A Novel Relay Channel Modeling Method with Validation of Micro-Cell MIMO Relay Measurement Results at 2.35GHz

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***Abstract*—This paper presents a multiple-input multiple-output (MIMO) relay channel model based on the International Telecommunication Union (ITU) generic channel model for the test evaluation of radio interface technologies (RITs). Each link is modeled by the conventional point-to-point channel model with specific parameter set. A MIMO relay measurement in a typical urban micro-cell environment at 2.35GHz with bandwidth up to 50MHz was performed, and the collected data are compared with the derived model. Capacity values in amplify-and-forward (AF) and decode-and-forward (DF) relay modes are selected to be the comparing metrics. Furthermore, another relay channel model with channel characteristics following Rayleigh or Rice distribution is provided as a baseline for comparison. It turns out that the proposed ITU generic channel model shows good comparison to the measurement data in this specific environment, for the capacity of modeled channel is quite similar to that of the measurement channel in both AF and DF modes.**

I. Introduction

Recently, a large amount of research has been focusing on the multiple-input multiple-output (MIMO) system and relay technology. MIMO system is believed to be able to improve the bit rate significantly [1], [2], and relay technology is paid lots of attention for its ability to enlarge system coverage, eliminate blind spots and provide diversity gains [3]. Both theory analysis and experimental results show that the coordination of MIMO and relay technology can achieve better performance. When evaluating the performance of MIMO relay channels, researchers often turn to realistic channel models. Previously reported survey often used a simplified relay channel model, which models the three links of relay system independently by treating each link as conventional point-to-point channel link. The small-scale fading characteristics of this channel is subject to Rayleigh distribution in the non-line of sight (NLoS) case or Rice distribution in the line-of-sight (LoS) case. However, it should be noted that this channel model may be oversimplified in many cases. In term of modeling the conventional point-to-point channel, a geometry-based double-directional channel model is provided in [4]. It is also called geometry-based stochastic channel model (GBSC), the parameters of which are subject to certain distributions, i.e., normal distribution or log-normal distribution, with expectations and standard deviations extracted from extensive measurement results or based on literature. In analogy to the idea of building a simplified relay channel model, we can derive a new model with each link modeled by the method given by International Telecommunication Union (ITU) generic channel model, which is more accurate than Rayleigh and Rician fading models at the level of single link simulation.

The measurement data are the most reliable tool to examine the accuracy of the presented channel model. A multiple-input multiple-output (MIMO) relay channel measurement with the center frequency of 2.35GHz and bandwidth up to 50MHz was performed in a typical urban micro-cell environment in downtown Beijing, China. The frequency setup is selected according to the frequency bands allocated to the International Mobile Telecommunication-Advanced (IMT-Advanced) system, where the relay technology is likely to be deployed.

Comparisons of capacity values of derived relay channel model with those of measurement data in both amplify-and-forward (AF) and decode-and-forward (DF) modes are presented in this paper. We treat base station (BS), relay station (RS) and mobile station (MS) as source, relay and destination terminals respectively. For the direct link (link between BS and MS) and the access link (link between RS and MS), both LoS and NLoS propagation conditions are taken into consideration, whereas the backhaul link (link between BS and RS) is fixed to be LoS under the constraint of the field measurement. The capacity of simplified relay channel model is also given as a baseline for comparison. From the results we conclude that ITU generic relay channel model shows good comparison with the measurement data, whereas the simplified model overestimates channel capacity to a large extent.

The remainder of this paper is organized as follows. Section II gives a brief description of the channel measurement campaign. Section III introduces the basic two-hop relay system and relay channel models. Capacity of MIMO relay channels in both AF and DF modes is presented in Section IV. In Section V, comparison results are illustrated and explained. Section VI concludes this paper.

II. Channel Measurement Description

The MIMO relay channel measurement campaign was performed in a typical urban micro-cell environment in downtown Beijing, China. The chosen measurement routes are shown in Fig. 1. MS was installed in a trolley moving along the routes at a constant velocity of 0.5m/s, RS was fixed on the top of a travel trailer, BS was located on the rooftop of a 5-floor high

