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Performance Trends of Millimeter Wave Energy Harvesting Networks with Base Station Cooperation

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Abstract: The great demand for high data rate transmission has evolved due to the booming wireless services, especially on the forthcoming fifth generation (5G) network. The upcoming cellular network is expected to utilize the higher segment of the frequency band, i.e., the millimeter wave (MMW), to meet the demand for extraordinarily high data rates to serve abundant applications. This paper focuses on developing a prediction tool for assessing the energy coverage of the downlink transmission in MMW energy harvesting networks with base station cooperation based on the stochastic geometry model. The signal-to-noise plus interference ratio (SINR) and energy coverage are evaluated by modeling the user and base station locations following the Poisson Point Processes (PPP). Joint transmission of two base stations is considered to investigate its impact on energy harvesting. The prediction tool is developed using MATLAB, where the unique characteristics of MMW propagation and antenna features are incorporated into the simulations. It is observed that the dense deployment of the MMW base station significantly improves both the SINR and energy coverage.

Keywords: *5G; millimeter-wave; energy harvesting; Poisson point process; base station cooperation.*

1.0 INTRODUCTION

The rapid development in wireless technology has led to excessive mobile data traffic demand [1]. On top of existing microwave networks, the upcoming 5G networks will utilize the millimeter wave (MMW) band, which spans between 30 GHz to 300 GHz, to fulfill the future mobile data traffic demand. There are many distinguishing characteristics of MMW communication as compared to the microwave counterpart. Firstly, the MMW spectrum has a broad underutilized bandwidth, which certainly has the potential to support high capacity and data rates. Secondly, the MMW signal is highly affected by the blockage leading to significant path loss characteristics for line-of-sight (LoS) and non-LoS communications. Therefore, to ensure reliable coverage, dense deployment of MMW base stations is highly recommended [2]. Thirdly, MMW has a small wavelength which is from 1 to 10 mm, compared to microwaves. As a result, more antenna elements can be packed and produce high directivity, which is advantageous for long-distance communication [3], [4].

From the perspective of energy harvesting (EH), the unique MMW characteristics could bring more benefits as more power can be harvested in the dense network. The high-directional antenna also allows energy to be harvested at a

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long distance, which is not feasible in the microwave band [5], [6]. Furthermore, interference mitigation techniques, such as base station cooperation and coordination have been considered as promising technologies that can further bring benefit to energy harvesting networks [7].

Generally, EH refers to a technology that uses ambient heat differences, vibration, sound, light, and radio waves to generate energy. With the evolving technologies, researchers have been trying to find a new energy source that does not depend on natural resources. Therefore, much research explores a new energy source from radio frequency (RF) signal, where the RF signal is not only transmitting information but also conveying energy to the user. Thus, the receiver can demodulate information and collect it through the design of the receiver circuit.

In the past few years, the continuous expansion of network scale, diversification of base stations, and other communication equipment have become an increasingly important part of the extensive application of information technology. Hence, the network energy consumption and difficulty with the base stations' energy supply have increased. This issue has led to the new finding of the EH method, which can enable the technology to resolve the difficulty of energy depletion in the future communication structure. The abundance of devices can collect energy from natural sources, such as wind, solar or renewable energy-powered devices [8], following the EH method. Since this technology have some limitations, the optimization of service quality in the network must be considered based on the most efficient use of energy. By focusing on this segment, the SWIPT technique offers an effective solution for EH where it can transmit power and carry information simultaneously, enhancing energy coverage and capacity.

2.0 RELATED WORKS

Integrating EH technologies into wireless communication has sparked a lot of attention as the 5G cellular network is anticipated to implement effective interference management systems to improve communication performances. In the realm of 5G networks, SWIPT technologies can be important factors for energy supply and data trade with various super low power sensors that is useful in detect applications. It could also be considered an efficient way to support high throughput and energy sustainability. However, a challenging scenario arises when sources perform. Even though SWIPT is a powerful signal, it also creates interference [9]. The SWIPT is also potential to be used in MMW communication as one of the primary approaches to fulfill the ever-increasing demand for data transfer rates due to high bandwidth [10]. Due to higher frequencies, the blockage effects of MMW occur, and it will limit the performance of emerging the MMW cellular network. Several studies have recently been conducted to assess the energy coverage and capacity that will be considered interference or blockage effect, which are further discuss in this section.

