Edge aware cross-tier base station cooperation in heterogeneous wireless networks with non-uniformly-distributed nodes

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Abstract: This study investigates the cross-tier base station (BS) cooperation in non-uniform heterogeneous networks where the distribution of pico BSs (PBSs) is modelled as Neyman–Scott cluster process. The authors propose an edge aware cross-tier cooperation scheme to improve the performance of edge hotspot users that have weaker signal-to-interference-plus-noise ratio (SINR). Taking consideration of various user behaviours, non-hotspot users are only served by the nearest macro BS whilst the hotspot users with better SINR are only served by their serving PBSs. The edge hotspot users who suffer from high cross-tier interference operate in the cooperation mode. Stochastic geometry is utilised to derive the SINR and energy efficiency performance of the proposed scheme, which is compared with other classical schemes such as full cooperation (FC) and traditional non-cooperation scheme. Numerical results show that compared with the FC scheme, the proposed scheme can maximise the energy efficiency of the network by an optimal cooperation threshold, when SINR coverage is larger than a threshold. The authors also find that user behaviour have little effect on the tradeoff between SINR Coverage and energy efficiency, unless spatial aggregation coefficient is very small.

1 Introduction

As the rapid development of mobile network, the traffic demands of high quality of services grow exponentially [1]. Due to the shortage of wireless spectrum, all base stations (BSs) use the entire bandwidth in heterogeneous network. The performance in the cell edge region would be limited by inter-cell interference (ICI). An advanced wireless communication techniques are required to mitigate ICI and increase the cell edge performance. Coordinated multipoint (CoMP) transmission is a kind of cooperation scheme to enhance the received signal quality as well as decrease the received interference [2]. Hence, BS cooperation is very important in heterogeneous networks (HetNets). In the further fifth generation (5G) cellular networks, cooperation is one of the future wireless communication technologies to improve wireless capacity [3].

The concept of BS cooperation in wireless network works has been extensively studied in the past few years. In [4], a macro-assisted data-only architecture for 5G networks is proposed. This BS cooperation system can lead to 90% energy efficiency gain over the long-term evolution HetNets. Stochastic geometry is one of the theoretical tools to analyse network performance in previous BS cooperation works and this tool can obtain statistically optimal decision parameters [5–10].

In [5], the authors provided a tractable k-tier model and give the performance of this cellular network. In this model, every tier’s BS locations are distributed as a Poisson point process (PPP). The expression for the probability of coverage and average ergodic rate under both open and closed access are derived. The authors in [6] focused on the cross-tier cooperation in two-tier cellular networks. They proposed a novel location aware cross-tier cooperation scheme and derived the outage probability and average ergodic rate. This scheme can improve network performance while considering the load of macro BSs (MBSs). In [7], two downlink cooperation transmission cases were proposed in multi-tier networks where the backhaul network is ideal. In case one, user connected to the N BSs with the strongest received power and user connected to the N closest BSs in case two. The authors in [8] focused on the performance of macro diversity coordinated multipoint transmission in dense cellular networks. This scheme can significantly improve the network performance. A user-centric adaptive clustering scheme was described and there was no cluster edge where the mobile stations’ performance is poor.

In [9], a tractable BS cooperation model was proposed. In this model, a cluster of cooperative BSs was formed around the typical user. The authors found that the gains of cooperation increase with the path loss exponent and intra-cluster frequency reuse was favourable in moderately loaded cells with generous cooperation activation. In [10] a novel framework which includes the impact of overhead delay for CoMP was developed. The authors used this framework to downlink cooperation zero-forcing beamforming (ZFBF) and found that ZFBF did not increase throughout when the overhead channel delay is larger than 60% of the channel coherence time.

The spatial configuration of BSs in [5–10] is characterised by PPP. However, the practical deployment of BSs is not like that. Some other BS distribution models are considered in [11–13]. In [11], the authors proposed a multi-cell cooperation scheme to improve the coverage performance of macro-cell edge users in non-uniform network. This scheme can enhance the signal-to-interference-plus-noise ratio (SINR) coverage of edge users about 5% than traditional association scheme. In [12], the BS cooperation in Gauss Poisson process was modelled use stochastic geometry. The authors found that whether cooperation among BSs improves the energy efficiency depends on the proportion between the number of cooperative BSs and that of all BSs. In [13], the authors modelled the distribution of pico BSs
The stochastic geometry is used to evaluate the performance of the network. In current wireless network, some users in hotspot regions may need higher traffic demand than in other regions in both temporal and spatial domains. This behaviour is referred to as the large-scale user behaviour. In [14], the authors presented the concept of user social pattern (USP) to characterise the general user behaviour and USP can be used as an effective concept for network performance optimisation. In [15], some service control strategies based on large-scale user behaviour were proposed to improve the network energy efficiency.