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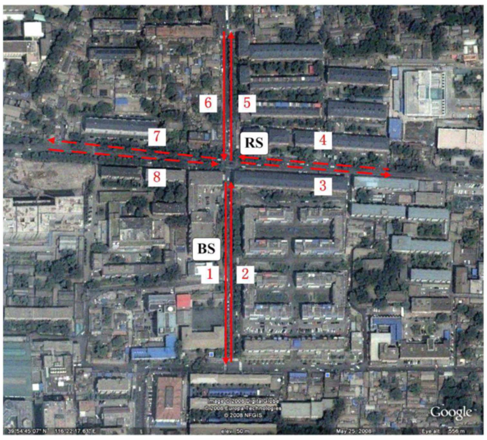


Fig. 1. Measurement environment and route plan

building. Antenna heights of MS, RS and BS are 1.8m, 7m and 22m respectively. Buildings on both sides of the routes are mostly 5 or 6 floors high. Line-of-sight propagation condition is the case in the backhaul link, and BS was clearly below the rooftops of the surrounding buildings.

Although BS and RS were placed in different positions, the routes where BS-MS and RS-MS have LoS propagation conditions are the same ones, which are marked with 1,2,5 and 6 in Fig. 1, the routes in NLoS case are marked with 3,4,7,8. Due to the constraint of the number of sounding devices, three links of the relay system were measured separately.

The sounding equipment used in this campaign is Elektrobit Propsound^{TM} channel sounder [5]. A pseudo-random sequence of length 1023 is generated at the transmitter with chip rate of 25MHz. The signal is received at the receiver and channel impulse responses are extracted by slide correlating it with a synchronized copy of the sequence. A three-dimensional dual-polarized $(\pm 45°)$ omni-directional array (ODA) was used, and 16 elements of the ODAs at both transmitter and receiver are enabled during the measurement campaign. The switched antenna access is used so that the sounder contains only one physical transmitter and receiver channel at a time when collecting the data. The duration of all the antenna elements being switched once is called a cycle.

III. Relay System and Relay Channel Models

A. Two-Hop Single Relay System

The basic relay system model considered here is shown in Fig. 2. We focus on a two-hop single relay system with multiple antennas at the BS, RS and MS. Half-duplex transmission protocol is considered. In this protocol, the source terminal communicates with both relay and destination terminals during the first slot. In the second slot, only relay terminal communicates with destination terminal. $\mathbf{H}_0$, $\mathbf{H}_1$ and $\mathbf{H}_2$ stand for the channel coefficient matrices of direct link, backhaul link and access link respectively. Consider the case that no feedback link to BS and RS exist in the channel, hence the suboptimal power allocation strategy, i.e., equal power allocation strategy is adopted for the antenna arrays at both BS and RS. We

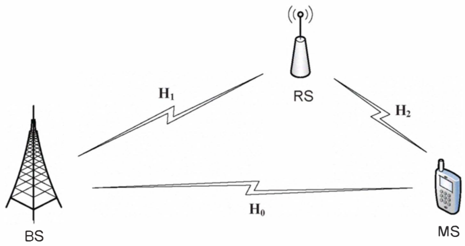


Fig. 2. Basic two-hop relay system

also assume the transmit powers of BS and RS are the same, denoted by P_t. Due to these assumptions, the channel capacity in which we take interest is not the Shannon capacity since the maximum bit rate of the channel has not been achieved. In the AF relay mode, RS simply amplifies and forwards the received signal to the MS, whereas in the DF relay mode, RS decodes the received signal before retransmitting it to the MS.

B. Simplified Relay Channel Model

The simplified relay channel model for both LoS case and NLoS case is presented here. According to the measurement, all three stations have the same number of antenna elements, which is denoted by M.

As shown in [6] [7], the conventional point-to-point MIMO channel link can be modeled as the sum of weighed LoS and NLoS components. The channel matrix for a point-to-point channel link can be written as

$$\mathbf{H} = \sqrt{\frac{K}{K+1}}\mathbf{H}_{LoS} + \sqrt{\frac{1}{K+1}}\mathbf{H}_{NLoS} \quad (1)$$

where K is the Rician K-factor, which is related to the propagation condition and the distance between transmitter and receiver. $\mathbf{H}_{LoS}$ represents the contribution of the LoS components in the channel. It is determined by the specific distance between transmitter and receiver and the configurations of the antennas. $\mathbf{H}_{NLoS}$ takes into account the influence of the scattering components during the propagation. The entries of $\mathbf{H}_{NLoS}$ are assumed to be zero-mean unit-variance complex Gaussian random variables. K is assumed to be 0dB in the NLoS case, while in the LoS case, K is often larger than 0dB, hence $\mathbf{H}$ shows Rician fading characteristics. Note that time correlation and spatial correlation are not considered in the model.

