On the communication range of millimeter-wave small-cells for the energy efficiency of a heterogeneous network

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Abstract: It is not difficult to predict that wireless data traffic will continue to grow and new cellular systems are to be built to provide higher data rates. Thus, for 5G (fifth generation) cellular systems, various approaches are studied including millimeter-wave (mm-wave) communications and HetNets (Heterogeneous Networks) with small cells. In mm-wave bands, since a much wider bandwidth is available, higher data rates can be achieved. However, mm-wave transmissions suffer from blockage. In order to take advantage of a wide bandwidth in mm-wave bands with mitigating the blockage problem, A HetNet consisting of micro-wave Base Stations (BSs) for macro cells and mm-wave BSs for small cells were consider and its energy efficiency in terms of the communication range of mm-wave BSs were studied . It is shown that the optimal communication range of mm-wave BSs can improve the energy efficiency.

Key words: heterogeneous networks, millimeter wave, small cells, micro-wave base stations, 5G

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1 Introduction

There has been a growing interest in 5G cellular systems^[1]. In 5G, it is expected to provide much higher data rates and support various types of communications including machine-to-machine communications^[2]. It is also expected that new approaches would be employed for 5G. For example, massive MIMO (Multiple Input Multiple Output)^[3], CoMP (Coordinated Multipoint), and small cells are considered in Ref.[4]. In Ref.[5], HetNets^[6] are considered for energy efficiency, which is an important issue in

5G^[7]. Besides new technology, exploiting a mm-wave (millimeter-wave) band is also extensively studied as a much wider bandwidth is available^[8,9].

In Refs.[8,9], mm-wave bands, which have been used for short-range communications (e.g., IEEE 802.11ad^[10]), are considered for cellular systems as a plentiful spectrum is available. In order to see whether or not signal transmissions over mm-wave bands can be reliable for outdoor communications, various measurements at 28 GHz are carried out^[8,9,11]. Since the path loss grows quadratically with the carrier frequency according to the Friis transmission

equation^[12], a mm-wave cellular system might be a miniature version of a micro-wave cellular system, which results in a cellular system with small size cells. This implies that the deployment cost of mm-wave cellular systems might be high. In addition, there is additional path loss due to atmospheric attenuation^[13].

Fortunately, the additional path loss due to atmospheric attenuation is negligible at 28 GHz as shown in Fig.1 based on the results in Ref.[13]. For example, if the cell radius is 100 meters, the additional path loss due to atmospheric attenuation is about 1 dB. In addition, the deployment cost can be lower by employing antenna arrays in mm-wave cellular systems, which can increase the communication range by beamforming to effectively enlarge the cell size. As a result, the number of cells or BSs can be lower to cover a service area. In addition, as demonstrated in Ref.[9], it seems that large antenna arrays can be easily built in mm-wave bands.

Figure 1 Additional path loss due to atmospheric attenuation at 28 GHz

It is noteworthy that beamforming in mm-wave bands is different from that in micro-wave bands. For example, beamforming in massive MIMO systems over micro-wave bands is to mitigate ICI by exploiting rich scattering environments. On the other hand,

beamforming in mm-wave bands is to extend the communication range by forming a beam through a LoS (Line-of-Sight) path as the scattering effect is limited and multipaths suffer from high path losses^[8,9,11]. Thus, the performances of mm-wave cellular systems depend on the existence of LoS paths or blockage effect^[14,15]. In particular, it is shown that although the communication range can increase to find a BS with LoS path from a user, the probability that there is no BS with LoS path, i.e., the outage probability, may not approach 0.

As discussed above, micro-wave cellular systems can employ massive MIMO to achieve a high spectral efficiency with limited spectrum. For mm-wave cellular systems, it is essential to exploit a wider bandwidth to meet the requirement of much higher data rates in 5G. To take advantage of both systems, it is possible to combine them, which results in a HetNet that consists of micro-wave BS for macro cells and mm-wave BS for small cells. As long as users can reach an mm-wave BS, they can enjoy a wide spectrum in mm-wave bands. Otherwise, users can be connected to a micro-wave BS. In this HetNet, users need to have dual mode transceivers for mm-wave and micro-wave communications, which increases the cost of user terminals. However, there are already a number of multi-mode transceivers in mobile terminals (for cellular, Wi-Fi, NFC (Near Field Communication), etc.). Thus, we believe that dual mode transceivers for mm-wave and micro-wave communications may not be an obstacle in building 5G cellular systems based on the HetNet with mm-wave small cells. Note that HetNets have been studied to improve the energy efficiency for cellular systems^[16,5]. The HetNet with mm-wave small cells can also be energy efficient by optimizing the communication range of mm-wave BSs for small cells.

In this paper, we study a HetNet consisting of micro-wave BSs for macro cells and mm-wave BSs for small cells as mentioned earlier. For the con-

sidered HetNet, we focus on the communication range of mm-wave BSs and study its impact on the average transmission power. Based on the analysis, we can find approximately optimal communication ranges for given conditions to improve the energy efficiency.

The rest of the paper is organized as follows. Section 2 presents a system model for the HetNet with mm-wave small cells. After reviewing the main drawback of mm-wave based cellular systems due to blockage in Section 3, we study the impact of the communication range of mm-wave BSs on performances in the HetNet with mm-wave small cells in Section 4. With an exemplary system, we present numerical results in Section 5. Finally, we conclude the paper with some remarks in Section 6.