Considering the practical distribution of hotspot regions and the assumption that hotspot users are served by PBSs, we model the distribution of PBSs as Neyman–Scott cluster process. A new BS cooperation scheme is proposed to enhance the performance of edge hotspot user. The contributions of the paper can be summarised as follows:

- A novel edge-aware cross-tier cooperation (EACTC) scheme is proposed to improve the performance of edge hotspot user which has weaker SINR. Non-hotspot user is only served by MBS. We define a cooperation threshold to decide the transmission mode of hotspot user.
- We use spatial aggregation coefficient \( h \) to describe the hotspot aggregation characterisation. When \( h \to 0 \), it means the all hotspot regions are overlapped or only one hotspot region in the network. When \( h \to 1 \), it means the all hotspot regions are evenly distributed across the entire network.
- The stochastic geometry is used to evaluate the performance of the proposed scheme in terms of the SINR coverage and energy efficiency as our key metrics. We compared the proposed scheme with other schemes such as full cooperation (FC) scheme and traditional non-cooperation (TNC) scheme. In FC scheme, all hotspot users are served in cooperation mode. A non-hotspot user is only served by the strongest MBS. In TRA scheme, hotspot user is only served by the PBS and non-hotspot user is only served by the strongest MBS.
- The proposed EACTC scheme has an optimal cooperation threshold, which can maximise energy efficiency when SINR coverage gets a certain promotion. Furthermore, we find that the network which has bigger spatial aggregation coefficients has lesser optimal cooperation threshold. User behaviours have little effect on the tradeoff between SINR coverage and energy efficiency unless spatial aggregation coefficient very small.

The layout of this paper is organised as follows. In Section 2, we describe the two-tier non-uniform network model, different modes of operation of the hotspot user, the distance analysis for the users and spatial aggregation coefficient. In Section 3, the SINR coverage and the energy efficiency of network are derived. In Section 4, the performance evaluation results are presented. Finally, Section 5 concludes the paper.

2 System model

2.1 Two-tier non-uniform heterogeneous networks

In this paper, we consider two types of users (i.e. the hotspot users and non-hotspot users), which are served by a two-tier heterogeneous wireless network. We assume that hotspot users are served by PBS and non-hotspot users are covered by MBS. The traffic demands of hotspot users are generally higher than non-hotspot users and the size of hotspot regions is generally smaller than non-hotspot regions [16].

To satisfy the coverage demands of non-hotspot users, we deploy the MBSs constitute a homogeneous PPP \( \Phi_x \) of intensity \( \lambda_x \). The locations of PBSs follow an independent MCP \( \Phi_s \) with the parent point process \( \Phi_h \) with density \( \lambda_h \). The number of PBSs in a typical cluster is a Poisson random value with parameter \( c \) and PBSs in each cluster are uniformly distributed in the circle of radius \( R \) around the parent point. The intensity of all PBSs can be expressed as \( \lambda_x \).

Hotspot users gather around the PBS in the circular area of radius \( r \) and non-hotspot users are uniformly scattered over the whole plane. For statistical analysis, without any loss of generality, we consider a typical hotspot user or non-hotspot user at the origin.

The transmit powers of MBSs and PBSs are \( P_1 \) and \( P_2 \), respectively. The static power of MBSs is \( P_1^0 \) and the static power of PBSs is \( P_2^0 \). The distance between users and BSs is \( x \) and the channel fading is assumed to follow exponential distribution (Rayleigh fading), i.e. \( K \sim \exp (1) \) [5]. We assume that all BSs use the same spectrum and each BS serves only one user during a transmission interval. So, there is no intra-cell interference [11]. The noise is assumed additive with power \( \sigma^2 \).

2.2 Mode of operation: edge-aware-cross-tier cooperation

In this paper, non-hotspot user chooses its serving MBS, which based on the maximum received power and the mode of operation is without cooperation. Hotspot user chooses its mode of operation through or without cooperation which based on the received power from each tier. In this paper, hotspot user can choose one of operation mode: non-CoMP and CoMP. In the non-CoMP mode, the hotspot user is connected to the PBS that results in the hotspot region which this hotspot user locates in. In the CoMP mode of operation, the hotspot user is served by two BSs that cooperate with each other to jointly transmit data to this hotspot user. In this mode, one PBS is selected based on the location and another MBS is selected based on the maximum received power. So, the users are split into three disjoint groups: non-CoMP non-hotspot users, non-CoMP hotspot users and CoMP hotspot users.