All three links of relay system can be modeled the same way as conventional point-to-point Rayleigh or Rice fading channel link. In the LoS case, K of each link is subject to a certain log-normal distribution with different set of expectations and standard deviations, which are extracted from the measurement data.

C. ITU Generic Channel Model

ITU generic channel model is a geometry-based stochastic channel model. It does not explicitly specify the locations of the scatterers but rather the directions of the rays, like the well-known spatial channel model (SCM) [8]. Geometry-based modeling of the radio channel enables separation of propagation parameters and antenna. ITU generic channel model supports a center frequency range from 2GHz to 6GHz and a bandwidth up to 100MHz. Four test scenarios and one optional test scenario are defined in the model. Furthermore, different scenarios have different sets of parameters but share the same modeling method.

The generic channel model is a stochastic model with two (or three) levels of randomness. First, large-scale parameters like shadow fading, delay spreads and angular spreads are drawn randomly from tabulated distribution functions. Next, small-scale parameters like delays, powers, and directions of arrival and departure are drawn randomly according to tabulated distribution functions and random large-scale parameters. At this stage the geometric setup is fixed and the only free variables are the random initial phases of the scatterers. By picking (randomly) different initial phases, an infinite number of different realizations of the model can be generated. When the initial phases are also fixed, there is no further randomness left.

For conventional single NLoS link, ITU generic channel coefficient matrix is given by

$$\mathbf{H}_{u,s,n}(t) = \sum_{l=1}^{L} \begin{bmatrix} F_{Rx,u,V}(\varphi_{n,l}) \\ F_{Rx,u,H}(\varphi_{n,l}) \end{bmatrix}^T \begin{bmatrix} \exp\left(j\Phi_{n,l}^{VV}\right) & \sqrt{\kappa^{-1}}\exp\left(j\Phi_{n,l}^{VH}\right) \\ \sqrt{\kappa^{-1}}\exp\left(j\Phi_{n,l}^{HV}\right) & \exp\left(j\Phi_{n,l}^{HH}\right) \end{bmatrix} \begin{bmatrix} F_{Tx,s,V}(\phi_{n,l}) \\ F_{Tx,s,H}(\phi_{n,l}) \end{bmatrix} \cdot \exp\left(jd_s 2\pi\lambda_0^{-1}\sin(\phi_{n,l})\right) \cdot \exp\left(jd_u 2\pi\lambda_0^{-1}\sin(\varphi_{n,l})\right) \cdot \exp\left(j2\pi v_{n,l} t\right) \tag{2}$$

where u and s denote the u^{th} transmit antenna and s^{th} receive antenna respectively, n and l denote the n^{th} cluster and l^{th} ray within it. A cluster equals to a propagation path diffused in space, either or both in delay and angle domains, A number of rays constitute a cluster. φ and ϕ denote the angle of arrival (AoA) and angle of departure (AoD), $\{\Phi_{n,l}^{VV}, \Phi_{n,l}^{VH}, \Phi_{n,l}^{HV}, \Phi_{n,l}^{HH}\}$ is the random initial phase set for l^{th} ray of n^{th} cluster and for four different polarization combinations, i.e. VV, VH, HV, HH. κ is the cross-polarization power ratio (XPR) in linear scale, d_s stands for the distance between the s^{th} antenna element and the first element at receiver, $F_{Rx,s,V}$ and $F_{Rx,s,H}$ are the field patterns for vertical and horizontal polarizations of the n^{th} receive antenna element, respectively. For transmit antenna elements, d_u, $F_{Tx,u,V}$ and $F_{Tx,u,H}$ hold the same meanings with d_s, $F_{Rx,s,V}$, $F_{Rx,s,H}$ respectively. v is the velocity of receiver and t is the time. When RS is fixed, v is set to 0 in the backhaul link.

