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Citation for the original published paper (version of record):
Tang, X., Xu, X., Svensson, T. et al (2017). Coverage Performance of Joint Transmission for Moving Relay Enabled Cellular Networks in Dense
Urban Scenarios. IEEE Access, 5: 13001-13009. http://dx.doi.org/10.1109/ACCESS.2017.2727516

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IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 30, 2017, accepted July 11, 2017, date of publication July 17, 2017, date of current version July 31, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2727516

Coverage Performance of Joint Transmission for Moving Relay Enabled Cellular Networks in Dense Urban Scenarios

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This work was supported in part by the National Natural Science Foundation of China under Grant 61471068, Grant 61421061, and Grant 61325006, in part by the National Major Project under Grant 2016ZX03001009-003, and in part by the 111 Project of China under Grant B16006.

ABSTRACT Communication plays a significant role in terms of providing connectivity for urban users as well as sensors in smart cities. It has been shown that better communication capability for vehicular users can be obtained by introducing moving relays (MRs). With MRs, it is possible for macro base stations and moving relays to serve non-vehicular macro-users by performing coordinated multipoint (CoMP) joint transmission (JT). A bias-based CoMP scheme for MR enabled cellular network is analyzed in this paper. Motivated by antenna design constraints, in this paper, we assume that the outdoor antenna system of the MR can only be used for the moving backhaul link, i.e., the in-vehicle antenna system is also serving the non-vehicular macro-users. Using the stochastic geometry approach, a tractable model of the network is proposed. Based on the proposed model, integral expressions for CoMP-JT probability and coverage probability of non-vehicular macro user equipment are derived. Simulations verify the accuracy of the derived expressions. The results show that the probability for macro user equipment to be served with CoMP-JT is up to 70% when the intensity of MRs is ten times that of MBSs. This paper also includes a performance comparison among the analyzed scheme and related works. CoMP-JT with MRs provides better coverage performance for nearby macro user equipment. It can be found that the coverage gain of CoMP increases when the intensity of MRs increases within a certain range. Simulation results provide insights for practical system design in smart cities, such as the optimal MR intensity and the feasibility for opening access of MRs to macro user equipment.

INDEX TERMS Smart city, moving relay (MR), coverage probability, coordination multipoint joint transmission, stochastic geometry.

I. INTRODUCTION

According to the United Nations, about 70 percent of the world's population will be concentrated in the densely populated urban areas by 2050 [1]. With millions of dedicated and reliable sensors, smart cities may be a solution to offer citizens of urban areas a higher quality life. Since the exponential growth of traffic demand in cellular networks, communication plays a crucial role in terms of providing connectivity for urban users as well as sensors. Various advanced communication technologies, such as wireless sensor networks, machine-to-machine (M2M) communication, vehicle-to-vehicle (V2V) communication, network virtualization, and gateways, to name a few [2], [3], are exploited to provide better service for the administration of smart cities.

With the development of cities all over the world, vehicle population has unprecedentedly increased in the last decades. Thus, a growing number of cellular devices/user equipments (including laptops, smart phones, sensors, etc.) are vehicular, i.e. traveling in public transports. The communication of the vehicular user equipments (VUEs) is affected by high vehicle penetration loss (VPL) which is as high as 25 dB at the frequency of 2.4 GHz [4]. In order to meet the exponential growth of traffic demand for VUEs, moving relay (MR) is introduced in current cellular networks [5]–[12]. MRs are

usually mounted on top of vehicles (e.g. buses, trams, etc.) with an in-vehicle antenna to transmit/receive signals to/from VUEs and an outdoor antenna to receive/transmit signals from/to Macro Base Stations (MBSs). Besides effectively mitigating VPL for the VUEs, MRs provide the possibility to deploy various smart antenna techniques and exploit better propagation conditions than MBSs. Thus, MRs have proved to be a promising solution to boost the performance for VUEs [10]. Along with the rapid process of urbanization, vehicles are becoming denser and the complexity of road map topology is higher [13]. Thus, MRs can provide a significant number of access points for non-vehicular user equipments (macro user equipments, MUEs) as well as for VUEs. As the cellular network becomes denser, the interference will become an even more critical challenge. To that end, coordinated multi-point (CoMP) might be effective to convert the dominant interfering signal from the MR into useful signals by joint transmission (JT) [14].

A. RELATED WORKS AND MOTIVATION

Fixed relays are introduced in communication networks to increase coverage and enhance capacity. Various researches of fixed relays have been done, including downlink performance [15], uplink performance [16], coverage [17], resource allocation [18], mobile association [19] and so on. However the conclusions about fixed relays can't be applied to researches on MRs. The impact of deploying MRs still need plenty of explorations.