To hotspot user, if the received signal power from the serving PBS is sufficiently higher than the received interference power from the nearest MBS, the hotspot user operates in the non-CoMP. On the other hand, if the received interference power from the nearest MBS is compared with the received signal power from the serving micro BS, the hotspot user operates in the CoMP mode. In this case, network takes advantage of the interference MBS and makes it to cooperate transmit data to the hotspot user. This technology increases the received signal power and mitigates the interference power.

For a typical hotspot user located at the origin, we denote \( x_1 \) and \( x_2 \) as the minimum distances between the typical hotspot user and the BSs in macro-tier and pico-tier.

We denote BS as the set of BSs that serve a typical hotspot user, which can be written as follows

\[
\text{BS} = \begin{cases} 
\text{PBS}, & P_{x_1} > \beta \quad \text{non-CoMP} \\
\text{MBS, PBS}, & P_{x_2} \leq \beta \quad \text{CoMP}
\end{cases}
\]

where \( \beta \) is referred to as the cooperation threshold.

As shown in Fig. 1, User 1 is a non-hotspot user and it only associates with MBS since the received power from MBS is large enough to satisfy the hotspot user’s requirement. User 2 is a hotspot user, it’s received power from PBS is prominent stronger than that from the nearest MBS. Therefore, User 2 operates in the non-CoMP mode and only associates with PBS. On the other hand, if a typical hotspot user’s (User 3) received signal power from PBS is \( \beta \) times smaller than that from the nearest MBS, this hotspot user operates in the CoMP mode. The network cooperates MBS and PBS to jointly transmit the hotspot user’s data.

In the proposed EACTC scheme, the operation threshold \( \beta \) is very important. The higher the cooperation threshold, the larger hotspot users operate the CoMP mode, and it can improve network SINR coverage. However, the spectrum resource is limited in the network. The hotspot users which use CoMP mode occupy more...
distance between a non-hotspot user and its serving MBS. Denote a non-hotspot user or hotspot user) and its serving BS(s) in the network. Denote by \( f_i(x) \) the PDF of the distance between a non-hotspot user and its serving BS. Denote by \( f_i(x) \) the PDF of the distance between a non-CoMP hotspot user and its serving PBS. Finally, \( f_i(x_1, x_2) \) is the joint PDF of the distances between the typical hotspot user and its two serving BSs.

**Lemma 1**: The PDF of the distances between a user (non-hotspot user or hotspot user) and its serving BS(s) are

\[
\begin{align*}
 f_1(x) &= \frac{2\pi\lambda_1}{A_1} x \exp(-\pi\lambda_1 z^2), \\
 f_2(x) &= \frac{2x}{r^2 A_2} \exp(-\pi\lambda_1 \left( \frac{BP_1}{P_2} \right)^{(2/a)} z^2), \\
 f_i(x_1, x_2) &= \frac{4\pi\lambda_1}{r^2 A_c} x_1 x_2 \exp(-\pi\lambda_1 z^2),
\end{align*}
\]

where \( x_1 > 0; \left( P_2 / BP_1 \right)^{(1/a)} x_1 < x_2 < r \) and

\[
\begin{align*}
 A_1 &= 1, \\
 A_2 &= \frac{1}{\pi r^2 A_1} \left( \frac{P_2}{BP_1} \right)^{(2/a)} \left[ 1 - \exp\left(-\pi A_1 \left( \frac{BP_1}{P_2} \right)^{(2/a)} z^2 \right) \right], \\
 A_i &= 1 - A_2.
\end{align*}
\]

**Proof**: In our assumption, non-hotspot user only connects to MBS. So, the probability that served by MBS is \( A_i = 1 \). The MBSs constitute a PPP \( \Phi_i \) of intensity \( \lambda_i \). So, the PDF of the distance between a typical non-hotspot user and the nearest MBS is

\[
f_i(x) = \frac{d}{dx} \left( P(X_1 < x) \right) = \frac{2\pi\lambda_1}{A_i} x \exp(-\pi\lambda_1 x^2).
\]

The probability that a hotspot user only served by PBS is (see (5))

The PDF of the distance between hotspot user and its serving pico in non-CoMP mode is given by (see (6))

Then, we can obtain the probability that a hotspot user to operate in CoMP mode: \( A_i = 1 - A_2 \).