2 System model

In this section, we present a system model for a HetNet consisting of mm-wave small cells and micro-wave macro cells.

Throughout this paper, we consider a HetNet with two types of BSs: SBS (Small cell BS) and MBS (Macro cell BS). We assume that a user can always communicate with an MBS, while a user may not be able to connect to an SBS. We also assume that users have dual-mode transceivers for mm-wave and micro-wave communications to SBS and MBS, respectively. The HetNet with mm-wave small cells is illustrated in Fig.2. For convenience, let f_M and f_S denote the carrier frequencies associated with MBS and SBS, respectively. Clearly, $f_M < f_S$. Note that there is no interference between small and macro cells as they use different frequency bands, which are different from the conventional HetNets^[6] that suffer from inter-tier interference.

As a special case, we can consider a cellular sys-

tem with SBSs only. In this case, since SBSs need to cover the whole area, it may not be proper to call them SBSs. Thus, we refer to them as mm-wave BSs. Consequently, we assume that SBS and mm-wave BS are interchangeable and MBS and micro-wave BS are interchangeable if there is no risk of confusion.

Figure 2 A HetNet consisting of mm-wave BSs for small cells and micro-wave BSs for macro cells

In addition, since an SBS can provide a wider bandwidth in an mm-wave band, we assume that users prefer an SBS to an MBS if both are available to communicate with users. For convenience, let W_M and W_S denote the bandwidths per user associated with MBS and SBS, respectively, and we have $W_M < W_S$ as assumed above. Throughout the paper, we consider the following assumptions.

A1) SBSs and MBSs are uniformly distributed with intensity λ_S and λ_M , respectively, according to homogeneous PPPs (Poisson Point Processes)^[14,17].

A2) The (average) received signal power, denoted by $\mathcal{P}_{rx}$, is given by^[12]

$$\mathcal{P}_{rx} = \frac{C\mathcal{P}_{tx}}{d^\eta}, \quad (1)$$

where C is a constant that depends on the carrier frequency¹ and antenna gains, $\mathcal{P}_{tx}$ is the transmission power, d is the distance between the receiver and

¹ According to the Friis law, $C \propto \frac{1}{f^2}$, where f is the carrier frequency.

transmitter, and η is the path loss exponent.

In A2), for the sake of simplicity, we only consider the large-scale fading due to the path loss. Furthermore, we assume that the transmission power is decided to keep the receive power constant for certain QoSs (Quality of Services). Thus, the transmission power is proportional to the distance, d . For the communication between a user and a BS, from Eq.(1), the transmission power is given by

$$\mathcal{P}_{tx} = \begin{cases} G_M d^{\eta_M}, & \text{with an MBS,} \\ G_S d^{\eta_S}, & \text{with an SBS,} \end{cases} \quad (2)$$

where η_M and η_S are the path loss exponents of the channels associated with MBS and SBS, respectively. In addition, G_M and G_S are the overall path loss factors of the channels associated with MBS and SBS, respectively. Since G_M and G_S are inversely proportional to C in Eq.(1), they grow quadratically with the associated carrier frequencies, i.e., $G_i \propto f_i^2$, $i \in \{M, S\}$. Thus, we can assume that G_M is smaller than G_S , i.e., $G_M < G_S$. From this, we can see that the transmission power for communication with SBS would be higher than that with MBS. However, as an SBS can provide a wider bandwidth than an MBS, users may want to communicate with SBSs as long as the transmission power is not prohibitively high. Consequently, it might be worth to consider a cellular systems with mm-wave BSs only, while the coverage of each small cell is to be extended by increasing the transmission power. In the next section, unfortunately, we show that there is a fundamental limit although the transmission power can be high due to the blockage of mm-wave transmissions.

3 Limitations of mm-wave BSs only

In this section, we consider a mm-wave cellular system. This system is an extreme case of the HetNet in Section 2 where there are only mm-wave BSs. Most

results in this section are based on Ref.[15].

For convenience, denote by Q the number of mm-wave BSs within a circle of radius R , $\mathcal{A}$, centered at a user, which is a random variable. Note that the area of $\mathcal{A}$ is πR^2 . The probability that there are $Q=q$ mm-wave BSs within $\mathcal{A}$ is

$$P_Q(q) = \frac{(\lambda_s \pi R^2)^q}{q!} e^{-\lambda_s \pi R^2}, \quad q = 0, 1, \dots \quad (3)$$

Note that the average number of mm-wave BSs within $\mathcal{A}$ is

$$\omega = E[Q] = \lambda_s \pi R^2,$$

where $E[\cdot]$ stands for the statistical expectation. Let d_i denote the distance between the user and the i th BS. From Ref.[14], the probability of no blockage or LoS path to mm-wave BS i is

$$D_i = \exp(-\beta d_i),$$

where β is the parameter that depends on the density and sizes of buildings or obstacles that block the LoS path from a mm-wave BS to the user, which is independent of the mm-wave BS intensity, λ_s . From Ref.[15], we have the following result.

Lemma 1 Under A1), the outage probability, which is the probability that a user cannot find any mm-wave BS with LoS within a communication range R , is given by

$$P_{out}(R) = \exp\left(-\frac{2\pi\lambda_s}{\beta^2}(1 - (1 + \beta R)e^{-\beta R})\right). \quad (4)$$

Proof 1 For the proof, see Ref.[15]. Since

$$\lim_{R \rightarrow \infty} P_{out}(R) = e^{-\frac{2\pi\lambda_s}{\beta^2}}, \quad (5)$$

it indicates that a user cannot find any mm-wave BS with LoS although the communication range, R , approaches ∞ or the transmission power can be arbitrarily high with a non-zero probability. In other words, it may not be possible to build a cellular system with mm-wave BSs only unless λ_s is sufficiently high.