MR was proposed by EUROPE 5th generation (5G) project Mobile and wireless communications Enablers for Twenty-twenty Information Society (METIS) as the most promising solution to enhance and extend coverage for VUEs [5]. Previous research about MRs can be divided into two categories: MRs on high speed railways and MRs on vehicles. Most of the existing research focused on a high speed railway scenario. Based on a simple system model without fast fading, the authors in [6] investigated the capacity and handover performance gain of MRs in high speed railway scenario. It is proved that predictor antennas mounted on top of trains can enhance the reliability of the backhaul links [7]. Some enhanced schemes for the Long Term Evolution Advanced (LTE-A) have been proposed to accelerate measurement and in-network handover procedures. Authors of [8] proposed a scheme containing an enhanced measurement procedure and a group in-network handover procedure. Authors of [9] proposed an efficient fast handover scheme to mitigate the tunneling burden and handover latency with the city section mobility model. As a promising solution to boost the performance for VUEs, deploying MRs on the vehicles also faces many challenges, especially in typical urban scenario. Authors of [10] showed the great potential of MRs to improve the VUE experience compared to fixed relays. When the VPL is moderate to high, authors of [11] proved that MR assisted transmission has a better performance than transmission assisted by a fixed relay as well as direct transmission. From an energy efficiency point of view, the authors investigated the benefits of deploying MRs [12]. However, the interferences from other transmitters were ignored. Changes brought by the MRs have an effect on both VUEs and MUEs. Influences, specially interferences, have not yet received much attention and research on MUEs.

Since the huge quantity and mobility behavior of MRs, interference becomes an even more serious problem in smart cities compared to the traditional cellular networks. So interference mitigation is of critical importance. CoMP, as one of the key technologies for the 4th generation (4G) of cellular communication systems, is a kind of cooperation scheme to mitigate interference. In [20], each MBS's and mobile station's location is assumed to follow a Poisson Point Processe (PPP) distribution, which is employed mainly for its mathematical tractability. The authors verified that CoMP in dense cellular networks could significantly improve coverage performance. Authors of [21] derived an integral expression for the coverage probability of a user located outside a prescribed distance from any macro BSs. It is proved that the proposed scheme outperforms the traditional maximum-received-power association scheme. The authors of [14] proposed a CoMP scheme with a user-centric fixed geographic cooperation region. Based on stochastic geometry, the signal-to-interference-plus-noise ratio (SINR) distribution with coordination was characterized in a generality-preserving form. It turned out that increasing the network-wide density of BSs decreases SINR outage probability exponentially, which can be applied to practical design problems. However, there is no research to analyze the performance enhancement from CoMP in MR enabled cellular networks.

The traditional method to analyze the cellular networks is carried out via performing system simulations following the hexagonal grid model. The formulas deduced from such a model are usually complex and influenced by multiple stochastic variables. As the introduction of MRs, the cellular network is getting more complex. The regular assumption of the cellular networks is oversimplified as well as inaccurate for the randomness and irregularity of the MR enabled cellular networks. Recently, stochastic geometry has been widely used as an analytical approach to model and quantify the key metrics (coverage probability, throughput, delay, etc.) in wireless networks [22]. It is employed mainly for its mathematical tractability. In stochastic geometry, PPPs are statistic-based which are proved to fairly accurately describe the randomness of node deployment in heterogeneous network [23], especially in dense cellular networks. To the best of our knowledge, most research of MRs are based on a simple system architectures or ignoring the mobility behavior of MRs. There is no detailed research about CoMP with MRs in smart cities.

B. CONTRIBUTION

Compared with the existing works, our objective in this paper is to model and analyze CoMP with MRs in smart cities. A tractable mobility model is needed to describe the

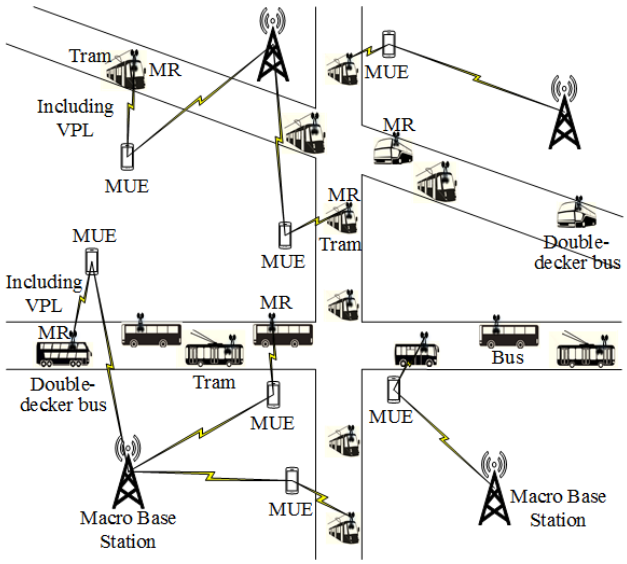

FIGURE 1. Moving Relay enabled Cellular Networks with CoMP.