In the LoS case, define $\mathbf{H}'_{u,s,n} = \mathbf{H}_{u,s,n}$, and determine the channel coefficients by adding a single LoS ray and scaling down the other channel coefficients generated by (2). The LoS channel coefficients can be written as

$$\mathbf{H}_{u,s,n}(t) = \sqrt{\tfrac{K}{K+1}}\mathbf{H}'_{u,s,n} + \delta(n-1)\sqrt{\tfrac{1}{K+1}} \begin{bmatrix} F_{Rx,u,V}(\varphi_{LOS}) \\ F_{Rx,u,H}(\varphi_{LOS}) \end{bmatrix}^T \begin{bmatrix} \alpha_1 & 0 \\ 0 & \alpha_2 \end{bmatrix} \begin{bmatrix} F_{Tx,s,V}(\phi_{LOS}) \\ F_{Tx,s,H}(\phi_{LOS}) \end{bmatrix} \cdot \exp\left(jd_s 2\pi\lambda_0^{-1}\sin(\phi_{LOS})\right) \cdot \exp\left(jd_u 2\pi\lambda_0^{-1}\sin(\varphi_{LOS})\right) \cdot \exp\left(j2\pi v_{LOS} t\right) \tag{3}$$

where $\delta(\cdot)$ is the Dirac's delta function, φ_{LOS} and ϕ_{LOS} are the AOD and AOA of the LoS ray respectively, $\alpha_1 = \exp\left(j\Phi_{LOS}^{VV}\right)$ and $\alpha_2 = \exp\left(j\Phi_{LOS}^{HH}\right)$, with $\{\Phi_{LOS}^{VV}, \Phi_{LOS}^{HH}\}$ the random initial phase set for the LoS ray and for both VV and HH polarizations.

IV. Capacity calculation in AF anf DF modes

Assuming the transmit powers at BS and RS are equal to P_t, we can have that the total transmit power equals to $2P_t$. It is further assumed that RS has the full knowledge of channel characteristics of the backhaul channel. This assumption is practical and often realized by sending pilot signals in real-life communication systems.

The common gain factor g of the RS in the AF mode is given by

$$g = \sqrt{\frac{P_t}{\frac{P_t}{M}\|\mathbf{H}_1\|_F^2 + MN_0}} \tag{4}$$

where $\|\cdot\|_F^2$ denotes the squared Frobenius norm. The entries of noise vectors at the receiver side are independent zero-mean complex Gaussian random variables with variance of N_0. Noises are assumed to be time-uncorrelated so that noises in different time slots are independent. Amplifying matrix $\mathbf{G}$ is a diagonal matrix with diagonal entries all equaling to g.

The received signal at MS of a narrowband AF relay channel can be written as

$$\begin{aligned} \mathbf{y}_{AF} &= \mathbf{H}_{AF}\mathbf{s} + \mathbf{n}_{AF} \\ &= \begin{bmatrix} \mathbf{H}_0 \\ \mathbf{H}_2\mathbf{G}\mathbf{H}_1 \end{bmatrix}\mathbf{s} + \begin{bmatrix} \mathbf{n}_{MS} \\ \mathbf{H}_2\mathbf{G}\mathbf{n}_{RS} + \mathbf{n}'_{MS} \end{bmatrix} \end{aligned} \tag{5}$$

where $\boldsymbol{s}$ is the transmitted signal which satisfies $\mathbf{E}\{ss^H\} = \frac{P_t}{M}\mathbf{I}_{2M}$. $\boldsymbol{n}_{RS}$ and $\boldsymbol{n}_{MS}$ are the noise vectors at RS and MS respectively, $\boldsymbol{n}'_{MS}$ is the noise vector at MS in the second slot. The covariance correlation matrix of noise vector $\boldsymbol{n}_{AF}$ is

$$\begin{aligned} \mathbf{R}_{n,AF} &= \mathbf{E}\left\{\mathbf{n}_{AF}\mathbf{n}_{AF}^H\right\} \\ &= \begin{bmatrix} N_0\mathbf{I}_M & 0 \\ 0 & N_0\mathbf{H}_2\mathbf{G}\mathbf{G}^H\mathbf{H}_2^H + N_0\mathbf{I}_M \end{bmatrix} \end{aligned} \tag{6}$$

The capacity of AF relay channel is

$$C_{AF} = \log\det\left(\mathbf{I}_{2M} + \frac{1}{M}R_{n,AF}^{-1}\mathbf{H}_{AF}\mathbf{H}_{AF}^{\mathbf{H}}\right) \tag{7}$$