The stochastic geometry by implementing the PPP model is one of the approaches that has been widely used to evaluate the performance of MMW networks. The work in [11] investigated the blockage effects in urban areas. The authors also proposed a mathematical framework to model blockages and eliminates the limitation on the orientations and sizes of the blockages as in prior lattice models. Specifically, random buildings in urban areas are modeled by using PPP. Such a blockage model has been widely used in the study of MMW networks. The work in [12], [13] presented an analytical framework to evaluate the SINR coverage in the uplink of MMW cellular networks by following the stochastic geometry method. The framework measured the blockage effect using a distance dependent LOS probability function and modeled the location of LOS and non-line-of-sight (NLOS) users as two independent non-homogeneous PPP. The proposed framework in [12], [13] presented the analytical expression of SINR coverage probability in the uplink of MMW and demonstrated a solid match with the simulation. The authors in [14] studied the advantages of base station cooperation in the downlink of a diverse MMW network system to reduce signal outages. They used the stochastic geometry-based model for the single path channel models that can be consider either in LOS or NLOS link. In the presence of the blockage, the derivation of integral expressions is applied in the coverage probabilities with different fading distributions.

Recently, the authors in [6] proposed the EH on the combination of MMW and Sub-6 GHz networks, where the user equipment (UE) receives and harvests information and energy simultaneously from sub-6 GHz and MMW BSs. They used the PPP model and Poisson cluster process (PCP) to produce analytical expressions for the energy coverage probability (ECP) and signal-to-interference-plus-noise coverage probability (SCP) of a typical user. According to the results, they discovered that ECP varies depending on the considered UE models. As BS cluster size grows, ECP increases. However, for the PCP model, ECP decreases as BS cluster size increases. In the other approach, research shows that the MMW WPT network's performances can be accurately represented by using the Gaussian antenna model with the actual pattern. The researchers considered an MMW WPT network, where the locations of the transmitters followed a PPP model [15]. The authors analytically characterized both the link and network-level performance while incorporating diverse network interference in their model, thus modeling the locations of the transmitters and receivers using independent PPPs. The authors provide a concise framework for assessing the system's performance. However, to the best of our knowledge, no work so far considers the joint-transmission element in EH networks. Therefore, this work focuses on the simulation of EH networks consisting of base-station cooperation.

This paper presents the evaluation of ECP from joint transmission on the EH network using the stochastic geometry framework. The significant factor that makes the energy evaluation in EH networks distinct from other works is that this paper considers base-station cooperation of two base stations and investigates the impact of the joint transmission.

3.0 SYSTEM MODEL

3.1 Base Station Cooperation Modeling

We consider the joint transmission of EH network as illustrated in Figure 1, where SBSs placement are distributed following another independent PPP$\{x_s\} = \Phi_s$ with SBS intensity λ_s. Mobile UEs are distributed independently following a homogeneous PPP Φ_u with intensity λ_u. We assumed that all the BS in the one-tier are transmitting the same power in the downlink denoted by P_k. In our case, we only considered a one-tier network, and this tier is characterized by the non-negative blockage constant, β. The parameter β is determined using the density and average size of objects within the tier. The path loss, α is a random variable that takes on values αLOS and αNLOS with probability $e^{-\beta v}$ and $1 - e^{-\beta v}$, respectively. v represents the distance between base station and the typical user.

3.2 Antenna Modeling

We assume that all MMW SBSs are equipped with a directional antenna to compensate for higher propagation losses. The BSs and users are fitted with N_t and N_r antenna elements. We use the sectored antenna model in Figure 2, similar to the one considered in [11][12]. For the interfering BSs, we assume that each of the interference is transmitting with the main-lobe beam pointed in a random direction. We model the directivity gain, D_i as a random variable. We assume the steering angle of the interfering BSs is modeled as independently and uniformly distributed $[0, 2\pi]$. In this case, the antenna gain of an interfering link is given by [12]

$$D_i = \begin{cases} b_1 = M_1 M_2 \quad wp \quad a_1 = \dfrac{\theta_t}{2\pi}\dfrac{\theta_r}{2\pi} \\ b_2 = M_1 m_2 \quad wp \quad a_2 = \dfrac{\theta_t}{2\pi}\dfrac{\theta'_r}{2\pi} \\ b_3 = m_1 M_2 \quad wp \quad a_3 = \dfrac{\theta'_t}{2\pi}\dfrac{\theta_r}{2\pi} \\ b_4 = m_1 m_2 \quad wp \quad a_4 = \dfrac{\theta'_t}{2\pi}\dfrac{\theta'_r}{2\pi} \end{cases} \tag{1}$$

where b_i is the probability distribution with probability (wp), a_i such that i ∈ (1, 2,3,4).