characteristics of MR enabled cellular networks. To the best of our knowledge, no such research on MRs has been conducted with focus on MUEs. This paper proposes a tractable model for MR enabled cellular networks by using stochastic geometry. Motivated by antenna design constraints, we assume that the outdoor antenna system of the MR is optimized for the moving backhaul link, so that the in-vehicle antennas must be used for the MUEs as well. A flexible bias-based CoMP-JT scheme is analyzed in the downlink for such moving relay enabled cellular networks. Based on the proposed model, we derive the probability that MUEs operate in CoMP mode with MRs. In addition, an expression for the coverage of MUEs operating in CoMP mode is obtained. Simulation results verify the accuracy of the model and show the high probability for CoMP with MRs. The coverage probability for MUEs can also be quite enhanced by CoMP-JT. Insights are provided for practical system design in smart cities, such as the optimal MR intensity for different schemes and the feasibility for opening access of MRs to MUEs.

C. OUTLINE

The remainder of this paper is organized as follows: Section II describes the network model, bias-based CoMP JT scheme in detail. The CoMP probability and coverage performance analyzed are in Section III. Simulation results and analysis results are presented in Section IV to verify the accuracy of the derived expressions and theoretical results. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL

A. NETWORK MODEL

As depicted in Fig. 1, MRs are mounted on various vehicles. The distribution of MRs is getting denser and more randomized with the urbanization due to the growing number of vehicles and higher coverage of vehicle routing in smart cities [24]. We consider a heterogeneous cellular network composed of two independent network tiers of MBS tier (tier 1) and MR tier (tier 2). According to the deployment in a dense urban scenario, tier 1 and tier 2 can be reasonably modeled by two independent homogeneous PPP Φ_1 and Φ_2 with density parameters of λ_1 and λ_2, respectively [20]. Besides, we suppose that each node in tier i ($i = 1, 2$) uses an identical transmit power T_i and path loss α_i. The 3rd generation partnership project (3GPP) standardized channel propagation model for heterogeneous networks [25] including distance-based path loss and Rayleigh fading is applied. Based on evaluation assumptions in the above project for heterogeneous networks, the path loss exponents are approximated such that $\alpha_1 \approx \alpha_2 = \alpha$ [25]. According to the antenna design constraints, VPL is considered when the MR transmits radio signals to MUEs outside of vehicles.

For the typical MUE at point y, we define x_i as the location of the transmitter belonging to the *i-th* tier that results in the strongest long-term average received power at the location y.

$$x_i = \arg\max_{x \in \Phi_i} \left\{ P_i |x - y|^{-\alpha} \right\} \tag{1}$$

where $|\cdot|$ is the Euclidean distance between x and y, and $P_i = \gamma_i T_i$. γ_i is the VPL of tier i and $\gamma_1 = 1$.

The long-term averaged downlink Received Signal Strength (*RSS*) for the typical user is given by:

$$\mathrm{RSS}_i(|x_i - y|) = P_i |x_i - y|^{-\alpha}. \tag{2}$$

When the MR passes by the typical user, the coordinated MR is assumed to travel at a constant speed V in a straight line. Although in movement, MUEs are approximated as stationary due to their relatively low speed.

B. BIAS-BASED CoMP JT SCHEME

Without loss of generality, we assume that a typical MUE is located at the origin. Based on the *RSS* from each tier, the typical MUE independently operates in different mode such as CoMP or non-coordinated mode. The typical user is only served by the strongest MBS when the *RSS* from the strongest MBS is sufficiently higher than that received from the strongest interfering passing MR. The MBS and MR start CoMP-JT to the user when the *RSS* from the strongest interfering MR is comparable to that of the connecting MBS with a bias factor η (≥ 0 dB) [26]. In this case, the typical user begins to operate in CoMP mode. The typical user keeps operating in CoMP mode while the signal power from the MR is lower than that from MBS. As the MR moves, the typical UE only accesses the MR when the RSS from the passing by MR is larger than that from the connecting MBS. We focus on whether the MR would keep CoMP with MBS rather than the non-coordinated circumstance. A flexible CoMP association scheme is defined with an adjustable threshold that encourages MUEs to access low-load MRs. The bias-based CoMP association criterion is designed as

