUEMIN HONG (x.hong@hw.ac.uk) received his Ph.D. degree in 2008 from Heriot-Watt University, where he is currently a postdoctoral research associate. Previously he was a postdoctoral fellow at the University of Waterloo, Canada. His research interests include (beyond) 4G systems, cognitive radio networks, cooperative communications, and wireless channel modeling. He has published one book chapter and 17 papers in journals and conferences. He is a publicity chair for CMC 2010 and has served as a TPC member for several conferences.

XIAOHU GE (xhge@mail.hust.edu.cn) received his Ph.D. degree in communication and information engineering from Huazhong University of Science and Technology (HUST), China, in 2003. He has been working at HUST since 2005 and is currently an associate professor. Prior to that, he worked as an assistant researcher at Ajou University, South Korea, and Politecnico Di Torino, Italy. His research interests include mobile communications, traffic modeling, and interference modeling in wireless networks.

XIANG CHENG (xc48@hw.ac.uk) received his B.Sc. and M.Eng. degrees in communication and information systems from Shandong University, China, in 2003 and 2006, respectively, and his joint Ph.D. degree from Heriot-Watt University and the University of Edinburgh, United Kingdom, in 2009. His current research interests include mobile propagation channel modeling and simulation, multiple antenna technologies, mobile-to-mobile communications, and cooperative communications. He has published approximately 30 journal and conference papers. He has served as a TPC member for several international conferences.

GONG ZHANG (nicholas@huawei.com) received his M.Sc. degree in electrical engineering from Harbin Institute of Technology. He has been with Huawei Technologies since 1998. He joined the UMTS product unit in 1999, became the product development team leader in the smart terminal unit in 2002, and was system architect in charge of mobile TV solutions in 2005, in charge of the LTE-SAE program in 2007, and in charge of the interference coordination and cooperation project in 2008. He is now head of the Network Architecture Department in Huawei Corporate Research.

JOHN THOMPSON (john.thompson@ed.ac.uk) received his B.Eng. and Ph.D. degrees from the University of Edinburgh in 1992 and 1996, respectively. He has been working at the University of Edinburgh, first as a postdoctoral researcher, then a lecturer, and now a reader since October 2005. His research interests include signal processing algorithms for wireless systems, antenna array techniques, and multihop wireless communications. He has published approximately 150 papers, a few book chapters, and an undergraduate textbook on digital signal processing. He is currently Editor-in-Chief of the *IET Signal Processing* journal and was a Technical Program Co-Chair for IEEE ICC 2007.