where $\mathbf{I}_{2M}$ is the $2M$-order identity matrix, $(\cdot)^H$ stands for the matrix conjugate transpose. It should be noted that a wideband system is considered, therefore we adopt the orthogonal frequency division multiplexing (OFDM) and treat the wideband channel as a set of narrowband channels in the frequency domain that the subcarrier spacings are of the same value [9]. Define $\mathbf{H}_{f,AF} = \mathbf{H}_{AF}$, where $\mathbf{H}_{f,AF}$ is the f^{th} narrowband channel matrix of total F channel matrices and $\boldsymbol{n}_{f,AF}$ as the f^{th} narrowband channel noise vector of total F noise vectors. Each narrowband relay channel noise vector has the same expression as (6), hence the capacity of each one is calculated by (7). The capacity of f^{th} narrowband relay channel is denoted by $C_{f,AF}$. The wideband AF relay channel capacity is given by

$$C_{AF} = \frac{1}{F}\sum_{f=1}^{F} C_{f,AF} \tag{8}$$

The received signal at MS in DF relay mode can be written as

$$\begin{aligned} \mathbf{y}_{DF} &= \mathbf{H}_{DF}\mathbf{s} + \mathbf{n}_{DF} \\ &= \begin{bmatrix} \mathbf{H}_0 \\ \mathbf{H}_2 \end{bmatrix} \mathbf{s} + \begin{bmatrix} \mathbf{n}_{MS} \\ \mathbf{n}'_{MS} \end{bmatrix} \end{aligned} \tag{9}$$

The covariance correlation matrix of noise vector $\boldsymbol{n}_{DF}$ is

$$\mathbf{R}_{n,DF} = \mathbf{E}\left\{\mathbf{n}_{DF}\mathbf{n}_{DF}^{\mathbf{H}}\right\} = N_0\mathbf{I}_{2M} \tag{10}$$

The capacity of backhaul link is given by

$$C_{DF}^{1} = \log\det\left(\mathbf{I}_M + \frac{P_t}{N_0 M}\mathbf{H}_1\mathbf{H}_1^H\right) \tag{11}$$

The capacity of direct link and access link with maximal-ratio combining at MS is given by

$$C_{DF}^{02} = \log\det\left(\mathbf{I}_{2M} + \frac{P_t}{M}\mathbf{R}_{n,DF}^{-1}\mathbf{H}_{DF}\mathbf{H}_{DF}^H\right) \tag{12}$$

The capacity of DF relay channel is then given by the minimum of C_{DF}^{1} and C_{DF}^{02}

$$C_{DF} = \min\left\{C_{DF}^{1}, C_{DF}^{02}\right\} \tag{13}$$

For the wideband DF relay system, we use the same method as proposed for the AF wideband relay system, each narrowband DF relay channel capacity which is denoted as $C_{f,DF}$ is derived by the expression in (13). Then the wideband capacity can be given by

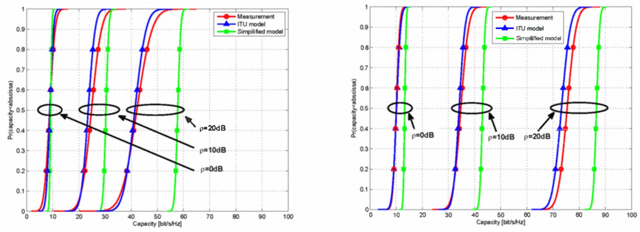
$$C_{DF} = \frac{1}{F}\sum_{f=1}^{F} C_{f,DF} \tag{14}$$

V. Simulation Results

It should be noted that both models have been modified to keep the comparison on a fair level. In ITU generic channel model, the uniform linear array (ULA) is the default antenna configuration. Arbitrary antenna configuration is modeled by the method given in [4]. To get fair comparison results, we need the configuration of the ODA utilized in the measurement. However, the ODA is a solid-core octagonal column with elements set around it. Modeling of the element geometry of the ODA brings large amounts of calculations. Therefore, the uniform circular array (UCA) is used to approach the element positions in the ODA. Meanwhile, the simplified relay channel model takes the polarization into account, and the cross-polarization ratios of three links are extracted from the measurement data. Fig. 3(a) and Fig. 3(b) show the cumulative distribution functions of the conventional point-to-point channel capacity values of ITU generic channel model, Rayleigh or Rician fading channel model and measured direct link channel at different signal-to-noise ratios (SNR) in LoS and NLoS propagation condition respectively. ρ stands for the fixed SNR at the RS in these figures. We use Urban micro (UMi) scenario in the ITU generic channel model which focuses on smaller cells and higher user densities and traffic loads in city centers and dense urban areas. Note that we concentrate only on the small-scale fading of channel coefficients, i.e., path loss and shadow fading are not considered. A normalization factor β is used to realize this restraint. β is given by