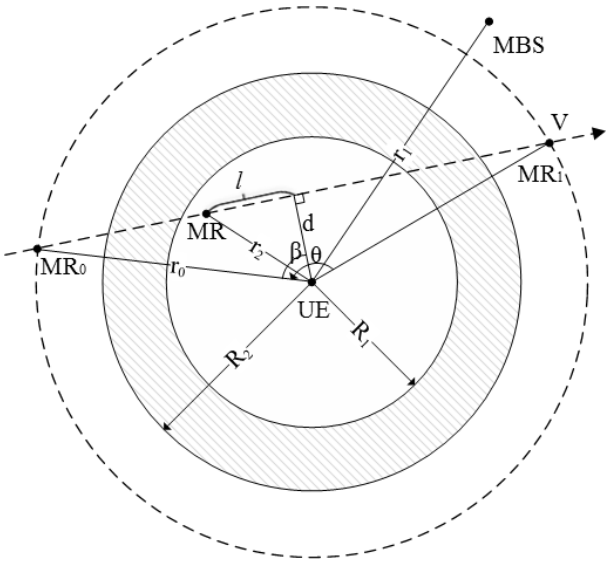

FIGURE 2. Illustration of the nearest MR trajectory.

follows:

$$1 < \frac{P_1 r_1^{-\alpha_1}}{P_2 r_2^{-\alpha_2}} < \eta, \tag{3}$$

where we refer to η as the coordination threshold. r_i is the distance from the typical user to the strongest transmitter in the *i-th* tier.

III. CoMP PROBABILITY AND COVERAGE PERFORMANCE

As we can see from Fig. 2, let's assume that the random trajectory of the strongest MR located at x_2 is a straight line. The straight line is determined by the two points $MR_0 \in \Phi_2$ and MR_1. r_0 represents the distance between the MR_0 and the typical user. MR_1 is any arbitrarily chosen point on the dotted circle of radius r_0 centered at the typical user. $\theta \in [0, 2\pi]$ is a random orientation which represents the moving direction of the strongest MR [27]. Without loss of generality, we focus on the region where MUEs operate in CoMP mode. Based on (3), around the typical user, the annular observation region Γ is delimited by the minimum and maximum radii $R_1 = (P_2/P_1)^{1/\alpha} r_1$ and $R_2 = (\eta P_2/P_1)^{1/\alpha} r_1$, respectively, that is $\Gamma = \{(r_1, r_2) : r_1 > 0 \text{ and } R_1 < r_2 < R_2\}$. According to the association criterion, the CoMP procedure will initiate when the nearest MR enters into the region Γ. As is shown in Fig. 2, d is the distance from the typical user to the movement trajectory of its nearest MR. The probability of CoMP can be expressed as the probability that the random trajectory of the MR have intersections with the annular. In other words, $d \le R_2$ is the condition that users start to operate in CoMP mode. Let Q denote the probability that the typical user operates in CoMP mode with a nearby MR passing by the user. Conditioned on that event, we derive the probability density function (*pdf*) of d.

Firstly, the distribution of the angle β will be derived based on the trajectory of the coordinated MR.

Lemma 1: The pdf of B is derived as:

$$f_B(\beta) = \frac{2}{\pi}, \ 0 < \beta < \frac{\pi}{2}. \tag{4}$$

Proof: See Appendix A.

Lemma 2: The probability for the typical user operating in CoMP mode is given by:

$$Q = \frac{1}{\sqrt{1 + \frac{\lambda_1}{\lambda_2}\left(\frac{P_1}{\eta P_2}\right)^{1/\alpha}}}. \tag{5}$$

Proof: See Appendix B.

As can be seen from (5), the probability for the typical user operating in CoMP has positive correlation with the ratio of MR and MBS intensity. We find that larger bias factor η leads to higher probability. Based on the property of function $Q(\frac{\lambda_2}{\lambda_1})$, the positive slope is pretty high when the independent variable $\frac{\lambda_2}{\lambda_1}$ is less than a certain ratio decided by the constant value $\frac{P_1}{\eta P_2}$ and the growth of CoMP probability Q will eventually slow down and stabilize when the ratio is greater than the certain value. For example, the certain value mentioned before is about 20 when $\eta = 12$ dB and $\alpha = 4$. The result shows that it is inefficient to blindly increase the MR intensity in the practical design of smart cities.

The coverage probability is defined as the probability that the instantaneous SINR of a randomly located user is more than a predetermined threshold τ.

$$C = \int_{\Gamma} \prod_{j=1}^{2} \exp\left(-2\pi\lambda_j \left(\tau P_j / \sum_{i=1}^{2} P_i \|r_i\|^{-\alpha}\right)^{\frac{2}{\alpha}} \int_{\left(\tau P_j / \sum_{i=1}^{2} P_i \|r_i\|^{-\alpha}\right)^{-\frac{1}{\alpha}} r_j}^{\infty} \frac{r}{1+r^{\alpha}} \mathrm{d}r\right) f_L(l) f_D(d) f_{R_c}(r_0, r_1)) \mathrm{d}l \mathrm{d}d \mathrm{d}r_0 \mathrm{d}r_1 \tag{6}$$

$$C = \int_{\Gamma} \left(\exp\left(-\pi \sum_{i=1}^{2} \left(\tau P_j / \sum_{i=1}^{2} P_i \|r_i\|^{-\alpha}\right)^{\frac{2}{\alpha}} \arctan\left(\frac{\tau P_j \|r_i\|^{-\alpha}}{/} \sum_{i=1}^{2} P_i \|r_i\|^{-\alpha}\right)^{\frac{2}{\alpha}}\right)\right) f_L(l) f_D(d) f_{R_c}(r_0, r_1)) \mathrm{d}l \mathrm{d}d \mathrm{d}r_0 \mathrm{d}r_1 \tag{7}$$