4 Energy efficiency of HetNet

As shown in Section 3, it may not be desirable to build a cellular systems with mm-wave BSs only. Thus, we could consider both SBSs (i.e., mm-wave BSs) and MBSs in a cellular system. In this case, the communication range of SBS, R , plays a crucial role in improving performances.

4.1 Average transmission power in hetnet

In this section, we focus on the average transmission power per user for a given communication range in the HetNet with mm-wave small cells.

Denote by $\mathcal{P}_M$ and $\mathcal{P}_S$ the average transmission powers for communications with an MBS and an SBS (within in a communication range), respectively. Note that the average transmission power can be different for uplink and downlink transmissions. However, for the sake of simplicity, we assume that they are the same. In our HetNet, if $Q = 0$, the user is to connect to the nearest MBS. If $Q \geq 1$ and there is at least one SBS with LoS, the user is to connect to this SBS. Furthermore, if there are more than one SBSs with LoS, we assume that the user can choose one of them randomly for the tractable analysis (we will consider the case that the nearest SBS is chosen with approximations later). Thus, the transmission power depends on Q , and the average transmission power can be found in the following result.

Lemma 2 Denote by $\mathcal{P}(R)$ the average transmission power. Then, under A1), we have

$$\begin{aligned} \mathcal{P}(R) &= \mathcal{P}_S + (\mathcal{P}_M - \mathcal{P}_S)e^{-\omega\psi} \\ &= \mathcal{P}_M e^{-\omega\psi} + \mathcal{P}_S(1 - e^{-\omega\psi}) , \end{aligned} \quad (6)$$

where ψ is the average probability of no blockage to an SBS within a communication range R , i.e.,

$$\psi = E[P_{\text{LoS},i} | 0 \leq d_i \leq R] . \quad (7)$$

Proof 2 If $Q=0$, the user has to communicate with an MBS. Thus, the transmission power becomes $\mathcal{P}_M$. If $Q=1$ (i.e., one SBS within a communication range),

the user can communicate with the SBS provided that there is no blockage. Otherwise, the user has to communicate with an MBS. In this case, the transmission power becomes $\mathcal{P}_M(1-\psi) + \mathcal{P}_S\psi$. With $Q=q$ SBSs, the user has to communicate with an MBS if all $Q=q$ SBSs are blocked, which has a probability of $(1-\psi)^q$. Thus, the average transmission power is given by

$$\begin{aligned} \mathcal{P}(R) &= \sum_{q=0}^{\infty} \Pr(Q=q)(\mathcal{P}_M(1-\psi)^q + \mathcal{P}_S(1-(1-\psi)^q)) \\ &= \mathcal{P}_S + (\mathcal{P}_M - \mathcal{P}_S) \sum_{q=0}^{\infty} \Pr(Q=q)(1-\psi)^q . \end{aligned} \quad (8)$$

Substituting Eq.(3) into Eq.(8), we have

$$\begin{aligned} \mathcal{P}(R) &= \mathcal{P}_S + (\mathcal{P}_M - \mathcal{P}_S) e^{-\lambda_s \pi R^2} \sum_{q=0}^{\infty} \frac{(\lambda_s \pi R^2 (1-\psi))^q}{q!} \\ &= \mathcal{P}_S + (\mathcal{P}_M - \mathcal{P}_S) e^{-\omega} e^{(1-\psi)\omega} , \end{aligned} \quad (9)$$

which becomes Eq.(6). This completes the proof.

From (6), we can show that

$$\min\{\mathcal{P}_S, \mathcal{P}_M\} \leq \mathcal{P}(R) \leq \max\{\mathcal{P}_S, \mathcal{P}_M\} . \quad (10)$$

Since $\mathcal{P}(R)$ in Eq.(6) depends on a few parameters, we need to derive them. Under A1), the distances between a user and the SBS within a communication range (from this user) have the following pdf (probability density function) and cdf (cumulative distribution function):

$$\begin{aligned} f_R(x) &= \frac{2x}{R^2} , \\ F_R(x) &= \left(\frac{x}{R} \right)^2 , 0 \leq x \leq R \end{aligned} \quad (11)$$

respectively. Then, the average probability of LoS or no blockage is given by

$$\begin{aligned} \psi &= E[P_{\text{LoS},i} | 0 \leq d_i \leq R] \\ &= \int_0^R e^{-\beta x} \frac{2x}{R^2} dx \\ &= \frac{2}{R^2} \int_0^R x e^{-\beta x} dx \\ &= \frac{1}{(\beta R)^2} \gamma(2, \beta R) , \end{aligned} \quad (12)$$

where $\gamma(s, x) = \int_0^x t^{s-1} e^{-t} dt$ is the lower incomplete gam-

ma function. Using the closed-form expression for ψ in Eq.(11), we can find an upper-bound on $\mathcal{P}(R)$ as follows.