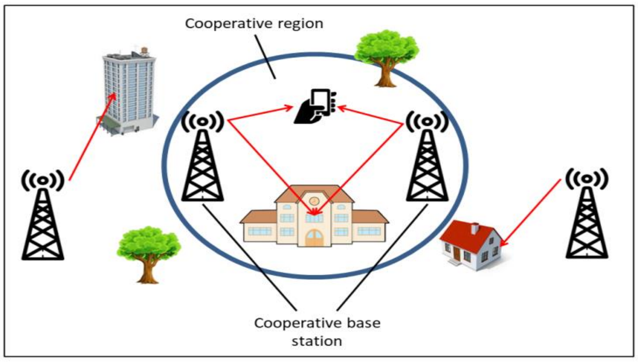

Figure 1: Cooperative BSs is formed around the typical user

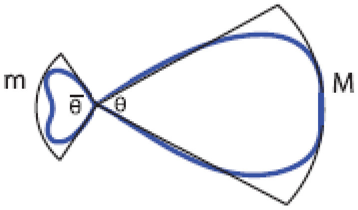

Figure 2: Sectored antenna model. The antenna beam pattern is parameterized by the directivity gains for the main lobe (M) and side lobe (m), and the halfpower beamwidths for the main lobe (θ) and side lobe (θ').[11][12]

3.3 Propagation Modeling

Blockage modeling: The path loss laws for LOS and NLOS propagation are fundamentally different because the MMW signals are prone to high penetration losses. Following the work in [10][12] a MMW link can either be in LOS or NLOS condition. By incorporating the blockage model in [3], the probability of LOS and NLOS links are respectively given by, $p_L(r) = e^{-\beta v}$ and $p_N(r) = 1 - e^{-\beta v}$. It was shown that this model is straightforward yet adaptable enough to explain the effects of the obstruction in MMW bands.

Small-scale fading: Nakagami fading is considered in MMW communications in order to make use of the sparse scattering element of the MMW channel, which is denoted by $h_i \sim \Gamma(N, 1/N)$ with N ∈ (N_L, N_N) is the Nakagami fading parameters [28], [30]. N_L is LOS link and N_N is NLOS links, for the Nakagami fading parameters.

3.4 Cell Association

The typical UE is assumed to be served by MMW SBS that is in LOS condition to guarantee the service quality of the user. We consider the strongest average received power provided by user associates with a set of cooperating base stations which is expressed as