Theorem 1: The coverage probability for the typical user operating in CoMP mode is provided by (6), shown at the bottom of the previous page, where $f_L(l)$, $f_D(d)$ and $f_{R_c}(r_0, r_1)$ are given in the proof below.

Specifically, when $\alpha = 4$, the expression can be further simplified to (7) [28], shown at the bottom of the previous page.

Proof: Before we calculate the coverage probability of the typical user, we compute the *pdf*s of D and L (as shown in Fig. 2) and the joint *pdf* of $R_c = (R_0, R_1)$. From the geometric configuration in Fig. 2, we get

$$r_2 = \sqrt{d^2+l^2},\ \left(\frac{P_2}{P_1}\right)^{1/\alpha} r_1 < r_2 < \left(\frac{\eta P_2}{P_1}\right)^{1/\alpha} r_1. \quad (8)$$

Based on (18), (20) and (21), the *pdf* of D can be derived as

$$f_D(d) = \frac{2}{\pi\sqrt{r_0{}^2 - d^2}},\ 0 < d < \left(\frac{\eta P_2}{P_1}\right)^{1/\alpha} r_1. \quad (9)$$

According to the definition of the MR's trajectory, for different range of variable d, the *pdf* of L becomes

$$f_L(l) = \begin{cases} \dfrac{1}{\sqrt{\left(\frac{\eta P_2}{P_1}\right)^{2/\alpha} r_1{}^2 - d^2} - \sqrt{\left(\frac{P_2}{P_1}\right)^{2/\alpha} r_1{}^2 - d^2}}, \\ 0 < d < \left(\frac{P_2}{P_1}\right)^{1/\alpha} r_1 \\ \dfrac{1}{\sqrt{\left(\frac{\eta P_2}{P_1}\right)^{2/\alpha} r_1{}^2 - d^2}},\ \left(\frac{P_2}{P_1}\right)^{1/\alpha} r_1 < d < \left(\frac{\eta P_2}{P_1}\right)^{1/\alpha} r_1. \end{cases} \quad (10)$$

The probability of the distance between the typical user and its nearby transmitters can be derived on the basis of PPP properties. In particular, the joint *pdf* of R_c can be derived as

$$f_{R_c}(r_0, r_1) = 4\pi^2\lambda_1\lambda_2 r_1 r_0 \exp\left[-\pi(\lambda_1 r_1{}^2 + \lambda_2 r_0{}^2)\right]. \quad (11)$$

The coverage probability of the typical user can be derived as

$$\begin{aligned} C &= \mathbb{P}\{SINR > \tau\} \\ &\overset{(a)}{=} \mathbb{P}\left\{\left|\sqrt{P_1}\|r_1\|^{-\frac{\alpha}{2}} h_1 + \sqrt{P_2}\|r_2\|^{-\frac{\alpha}{2}} h_2\right|^2 > \tau I\right\} \\ &\overset{(b)}{=} \mathbb{E}_{I,r_1,r_2}\left[\exp\left(\frac{-\tau i}{\sum_{i=1}^{2} P_i\|r_i\|^{-\alpha}}\right)\right] \\ &\overset{(c)}{=} \mathbb{E}_{r_1,r_2}\left[\prod_{j=1}^{2}\mathcal{L}\left(\frac{\tau}{\sum_{i=1}^{2} P_i\|r_i\|^{-\alpha}}\right)\right], \end{aligned} \quad (12)$$

where (a) follows the definition of cumulative distribution function (*cdf*) of SINR, (b) is caused by the assumption that $h_i s$ are i.i.d. and $\sim CN(0, 1)$, and (c) follows from the definition of the Laplace transform. The Laplace transform of I_i is calculated as follows:

$$\begin{aligned} \mathcal{L}_{I_j}(s) &= \mathbb{E}_{I_j}\left[\exp(-sI_j)\right] \\ &= \mathbb{E}_{\Phi_k}\left[\exp(-sP_j \sum_{x_i\in\Phi_k\setminus x_k} |h_j|^2 R_j{}^{-\alpha})\right] \\ &\overset{(d)}{=} \exp\left[-2\pi\lambda_j \int_{r_j}^{\infty}\left(1 - \frac{1}{1+sP_j r^{-\alpha}}\right) r\mathrm{d}r\right] \\ &\overset{(e)}{=} \exp\left[-2\pi\lambda_j (sP_j)^{2/\alpha} \int_{(sP_j)^{-1/\alpha} r_j}^{\infty} \frac{x}{1+x^\alpha}\mathrm{d}x\right], \end{aligned} \quad (13)$$

where (d) is derived by applying the Laplace Functional of PPP [29], and (e) is obtained by replacing $x = (sP_j)^{-1/\alpha}$.