Lemma 3 If $\mathcal{P}_M < \mathcal{P}_S$, an upper-bound on $\mathcal{P}(R)$ can be found as

$$\mathcal{P}(R) \leq \mathcal{P}_M \alpha + \mathcal{P}_S (1 - \alpha), \quad (13)$$

where

$$\alpha = \exp\left(-\frac{2\pi\lambda_s}{\beta^2}\right).$$

Proof 3 Since $e^{-\psi\omega} = e^{-\psi\lambda_s\pi R^2} = \exp\left(-\frac{2\pi\lambda_s\gamma(2, \beta R)}{\beta^2}\right)$,

we can see that $e^{-\psi\lambda_s\pi R^2}$ is a decreasing function of R . Furthermore, from

$$\lim_{R \rightarrow \infty} \psi\omega = \frac{2\pi\lambda_s}{\beta^2} \text{ and } \lim_{R \rightarrow 0} \psi\omega = 0, \quad (14)$$

it can be shown that

$$\lim_{R \rightarrow \infty} e^{-\psi\omega} = \alpha \text{ and } \lim_{R \rightarrow 0} e^{-\psi\omega} = 1. \quad (15)$$

Thus, since $\alpha \leq e^{-\psi\lambda_s\pi R^2}$ from the above and $\mathcal{P}_S > \mathcal{P}_M$, from Eq.(6), the following inequality holds:

$$\mathcal{P}(R) \leq \mathcal{P}_S + (\mathcal{P}_M - \mathcal{P}_S)\alpha.$$

This is identical to Eq.(12).

Note that $\psi\omega$ is the average number of SBSs with LoS from a user, i.e.,

$$E[\text{number of SBSs with LoS}] = \psi\omega = v(R). \quad (16)$$

We can see that the average number of SBSs with LoS cannot be arbitrarily large although $R \rightarrow \infty$, as

$$\lim_{R \rightarrow \infty} v(R) = \frac{2\pi\lambda_s}{\beta^2} < \infty \text{ from Eq.(13).}$$

We now derive closed-form expressions for $\mathcal{P}_S$ and $\mathcal{P}_M$. Since an SBS is randomly chosen from a group of SBSs within a communication range, under A1) and A2), the average transmission power with an SBS is given by

$$\begin{aligned} \mathcal{P}_S &= E[G_S x^{\eta_S} | 0 \leq d \leq R] \\ &= \int_0^R G_S x^{\eta_S} f_R(x) dx \\ &= \frac{2G_S}{R^2} \int_0^R x^{\eta_S+1} dx \\ &= \frac{2G_S R^{\eta_S}}{\eta_S + 2}. \end{aligned} \quad (17)$$

It is shown in Ref.[18] that the distance between a point and the nearest point of a homogeneous PPP of intensity λ has the following distribution

$$f(x) = 2\pi\lambda x e^{-\lambda\pi x^2}, x \geq 0.$$

Under A1), since the locations of MBSs are points of a homogeneous PPP of intensity λ_M , we can show that

$$\begin{aligned} \mathcal{P}_M &= E[G_M x^{\eta_M}] \\ &= \int_0^\infty G_M x^{\eta_M} 2\pi\lambda_M x e^{-\lambda_M\pi x^2} dx \\ &= G_M \frac{\Gamma\left(\frac{\eta_M}{2} + 1\right)}{(\lambda_M\pi)^{\frac{\eta_M}{2}}}, \end{aligned} \quad (18)$$

where $\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx$ is the Gamma function. Note that the average transmission power with the nearest MBS, $\mathcal{P}_M$, is independent of R .

In general, $\mathcal{P}(R)$ is neither an increasing nor decreasing function of R . However, asymptotic results on the average transmission power can be found as follows.

Lemma 4 The asymptotic average transmission powers are

$$\lim_{R \rightarrow \infty} \mathcal{P}(R) = \infty \text{ and } \lim_{R \rightarrow 0} \mathcal{P}(R) = \mathcal{P}_M. \quad (19)$$

Proof 4 As $R \rightarrow \infty$, $\mathcal{P}(R)$ approaches the upper-bound in Eq.(12) from Eq.(14). Since $\mathcal{P}_S$ is proportional to R^{η_S} , we can see that $\mathcal{P}(R)$ approaches ∞ as $R \rightarrow \infty$.

As $R \rightarrow 0$, since $e^{-\psi\omega} \rightarrow 1$ from Eq.(14), we can show that $\mathcal{P}(R)$ approaches $\mathcal{P}_M$. This completes the proof.

While the results in Lemma 4 show asymptotic behaviors of the average transmission power, it is desirable to see more properties of the average transmission power to understand the performance of the HetNet with mm-wave small cells. In particular, it is important to find the average transmission power when R is small. Note that if $R=0$, $\mathcal{P}(R) \rightarrow \mathcal{P}_M$, which means that users communicate with MBSs only. Thus,

if there might be any advantage of the HetNet with mm-wave small cells in terms of the transmission power, it is expected to see that $\mathcal{P}(R)$ decreases as R increases from $R=0$. That is, as soon as mm-wave SBSs have a non-zero communication range, the average transmission power is to decrease. This local behavior can be confirmed by the following result.