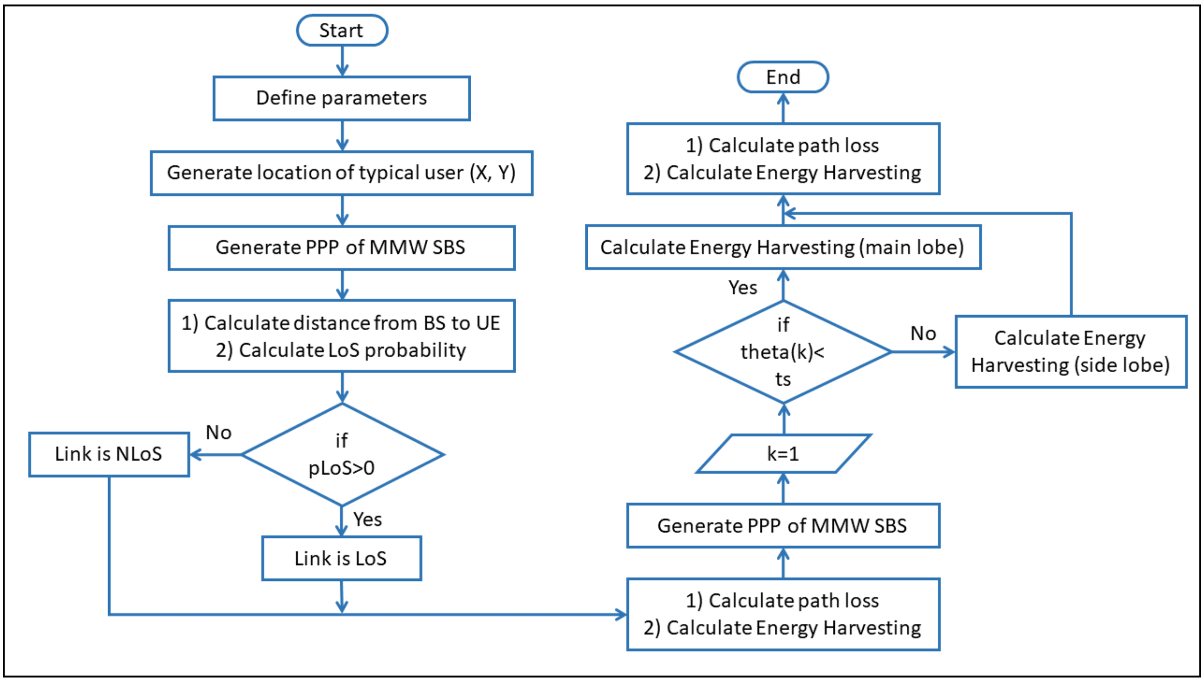

Figure 3: Flowchart of the MATLAB simulation.

$$\tau = arg_{x_i \leftarrow \phi} \max \sum_{i=1}^{n} \frac{P_k}{||x_i||^{-\alpha_s}} \qquad (1)$$

where P_k represents the power transfer. $||x_i||^{-\alpha_s}$ is the path loss of the typical UE from a BS with distance x. α_s is the path loss, where s can be either the LOS or NLOS link.

3.5 Energy Coverage Probability

Energy coverage probability is a metric to access the energy coverage analysis of joint transmission on the EH network. We analyze the energy coverage probability at the typical UE when it is served by one and two base stations. The total received signal at the typical UE from a BS located at X* is given by

$$S_{1,2}(X^*) = \sum_{i=1}^{n} P_k G_t G_r x^{-\alpha_s} h \qquad (2)$$

where G_t and G_r represents the gain of the SBS and UE, respectively, and h is the Nakagami fading.

Generally, the total energy coverage probability at any observation point is the sum of the energy from all the transmitting devices in the surrounding communication areas. This paper analyzes the energy coverage probability at the typical UE when it is served by one and two base stations. Therefore, the total energy coverage probability at the typical UE with the serving BS at X* is given by

$$P_d(X^*) = S(X^*) + I(X) \qquad (3)$$

where S(X*) refers to the energy comes from the serving BS and is given in (2). I(X) refers to the coverage probability from the interfering BSs in one-tier which is given by

$$I(X) = \sum_{i=1}^{|\tau_{c}|} P_t C x^{-\alpha s} D_i h \qquad (4)$$

4.0 RESULT AND DISCUSSION

In this section, the simulation results are presented to observe the performances of the base stations cooperation in EH networks. The network is designed with a single tier that is distributed as a PPP with the relevant intensity. In addition, the values of the parameters listed in Table 1 are used in the simulation. Several parameters were used in some estimation to analyze their effect on the probability of the energy coverage.

Table 1: Parameters used in the simulation

Notations	Values
Intensity of UE, λ_u	200/km^2
Intensity of SBS, λ_s	20/km^2, 50/km^2, 200/km^2
SBS carrier frequency, f_s	28 GHz
Wavelength of MMW frequency, w_{fs}	0.0107
Path loss exponent for nLOS (α_n) and LOS (α_L)	4, 2
Number of antenna, n_a	32

As shown in Figure 3, the EH simulation is developed using the stochastic geometry-based model through the MATLAB application. The flowchart shows the process of simulation in MATLAB. Firstly, all the parameters needed is defined for the simulation, such as intensity of SBS (λ_s), path loss exponent (α_N, α_L), blockage factor and Nakagami fading parameter (N_L, N_N). Then, the PPP of MMW SBS is generated followed by the calculation distance from BS and UE and the LOS probability. If the probability of LOS is greater than 0, the link is LOS. For NLOS link the probability of LOS must be less than 0. Next, we proceed to the calculation of path loss and energy harvesting. In our case we have two conditions: θ k is greater or less than certain threshold. If θ k is more significant than a certain threshold, EH of the main lobe is calculated. However, if θ k is less than the predefined threshold, we will calculate the EH of the side lobe. The final process of the simulation is to calculate the total EH for single and two base stations cooperation.