By substituting (13) in (12), the coverage probability can be derived as

$$C = \mathbb{E}_{r_1,r_2}\left[\prod_{j=1}^{2}\exp\left(-2\pi\lambda_j\left(\frac{\tau P_j}{\sum_{i=1}^{2} P_i\|r_i\|^{-\alpha}}\right)^{2/\alpha} \times \int_{(sP_j)^{-1/\alpha} r_j}^{\infty} \frac{x}{1+x^\alpha}\mathrm{d}x\right)\right]. \quad (14)$$

By combining (8), (9), (10) and (11), then substituting in (14), we obtain the coverage probability of a randomly located CoMP user as given in (6).

IV. SIMULATION AND DISCUSSIONS

In this section, simulation results are given to verify the accuracy of the expressions derived above and to quantify the performance of the system. For the evaluation, transmit powers of the MBS and the MR are assumed to be $P_1 = 46$ dBm and $P_2 = 30$ dBm, respectively. The path loss exponent is $\alpha = 4$. The tier 1 has an intensity of $\lambda_1 = (500^2\pi)^{-1}$. Unless otherwise stated, the intensity of tier 2 is 10 times that of tier 1, i.e. , $\lambda_2 = 10(500^2\pi)^{-1}$, the SINR threshold $\tau = -10$ dB the VPL is $\gamma_2 = 10$ dB and the bias factor η is assumed to be 6 dB.

Since the number of vehicles (up to 1000) is different in different 2000m $\times$ 2000m urban scenarios [13], simulation is performed with different intensities of MRs which is much less than that of vehicles. Fig. 3 illustrates the effects of varying both the ratio of MR and MBS intensity and the bias factor on the CoMP probability of a typical MUE. The curves indicate the feasibility of CoMP with MRs in moving relay enabled cellular networks. It can be seen that the analytical

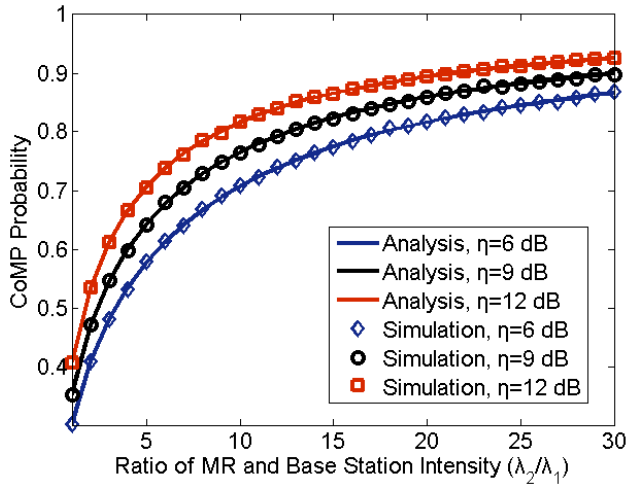

FIGURE 3. CoMP probability of MUEs vs. ratio of MR and MBS intensity.

results (see the expression given in (5)) match exactly with the simulation results which reflects the accuracy of our analysis. As we discussed earlier, it also shows that when the ratio of the MR and MBS intensity is increasing, the users are served monotonically more frequently in CoMP mode, but the monotonic increase is less than linear after a certain ratio. The probability growth will eventually slow down and stabilize when the intensity of MRs is much higher than that of MBSs. Moreover, the CoMP probability naturally increases with the bias factor. When the intensity of MRs is ten times that of MBSs and $\eta = 6$ dB, the CoMP probability is as high as 70%. The results also show that it is inefficient to blindly increase the MR intensity in the practical design of smart cities.

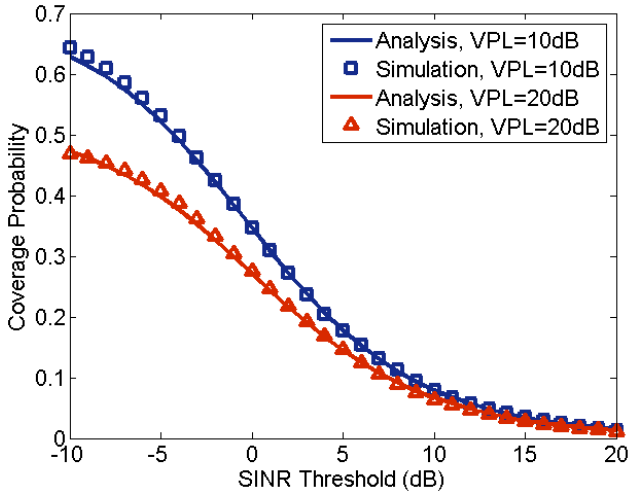

FIGURE 4. Analysis vs. simulation: Coverage probability for bias-based CoMP.