Lemma 5 Suppose that $\eta_s > 0$. For a sufficiently small R , we have

$$\mathcal{P}(R) = \mathcal{P}_M(1 - \lambda_s \pi R^2) + o(R^2), R \rightarrow 0. \quad (20)$$

Proof 5 For a sufficiently small R , we have

$$\begin{aligned} v(R) &= \lambda_s \pi R^2 \frac{2}{\beta R^2} \gamma(2, \beta R) \\ &= \lambda_s \pi R^2 + o(R^2), \end{aligned} \quad (21)$$

because $\gamma(s, x) = \frac{x^{-s}}{s} + o(x^{-s})$ as $x \rightarrow 0$. Then, from Eq.(6), we have

$$\begin{aligned} \mathcal{P}(R) &= \mathcal{P}_M e^{-v(R)} + \mathcal{P}_S(1 - e^{-v(R)}) \\ &= \mathcal{P}_M(1 - \lambda_s \pi R^2) + o(R^2), \text{ as } R \rightarrow 0, \end{aligned} \quad (22)$$

because $\mathcal{P}_S = O(R^{\eta_s})$ and $\eta_s > 0$.

According to Eq.(19), we can see that $\mathcal{P}(R)$ decreases as R increases from 0. However, as $\mathcal{P}(R)$ approaches ∞ as $R \rightarrow \infty$ from Eq.(18), it is expected that $\mathcal{P}(R)$ has a U-shape. Thus, there might be a communication range, R , that minimizes the average transmission power.

In above, we assume that a user can choose one of SBSs with LoSs in a communication range randomly. While this certainly simplifies the analysis to obtain the average transmission power, it may not realistic as a user is to connect to the nearest SBS with LoS to minimize the transmission power with SBS. Unfortunately, in this case, it is not easy to find the average transmission power for communications with SBS exactly. Thus, we consider an upper-bound.

For an approximation, although the probability of LoS or no blockage depends on the locations of SBSs, we assume that it is identical to all the SBSs within a communication range, R , i.e., $D_i = \psi$. That is, we have the following assumption.

A3) The probability of LoS for all Q SBSs within a communication range, R is identical, i.e., $D_i = \psi$.

Lemma 6 Suppose that a user can choose the nearest SBS with LoS. Then, under A3), the average transmission power is given by

$$\begin{aligned} \bar{\mathcal{P}}_n(R) &= \mathcal{P}_M e^{-v(R)} + 2G_S R^{\eta_s} v(R) \\ &\quad \times \int_0^1 e^{-v(R)t^2} t^{\eta_s+1} dt. \end{aligned} \quad (23)$$

In addition, without A3), $\bar{\mathcal{P}}_n(R)$ becomes an upper-bound on the average transmission, i.e.,

$$\mathcal{P}_n(R) \leq \bar{\mathcal{P}}_n(R), \quad (24)$$

where $\mathcal{P}_n(R)$ denotes the average transmission power if the nearest SBS with LoS within a communication range, R , is chosen. Note that the subscript ‘ n ’ is used to differentiate the average transmission power when the nearest SBS with LoS is selected from that when an SBS with LoS is randomly selected, which is given in Eq.(6).

Proof 6 Suppose that there are q SBSs within a communication range, R . Denote by $\mathcal{P}_k$ the transmission power when there are k SBSs with LoSs. Then, we have

$$\mathcal{P}_k = \begin{cases} \mathcal{P}_M, & \text{if } k = 0, \\ \mathcal{P}_{S,k}, & \text{if } k \in \{1, \dots, q\}, \end{cases} \quad (25)$$

where

$$\mathcal{P}_{S,k} = G_S E \left[\min_{1 \leq i \leq k} d_i^{\eta_s} \mid 0 \leq d_i \leq R \right], k = 1, \dots, q.$$

It can be shown that

$$\begin{aligned} \bar{\mathcal{P}}_n(R) &= E[E[\mathcal{P}_k \mid Q]] \\ &= \sum_{q=0}^{\infty} P_Q(q) E[\mathcal{P}_k \mid Q = q] \\ &= \sum_{q=0}^{\infty} P_Q(q) \sum_{k=0}^q \mathcal{P}_k \binom{q}{k} \psi^k (1 - \psi)^{q-k}. \end{aligned} \quad (26)$$

The last equality is valid under A3). For convenience, let $\mathcal{P}_{S,0} = 0$. Then, we have

$$\begin{aligned} \bar{\mathcal{P}}_n(R) &= \sum_{q=0}^{\infty} P_Q(q) \sum_{k=0}^q \mathcal{P}_{S,k} \binom{q}{k} \psi^k (1 - \psi)^{q-k} \\ &\quad + \mathcal{P}_M \sum_{q=0}^{\infty} P_Q(q) (1 - \psi)^q. \end{aligned} \quad (27)$$

From Eq.(3), the second term in Eq.(26) becomes

$$T2 = \mathcal{P}_M \sum_{q=0}^{\infty} P_Q(q)(1-\psi)^q = \mathcal{P}_M e^{-\nu(R)} . \quad (28)$$

For the first term in Eq.(26), we need to derive a closed-form expression for $\mathcal{P}_{S,k}$ using order statistics. From Eq.(10), it can be shown that^[19]

$$\begin{aligned} \mathcal{P}_{S,k} &= \int_0^R G_S x^{\eta_S} (1 - F_R(x))^{k-1} f_R(x) dx \\ &= 2G_S R^{\eta_S} k \int_0^1 (1-t^2)^{k-1} t^{\eta_S+1} dt . \end{aligned} \quad (29)$$

Then, after some manipulations, the first term in Eq.(26) becomes

$$\begin{aligned} T1 &= \sum_{q=0}^{\infty} P_Q(q) \sum_{k=0}^q \mathcal{P}_{S,k} \binom{q}{k} \psi^k (1-\psi)^{q-k} \\ &= 2G_S R^{\eta_S} \nu(R) \int_0^1 e^{-\nu(R)t^2} t^{\eta_S+1} dt . \end{aligned} \quad (30)$$

From Eq.(29) and Eq.(27), we can obtain Eq.(22).