The joint PDF of \( (x_1, x_2) \) of a hotspot user who operates in the CoMP mode can be obtained as follows: (see (7))

**2.4 Spatial aggregation coefficient**

We use nearest neighbour indicator to describe the hotspot region’s spatial aggregation performance. In our model, hotspot region is covered by one PBS. In this case, the distribution of PBS can mirror the aggregation behaviour of hotspot region. The spatial aggregation coefficient is defined as follows

\[
h_i = d(\text{NN}) / D(\text{ran}) = \frac{\sum_i \min(d_i)/N}{0.5A/N}, \quad (8)
\]

\( d(\text{NN}) \) is the mean nearest distance of the PBS, \( \min(d_i) \) is the distance from PBS \( i \) to its nearest PBS \( j \). \( D(\text{ran}) \) is the theoretical average distance under the uniform distribution; \( A \) is the area of whole network and \( N \) is the total number of PBSs.

**Lemma 2**: The spatial aggregation coefficient of our model is

\[
h_i = \frac{d(\text{NN})}{D(\text{ran})} = 1 + \frac{(\sum S_i / \pi R^2)}{(\sum S_i / \pi R^2) + 1}, \quad (9)
\]

where \( R \) is the radius of cluster; \( \lambda_i \) is the intensity of cluster; \( S_i \) is the overlap area between a cluster and \( i \)th nearest neighbour cluster.
Proof: In our model, we assume one typical cluster’s parent point at the origin and denote by \( x_i \) be the distance from origin to the \( i \)-th nearest neighbour parent point. Then the density of \( x_i \), denote by \( f_i(x_i) \), is given by

\[
f_i(x_i) = 2 \left( \frac{\pi \lambda}{(s - 1)!} \right)^{s-1} e^{-\lambda x_i^2}. \tag{10}\]

The mean values of these distances are

\[
E_s(s) = \int_0^\infty x_i^2 \left( \frac{\pi \lambda}{(s - 1)!} \right)^{s-1} e^{-\lambda x_i^2} \, dx_i = \frac{1}{2} \left[ \frac{1}{x_s} \sum_{k=2}^{\infty} \frac{2k - 1}{x_s^{2k-2}}, \right] \text{ other } \tag{11}\]

If \( E_s(s) > 2R \), it means that this typical cluster has some overlap area with \( s \)-th nearest cluster. The overlap area is

\[
S_s = 2R^2 \cos^{-1} \left( \frac{E_s(s)}{2R} \right) - s \sqrt{R^2 - E_s(s)^2 \frac{4}{4}}. \tag{12}\]

Therefore, the number of PBS in the range of this typical cluster is:

\[
N_{sum} = c / \pi R^2 \left( \sum S_s + \pi R^2 \right). \tag{13}\]

The approximate mean nearest distance of the PBS in the range of typical cluster is

\[
d(NN) \simeq 1 \left[ \sqrt{ \frac{A}{N_{sum}} } = \frac{1}{2} \sqrt{ \frac{\pi R^2}{c (\sum S_s / \pi R^2 + 1)} } \right]. \tag{14}\]

The theoretical average distance of the PBS in the plane is:

\[
D(ran) = \frac{1}{\sqrt{Ayc}}. \tag{15}\]

From the definition of spatial aggregation coefficient, we find that \( h_t \rightarrow 0 \) when all hotspot regions are overlapped or only one hotspot region in a network and \( h_t \rightarrow 1 \) when all hotspot regions are evenly distributed across the entire network.

### 3 SINR coverage and energy efficiency

In this section, we present our works on the analysing the SINR coverage and energy efficiency of downlink transmission for the proposed EACTC scheme. Based on the assumptions of this paper, the instantaneous SINR of a non-CoMP non-hotspot user is given by

\[
\text{SINR}_1 = \frac{P_1 K_1 x_1^{-\alpha} \sum_{k=1}^{\infty} I_k + \sigma^2}{I_1 + \alpha^2}. \tag{14}\]

where \( I_1 = P_1 \sum_{i \in \Phi_1 \setminus \{i \}} K_i \| x \|^{-\alpha} \) and \( I_2 = P_1 \sum_{i \in \Phi_2 \setminus \{i \}} K_i \| x \|^{-\alpha} \).

The SINR of a non-CoMP hotspot user is

\[
\text{SINR}_2 = \frac{P_2 K_2 x_2^{-\alpha} \sum_{k=1}^{\infty} I_k + \sigma^2}{I_1 + \alpha^2}. \tag{15}\]

where \( I_1 = P_2 \sum_{i \in \Phi_1 \setminus \{i \}} K_i \| x \|^{-\alpha} \) and \( I_2 = P_2 \sum_{i \in \Phi_2 \setminus \{i \}} K_i \| x \|^{-\alpha} \).