Fig. 4 demonstrates the analytical results and the simulation results for different VPL (i.e. $\gamma_2 = 10$ dB and 20 dB [30]) which prove the validation of our analysis (see the expression given in (6)). For a given SINR threshold, higher VPL degrades the coverage performance, especially with low

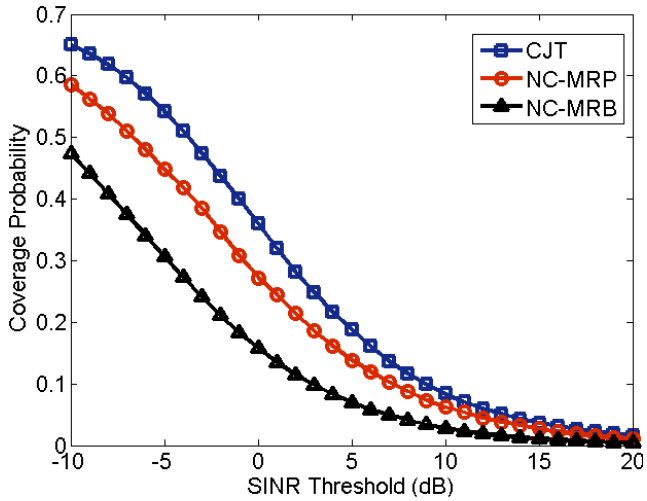

FIGURE 5. CJT vs. NC-MRP and NC-MRB: Coverage probability vs. coverage SINR threshold.

threshold τ. CoMP with MR provides better enhancement for MUEs when the VPL is not that high.

For comparison, we introduce the two main alternative schemes, namely, non-coordinated maximum-received-power-based network (NC-MRP) and non-coordinated MR-bias network (NC-MRB). The association of NC-MRP is based on the long-term received power. A typical user is only served by the strongest MBS or MR without any biasing (*i.e.*, $\eta = 0$). Users in the NC-MRB mode prefer associating to the MR, even when the received power from the MR is less than that from the MBS. The positive bias to the tier 2 association is defined as $\eta = 6$ dB. As depicted in Fig. 5, the curves compare the performance of the bias-based CoMP-JT scheme with those of the NC-MRP and NC-MRB schemes with different SINR threshold. The bias-based CoMP-JT scheme, which is denoted as CJT, can enhance the coverage probability of the typical user by about 9% when $\tau = 0$ dB. The CJT with MRs performs better than the other schemes since the coordination has effectively transferred the interferences from passing by MRs into useful signals.

Increasing the MR density λ_2 has two opposing effects: (1) it causes more interference, since the number of active MRs in the network is increased; (2) it increases the chances of MUEs being jointly served by MR and MBS. As we can see from Fig. 6, when the distribution of MRs is getting denser, which means the ratio of MR and MBS intensity is higher, the coverage performances with all schemes are getting better before the break point. The break point represents the balance point of two opposing effects from increasing the MR density. From this figure, it can be seen that the CJT scheme has two advantages over the other two schemes. Firstly, the coverage probability for the CJT scheme is better than that for the other two schemes. Furthermore, the break point of CJT is larger than the other two schemes which illustrates CJT can support 10% denser deployment of MRs. Although the coverage performance falls after the break point, the decline is gradual and

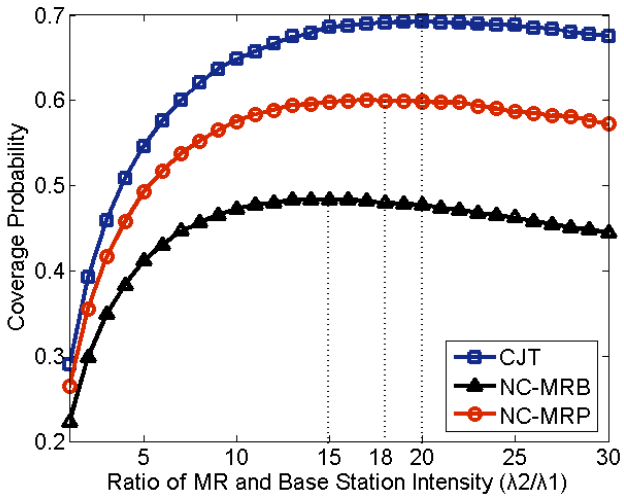

FIGURE 6. CJT vs. NC-MRP and NC-MRB: Coverage probability vs. ratio of MR and MBS intensity.

the decreasing extent is not high. From another perspective, when the distribution of MBSs is denser, which means the the ratio of MR and MBS lower, the coverage performances with all schemes are getting worse before the break point. Increasing the MBS density decreases the chances of MUEs being jointly served by MR and MBS and brings much more interference from the MBSs. These interesting findings can provide insights for practical system design in smart cities, like the optimal deployment of MRs.