As discussed in Ref.[15], A3) results in an upper-bound on the average transmission power for communications with SBSs. Thus, the average transmission power in Eq.(22) is an upper-bound on the average transmission power. This completes the proof.

We can also show that the average transmission power in Eq.(22) also has the same asymptotic results as those in Lemma 4. Furthermore, we can also show that

$$\overline{\mathcal{P}}_n(R) = \mathcal{P}_M (1 - \lambda_S \pi R^2) + o(R^2), \text{ as } R \rightarrow 0 . \quad (31)$$

because $\int_0^1 e^{-\nu(R)t^2} t^{\eta_S+1} dt \rightarrow \int_0^1 t^{\eta_S+1} dt$ as $R \rightarrow 0$, which implies that the second term on the right hand side in Eq.(22) is $O(R^{\eta_S+2})$. Thus, $\overline{\mathcal{P}}_n(R)$ would have a U-shape as $\mathcal{P}(R)$.

4.2 Throughput and energy efficiency

The spectral efficiency is based on the achievable rate

for a given signal-to-noise ratio (SNR), $\log_2(1+SNR)$. For convenience, denote by κ_M (κ_S) the spectral efficiency for communications with MBS (resp., SBS). Assuming that the receive signal power is to be identical regardless of the type of BSs, we can see that

$$\kappa_M, \kappa_S \propto \log_2(1+SNR),$$

where SNR is the SNR that is proportional to the receive signal² power. In addition, there might be spatial multiplexing gains if multiple antennas are used. In particular, in micro-wave communications, there might be MIMO gains by exploiting rich scattering environments^[20]. On the other hand, mm-wave communications suffer from various implementation constraints including beamforming^[21]. Thus, in general, it is expected that κ_M is higher than κ_S . With different spectral efficiency for connections to MBS and SBS, we can define the overall throughput as

$$T(R) = \kappa_S W_S (1 - P_{\text{out}}(R)) + \kappa_M W_M P_{\text{out}}(R) . \quad (32)$$

It is noteworthy that although $\kappa_M > \kappa_S$, since $W_S \gg W_M$, the effective data rate through mm-wave BSs can be higher than that through micro-wave BSs. In fact, this is the advantage of mm-wave band over micro-wave band, which has to be satisfied to justify mm-wave BSs. Otherwise, there is no point to exploit the mm-wave band.

Lemma 7 Suppose that

$$\kappa_S W_S > \kappa_M W_M . \quad (33)$$

Then, under A1), the throughput per user, $T(R)$, is a nondecreasing function of R . The limits of $T(R)$ are given by

$$\begin{aligned} \lim_{R \rightarrow \infty} T(R) &= W_S - (W_S - W_M) e^{-\frac{2\pi\lambda_S}{\beta^2}} , \\ \lim_{R \rightarrow 0} T(R) &= W_M . \end{aligned} \quad (34)$$

Proof 7 From Eq.(31), we have

$$T(R) = \kappa_S W_S - (\kappa_S W_S - \kappa_M W_M) P_{\text{out}}(R) , \quad (35)$$

² There is also interference such as ICI. Thus, the SNR is to be replaced with the signal-to-interference-plus-noise ratio (SINR). However, for simplicity, we assume that the ICI has been sufficiently mitigated and absorbed into the noise power term.

from which we can see that $T(R)$ is a nondecreasing function of R if $\kappa_S W_S - \kappa_M W_M > 0$, because $P_{\text{out}}(R)$ is a nonincreasing function. The asymptotic throughput in Eq.(33) when $R \rightarrow \infty$ can be found by substituting Eq.(5) into Eq.(34).

As $R \rightarrow 0$, $P_{\text{out}}(R) \rightarrow 1$ from Eq.(4). Thus, the asymptotic throughput as $R \rightarrow 0$ becomes $\kappa_M W_M$, which completes the proof.

The result in Lemma 7 shows that it is beneficial to have a large R to have a higher throughput. However, as shown in Lemma 4, the average transmission power can be arbitrarily high as R increases. In general, R may not be too small for a reasonable throughput, but not too large to avoid a high transmission power. In order to decide R , we could consider the energy efficiency in conjunction with the throughput^[22-26].

Define the average energy consumption³ for signal transmissions (Joule per bit per Hz) as

$$E(R) = \frac{\mathcal{P}(R)}{T(R)}. \quad (36)$$

If the nearest SBS with LoS is chosen, $\mathcal{P}(R)$ can be replaced with $\overline{\mathcal{P}}_n(R)$. In this case, $E(R)$ becomes an upper-bound. From Lemmas 4 and 7, we can have the asymptotic results for $E(R)$ as follows.

$$\begin{aligned} \lim_{R \rightarrow \infty} E(R) &= \infty, \\ \lim_{R \rightarrow 0} E(R) &= \frac{\mathcal{P}_M}{\kappa_M W_M}. \end{aligned} \quad (37)$$

This shows that a large R is not desirable as the energy per bit can be high. On the other hand, when R is small, the HetNet becomes a cellular system of micro-wave BSs only, which cannot exploit the advantage of mm-wave BSs. Thus, the optimal R to minimize the energy consumption that is given by

$$R^* = \arg \min_{0 \leq R < \infty} E(R) \quad (38)$$

would be not too small and not too large. Unfortunately, although we have a closed-form expression for $E(R)$ from Eq.(31) and Eq.(6) (for a randomly chosen

SBS) or Eq.(22) (for the nearest SBS), it is not easy to derive the optimal solution, R^* , as a closed-form expression. However, as both $\mathcal{P}(R)$ (or $\overline{\mathcal{P}}_n(R)$) and $T(R)$ are well-defined, it is easy to find R^* using numerical approaches.