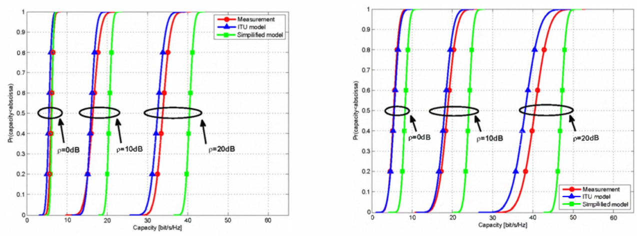
$$\beta = E\{\|\mathbf{H}\|_F\} \tag{15}$$

It is shown that ITU generic channel model is very close to the measurement data in term of capacity. Comparing Fig. 3(a) with Fig. 3(b), we can conclude that capacity of MIMO relay system in NLoS case is much higher than that in LoS case. The reason lies in the high spatial correlation in LoS case which greatly reduces the diversity gains MIMO system provides.



(a) The LoS case (b) The NLoS case

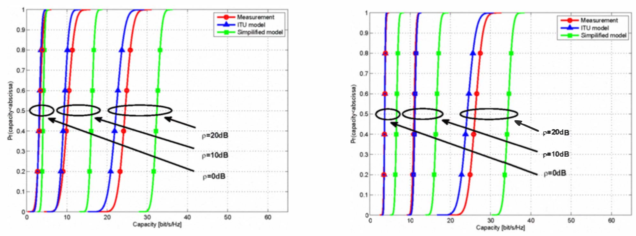
Fig. 3. Capacity of traditional point-to-point channel



(a) The LoS case (b) The NLoS case

Fig. 4. Capacity of relay channel in AF mode

Fig. 4(a) and Fig. 4(b) show the capacity values of AF relay channel of three considered channel realizations in the LoS and NLoS case respectively. We can observe that, like the point-to-point link, the capacity of ITU generic relay channel is very close to that of measurement channel in both LoS and NLoS case. It can also be observed that measurement capacity values are not so large as those reported in some literature. The reasons include the urban canyon effects during the measurement. As mentioned in section II, the buildings along the routes where MS moved are mostly higher than 25m, and the street width is less than 15m. Hence LoS components have great influence, and the rays reflected once by the buildings across the street arrive to the MS with large power. Besides, the maximum distances between MS and BS, MS and RS in the LoS case are 340m and 360m. This leads to a poor scattering environment, which decreases the diversity gains brought by MIMO system. Yet ITU generic model shows similar results to real channel without taking the urban canyon effect into account. We can observe from Fig. 4(a) and Fig. 4(b) that the capacity of ITU generic model is slightly lower than that of this measured channel, hence if an urban micro scenario without urban canyon effect is considered, the ITU generic model might underestimate the LoS capacity and be closer to the NLoS capacity.



(a) The LoS case

(b) The NLoS case

Fig. 5. Capacity of relay channel in DF mode

Fig. 5(a) and Fig. 5(b) show the capacity values in DF mode. When the SNR at the RS is fixed to be 10dB in the LoS case, the ergodic capacity of DF relay mode is 6.2bit/s/Hz less than that of AF mode, and in the NLoS case the value is 7.1bit/s/Hz. This is because the capacity of backhaul link is relatively low due to the LoS propagation condition between BS and RS, therefore DF capacity is mainly restricted by this link. The same case happens to both ITU generic channel model and the simplified channel model. Due to the measurement constraints, the case that MS has LoS propagation condition to RS and NLoS propagation condition to BS can not be analyzed. It should be pointed out that this paper only shows the capacity of a specific measurement campaign, the results here can not be extended to every case. But it proves that ITU generic channel model we proposed in this paper could be suitable for more accurate link-level and system-level simulations under certain conditions.

VI. Conclusions

In this paper we have presented a new method for modeling the relay system. Instead of modeling the channel coefficient matrix of each link of relay system with Rayleigh or Rician fading distribution, a double-directional geometry-based stochastic channel model based on ITU generic channel model is used. ITU generic channel model is developed based on extensive measurement data and aim to model the channel more accurately in the conventional point-to-point channel link. In this paper, a typical urban micro-cell scenario is chosen to perform the channel measurement campaign, and the capacity comparison between the proposed relay channel model, simplified relay channel model and the measurement channel shows that the proposed relay model has good accordance with the measurement data in both AF and DF relay modes in this specific environment.

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