We plot in Figure 4 the effect of joint transmission on the energy coverage probability. From the plot, we see that the joint transmission using two BSs has a much better energy coverage probability than a single BS transmission; this is because when the number of serving base stations increases, the interference is reduced. As a result, coverage probabilities increased. In addition, two cooperative base stations offer high transmission rate and a strong signal power at the typical user. In addition, we also observed the blockage effect on the ECP for the single base station and two base stations. The blockage parameters were varied, which are β= 0.1 and 0.01. Referring to Figure 5, we find that the blockage intensity leads to the decreasing of the ECP. The reason is that the increasing number of blockages has increases the likelihood of a link being in NLOS condition. Therefore, the energy harvested from NLOS is significantly smaller than those in LOS condition, which subsequently decreases the ECP. It appears that UE will have a greater chance to connect with LOS BS in an area with fewer buildings than in regions surrounded by crowded buildings. Therefore, characterizing the ECP performance by considering the LOS cluster is feasible. It is observed that the two base stations has produced higher ECP than the single base station, even though there is presence a blockage during the transmission of the signal. The two base stations gives better ECP at blockage parameters of 0.01 and 0.1.

5.0 CONCLUSION

This paper presented a simulation method to evaluate the WPT performance based on the stochastic geometry-based model and derived the ECP of the two cooperating base stations on the MMW EH network. The joint transmission using two base stations shows better energy coverage than the single base station. The two base stations also recorded higher ECP than the single base station, even though there is presence a blockage during the transmission of the signal. Therefore, the development of two base station can enhance the transmission of signal to the user.

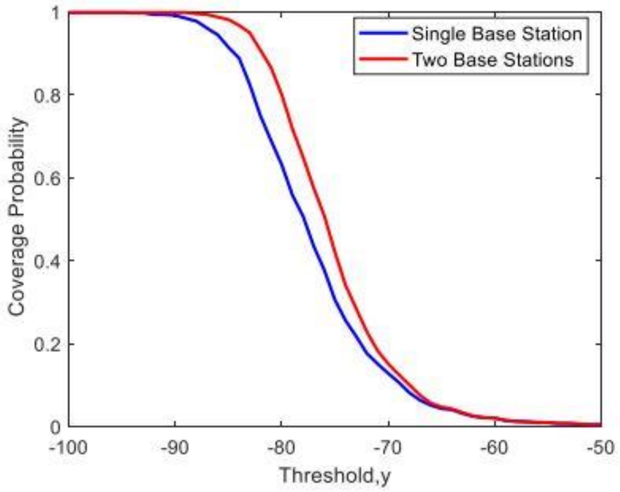

Figure 4: The impact of joint transmission on the energy coverage probability

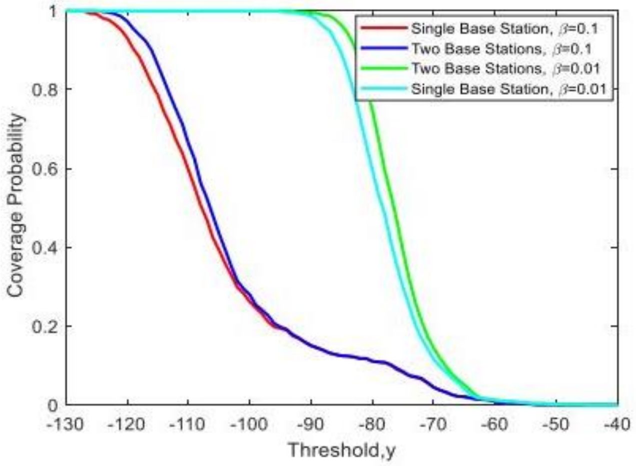

Figure 5: The blockage effect on the energy coverage probability.

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