Based on the following local property of $E(R)$, we can see that $E(R)$ can decrease as R increases from $R=0$. Thus, together with the asymptotic behaviors in Eq.(36), we can see that $E(R)$ might have a U-shape.

Lemma 8 For a sufficiently small R , with $\eta_S > 0$, we have

$$E(R) = \frac{\mathcal{P}_M}{\kappa_M W_M} \left(1 - \frac{\kappa_S W_S - \kappa_M W_M}{\kappa_M W_M} R \right) + o(R). \quad (39)$$

Proof 8 From Eq.(4), we can show that

$$P_{\text{out}}(R) = 1 - \frac{2\pi\lambda_S}{\beta} R + o(R), \text{ as } R \rightarrow 0. \quad (40)$$

From this, the throughput for a small R becomes

$$T(R) = \kappa_M W_M + (\kappa_S W_S - \kappa_M W_M) \frac{2\pi\lambda_S}{\beta} R + o(R). \quad (41)$$

Then, from Eq.(40), Eq.(21), and Eq.(30), we have have Eq.(38). This completes the proof.

From Eq.(38), if $\kappa_S W_S - \kappa_M W_M > 0$, we can see that $E(R)$ decreases as R increases from 0. This confirms that it is beneficial in terms of the energy efficiency if mm-wave BSs are used with a non-zero communication range in the HetNet with mm-wave small cells.

In the next section, we consider an exemplary system to see the energy efficiency of the HetNet and present numerical results with discussions.

5 Numerical results for an exemplary system

In this section, we first consider an exemplary system for the HetNet with mm-wave small cells. Then, numerical results with this system are presented.

³ For the sake of simplicity, we only take into account the energy consumption for signal transmissions. There is additional energy consumption by electronic circuitries.

5.1 An exemplary system

In Ref.[9], the measured path loss exponent in mm-wave communications lies within a range of 1.68–2.3 for LoS paths. Thus, as shown in Tab.1, we assume that $\eta_s=2$. According to Ref.[3], we assume⁴ $\eta_M=3.8$. The system bandwidths for MBSs and SBSs are assumed to be 40 and 500 MHz, respectively. It is also assumed that each BS can support 20 users on average. Thus, we have $W_M = \frac{40}{20}$ MHz and $W_S = \frac{500}{20}$ MHz. The spectral efficiency depends on transmission schemes, the frequency reuse factor, and so on. In Ref.[3], based on massive MIMO precoding, it is shown that the average spectral efficiency can be 1800/20=90 bit/s/Hz (with a frequency reuse factor of 1) or 730/20=36.5 bit/s/Hz (with a frequency reuse factor of 7), while the peak spectral efficiency of LTE-Advanced is 15 bit/s/Hz^[27]. While the performances of massive MIMO would be optimistic, it would be possible to improve the spectral efficiency of LTE-Advanced. Thus, we can assume that the spectral efficiency for MBSs could be 20 bit/s/Hz. On the other hand, in Ref.[9], the spectral efficiency can be 528/520≈1 bit/s/Hz (with 16 QAM (Quadrature Amplitude Modulation) and a LDPC (Low Density Parity Check) channel code of rate 1/2). Since the mm-wave system in Ref.[9] is an early trial, there could be more performance improvements in the near future. In summary, we assume⁵ that $\kappa_M=20$ bit/s/Hz and $\kappa_S=3$ bit/s/Hz. Then, we have

$$\kappa_M W_M = 40 \text{ Mbit/s} < \kappa_S W_S = 75 \text{ Mbit/s} .$$

In Ref.[9], a carrier frequency of 28 GHz is considered for mm-wave communications. For LTE-Advanced, various frequency bands can be considered. For convenience, we assume that the carrier frequency

is 2.8 GHz⁶, which is 10 times lower than the mm-wave band used in Ref.[9]. For convenience, we assume that $G_M=1$. Then, we have

$$G_S = \left(\frac{28}{2.8} \right)^2 = 100$$

with neglecting water absorption^[8].

We assume that the intensity of MBSs is $\lambda_M = \frac{1}{\pi}$ so that the average number of MBSs is 1 over an area of circle of radius 1 (here, we assume that the average radius of macro cells is normalized to be 1), while that of SBSs is variable, i.e., $\lambda_S = \lambda \lambda_M = \frac{\lambda}{\pi}$. Through this normalization, we can see that for a given λ , there are λ times more SBSs than MBSs (on average), and for a given R , the communication range of SBSs is R times longer than that of MBSs. Together with the communication range R , the intensity of SBSs, λ , would be a key design parameter. The obstacle intensity, β , is considered as a variable in order to see its impact on the performance of the HetNet with mm-wave small cells.