V. CONCLUSION

In smart cities, moving relays have proved to be a promising solution to provide connectivity for vehicular user equipments. With the introduction of moving relay, we verify the feasibility that macro base stations can coordinate with moving relays to serve macro user equipments jointly. With the coordination of macro base stations and moving relays, CoMP-JT can improve the coverage performance for macro user equipments. Based on the analyzed CJT scheme, we derived the CoMP probability and coverage probability of a randomly located macro user equipments. Simulations verified the accuracy of the derived expressions. We conclude that the probability that a user is served with CoMP is in general quite high, up to 70% when the intensity of moving relays is ten times that of macro base stations. Despite the signal strength deduction caused by the VPL, the CoMP-JT with moving relays improves the macro user equipments' coverage when the nearest moving relay passes by the macro user equipment. It is also found that when the ratio of moving relay and macro base station intensity equals to the break point, maximum achievable coverage gain is available for CoMP in moving relay enabled cellular networks. CJT can support 10% denser deployment of moving relays than the other two schemes. These results provide insights for practical system design in smart cities. Operators should open access of moving relays to macro user equipments and select a proper deployment intensity of moving relays to provide a better service.

APPENDIX A
PROOF OF LEMMA 1

As shown in Fig. 1, the angle β in the right triangle is within the interval $[0, \pi/2]$. According to the definition from [27], β can be expressed for different range of variable θ as follows:

$$\beta = \begin{cases} \dfrac{\theta}{2}, & 0 < \theta < \pi \\ \dfrac{2\pi - \theta}{2}, & \pi < \theta < 2\pi, \end{cases} \tag{15}$$

where the angle θ is formed by the intersection points between the trajectory of the MR and dotted circle. The distribution of Θ can be derived as follows:

$$F_\Theta(\theta) = \frac{(4\pi - \theta)\theta}{4\pi^2}, \quad 0 < \theta < 2\pi. \tag{16}$$

Combining (15) and (16), the *cdf* of B can be derived as

$$F_B(\beta) = \frac{2\beta}{\pi}, \quad 0 < \beta < \frac{\pi}{2}. \tag{17}$$

Taking the first-order derivative of (17), the *pdf* of B is given by

$$f_B(\beta) = \frac{2}{\pi}, \quad 0 < \beta < \frac{\pi}{2} \tag{18}$$

APPENDIX B
PROOF OF LEMMA 2

The distance from the typical user to the initial location of nearest MBS and MR is denoted as r_1 and r_0, respectively. In a homogeneous PPP, the *pdf* of r_1 and r_0, that is $f_{R_1}(r_1)$ and $f_{R_0}(r_0)$, can be derived as follows:

$$f_{R_1}(r_1) = 2\pi\lambda_1 r_1 \mathrm{e}^{-\pi\lambda_1 r_1^2} \tag{19}$$

$$f_{R_0}(r_0) = 2\pi\lambda_2 r_0 \mathrm{e}^{-\pi\lambda_2 r_0^2}. \tag{20}$$

From the geometric configuration in Fig. 2 we get

$$d = r_0 \cos\beta. \tag{21}$$

By the utilization of (19), (20) and (21) we can derive the probability for CoMP as follows:

$$\begin{aligned} Q &= \mathbb{P}[d \le R_2] \\ &= \mathbb{P}\left[r_0 \cos\beta \le \left(\frac{\eta P_2}{P_1}\right)^{1/\alpha} r_1\right] \\ &= \mathbb{P}\left[r_0 \le \left(\frac{\eta P_2}{P_1}\right)^{1/\alpha} \frac{r_1}{\cos\beta}\right] \\ &= \mathbb{E}_{\beta, r_1}\left[1 - \exp\left(-\pi\lambda_2 \left(\frac{\eta P_2}{P_1}\right)^{2/\alpha} \left(\frac{r_1}{\cos\beta}\right)^2\right)\right] \\ &= \mathbb{E}_\beta\left[\frac{1}{\left(\frac{\lambda_1}{\lambda_2}\left(\frac{P_1}{\eta P_2}\right)^{2/\alpha} \cos^2\beta + 1\right)}\right] \\ &= \frac{1}{\sqrt{1 + \frac{\lambda_1}{\lambda_2}\left(\frac{P_1}{\eta P_2}\right)^{1/\alpha}}}. \end{aligned} \tag{22}$$

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