Table 1 Some parameters of an exemplary system for the HetNet

type of BS	MBS (micro-wave)	SBS (mm-wave)
carrier freq.	2.8 GHz	28 GHz
BW per user	$\left(\frac{40}{20} \right)$ MHz	$\left(\frac{500}{20} \right)$ MHz
path loss exponent	3.8	2
spectral eff.	20 bit/s/Hz	3 bit/s/Hz
intensity	$\lambda_M = \frac{1}{\pi}$	$\lambda_S = \frac{\lambda}{\pi}$

5.2 Numerical results

Prior to presenting numerical results, we note that there is a closed-form expression for the integration in Eq.(22) when $\eta_s=2$, using

⁴ In this case, we assume that there is no LoS for communications with MBSs. If there is a LoS path, the path loss exponent can be lower.

⁵ Note that these spectral efficiencies can be considered as the maximum or peak values (and the resulting throughputs can be considered as peak throughputs), while the average spectral efficiencies might be proportional to them. Thus, we could see that with a certain scaling factor, the results might be valid for both peak and average throughputs (or energy consumptions).

⁶ Note that there is no frequency band of 2.8 GHz allocated for LTE/LTE-Advanced. A frequency band of 2.8 GHz is allocated in Europe for aeronautical radar services.

$$\int_0^1 t^3 \exp(-at^2) dt = \frac{1 - (1 + \alpha)e^{-\alpha}}{2\alpha^2}.$$

Thus, it becomes easy to find the optimal R that minimizes $E(R)$ when the nearest SBS with LoS is selected.

Fig.3 shows the average transmission power and energy consumption for various values of R when $\lambda=4$ and $\beta=2$. It is shown that if the nearest SBS with LoS is selected, the average transmission power can be lower. It is also shown that the average transmission power decreases as R increases and then increases as expected from the local and asymptotic behaviors of $\mathcal{P}(R)$ and $\bar{\mathcal{P}}_n(R)$. Note that if $R=0$, there are no users communicating with SBSs, and the average transmission power is that for MBSs only. For a small R (but not 0), a user can find an SBS with LoS with a higher probability as R increases. Thus, as R increases, the average transmission power can decrease by connecting a user to an SBS with LoS. However, as R increases further, the average transmission power increases as shown in Fig.3 (a). This is the case that the number of SBSs with LoSs does not increase quickly as R (it is rather saturated as in Eq.(13)), while the (maximum) transmission power increases at a rate of $R^{\eta_s}=R^2$. Consequently, the average transmission power for the connection to SBSs with LoS keeps increasing as R increases (even if the nearest SBSs with LoS is selected). In Fig.3(b), the energy versus throughput efficiency is shown. This shows that there could be a minimum energy point. Certainly, if the nearest SBS with LoS is selected, the energy consumption can be lower. The optimal values of R with randomly selected SBS (the dash-dot curve) is $R^*=0.158$, while that with the nearest SBS is $R^*=0.158$ according to the upper-bound, $\bar{\mathcal{P}}_n(R)$, and $R^*=0.172$ according to simulation results. Note that the optimal communication range does not exceed 1 (which is the average cell radius of MBSs), which justifies that the cells of mm-wave BSs are small cells.

Figure 3 Average transmission power and energy consumption for various values of R when $\lambda=4$ and $\beta=2$: (a) average transmission power versus R ; (b) energy consumption versus R (the circles represents the minimum values of the energy consumption)

Figure 4 Performances of the HetNet for various values of λ when $\beta=2$: (a) optimal value of R using the upper-bound on the average transmission power; (b) energy consumption with optimized R or fixed $R=0.1$

In the future, we may need to find a tighter-bound on $\mathcal{P}_n(R)$ for a better optimized result. However, as shown below, although R is optimized with $\overline{\mathcal{P}}_n(R)$, it is still possible to find a good value of R that can improve the energy efficiency for varying conditions in terms of λ or β .

For the case where the nearest SBS with LoS is chosen, using an upper-bound on the average transmission power, $\overline{\mathcal{P}}_n(R)$, it is possible to find the optimal R as in Eq.(37). In Fig.4 (a), we show the optimal value of R for various values of λ when $\beta=2$. As λ increases, we can see that the communication range, R , can be smaller. Clearly, for a large λ , there are more available SBSs. Thus, it is better to reduce the communication range so that the transmission power can be lower and, as a result, the energy consumption can also be lower. In Fig.4 (b), with optimized R and fixed $R=0.1$, it is observed that the energy efficiency can be improved with more SBSs. It is also shown that the energy efficiency can be improved by using the optimized R .

Fig.5 shows the optimized R and energy consumption for various values of β when $\lambda=10$. According to Fig.5 (a), we can see that there is no benefit by

increasing R when the obstacle intensity, β , increases. In other words, the communication range, R , should decrease with β . Fig.5 (b) shows that the energy consumption increases with β as more obstacles discourage the connection to SBSs.

Figure 5 Performances of the HetNet for various values of β when $\lambda=10$: (a) optimal value of R using the upper-bound on the average transmission power; (b) energy consumption with optimized R or fixed $R=0.1$

6 Concluding remarks

In this paper, we studied a HetNet consists of micro-wave BS for macro cells and mm-wave BS for small cells for 5G cellular systems. Although it is beneficial to connect to mm-wave BS due to a much

wider bandwidth, it was shown that this connection is not always available although the communication range increases. Due to a nonvanishing outage probability of the connection to mm-wave BSs, we studied the HetNet where users can connect to the nearest (micro-wave) MBS if they cannot connect to one of (mm-wave) SBSs.

We derived the average transmission power as well as throughput for the HetNet with mm-wave small cells. Based on the average transmission power and throughput, the energy efficiency was obtained. Furthermore, we showed that the optimal communication range of mm-wave BSs can be found to minimize the energy consumption.

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