The SINR of a CoMP hotspot user can be written as

\[
\text{SINR}_c = \frac{P_1 K_1 x_1^{-\alpha} + P_2 K_2 x_2^{-\alpha}}{I_1 + \sigma^2}. \tag{16}\]

where \( I_1 = P_1 \sum_{i \in \Phi_1 \setminus \{i \}} K_i \| x \|^{-\alpha} \) and \( I_2 = P_2 \sum_{i \in \Phi_2 \setminus \{i \}} K_i \| x \|^{-\alpha} \).

#### 3.1 SINR coverage

Using the SINR given in (14)–(16), we can obtain the SINR coverage of the non-hotspot user and hotspot user. SINR coverage is defined as the probability that the SINR greater than a given threshold \( \tau \). Denote by \( S_1, S_2, \) and \( S_c \), the SINR coverage of non-hotspot user, non-CoMP hotspot user and CoMP hotspot user, respectively. The SINR coverage of non-hotspot user is obtained by

\[
S_1 = \int_{x > 0} P(SINR_1 > \tau) f_1(x) \, dx. \tag{17}\]

The SINR coverage of hotspot user can be written as

\[
S_{hot} = A_2 S_2 + A_3 S_c. \tag{18}\]

where \( A_2 \) and \( A_3 \) are given in Lemma 1. The following theorem gives the SINR coverage of user which operates different cooperation modes.

**Theorem 1:** The SINR coverage of non-hotspot user, non-CoMP hotspot user and CoMP hotspot user are

\[
S_1 = \int_{x > 0} \left( \frac{-\sigma^2}{P_1 x_1^{-\alpha}} \right) \sum_{k=1}^{\infty} L_{I_k} \left( x_1^{\alpha} P_1^{-1} \right) f_1(x) \, dx, \tag{19}\]

\[
S_2 = \int_{x > 0} \left( \frac{-\sigma^2}{P_2 x_2^{-\alpha}} \right) \sum_{k=1}^{\infty} L_{I_k} \left( x_2^{\alpha} P_2^{-1} \right) f_1(x) \, dx, \tag{20}\]

(see (21))

where \( f_1(x), f_2(x) \) and \( f(x_1, x_2) \) are given in Lemma 1.

For the non-hotspot user, the Laplace transform of the interference from MBS is [17]

\[
L_{I_k}(s) = \exp \left( -\pi \lambda \left( \frac{c P_1}{2} \right)^{2/\alpha} \right) \int_0^\infty \frac{1}{1 + (s P_1)^{1/\alpha}} \, dt. \tag{22}\]

According to [18, 19], we have the Laplace transform of the interference from PBS in MCP model

\[
L_{I_k}(s) = \exp \left( -2 \pi \lambda \int_0^{R} \frac{e^{-cT(x, s)}}{1 + (s P_1)^{1/\alpha}} \, dx \right). \tag{23}\]

where

\[
T(x, s) = \int_{x}^{R} \frac{f(x)}{1 + (s P_2)^{1/\alpha} \| x + y \|^{\alpha}} \, dx \text{ and } \tag{24}\]

\[
f(x) = \begin{cases} \frac{1}{\pi R^{2\alpha}} \| x \|^{\alpha}, & \| x \| < R \\ 0, & \text{otherwise} \end{cases} \tag{25}\]

For the non-CoMP hotspot user, the Laplace transform of the
interference from MBS is

\[ L_{L_{12}}(s) = \exp\left(-\pi \lambda_1 (s P_i)^{(2/\alpha)} \int_0^\infty \frac{1}{1 + \rho k^{-1}} \, dt \right). \tag{24} \]

According to [18, 19], the Laplace transform of the interference from PBS in this model is

\[ L_{L_{12}}(s) = \exp\left\{-2 \pi \lambda_1 \int_0^R \left[1 - \exp(-c T(s, x))\right] \, dy \right\} \times \int_0^\infty \frac{d}{2 \pi} \exp(-c T(s, x)) f(y) \, dy. \tag{25} \]

For the CoMP hotspot user, the Laplace transform of the interference from MBS \( L_{L_{12}} = L_{L_{11}} \), and the Laplace transform of the interference from MBS \( L_{L_{12}} = L_{L_{22}} \).

**Proof:** Using the SINR given in (14) and (15), we can calculate the CCDF of non-hotspot user SINR \((\mu = 1)\) or non-CoMP hotspot user SINR \((\mu = 2)\) as follows

\[ P(\text{SINR} > \tau) = \mathbb{E} \left[ \exp\left(-\frac{\tau P K x^{-\alpha}}{\sum_{k=1}^{K_j} I_{k} + \sigma^2} \right) \right] \]

\[ = \mathbb{E} \left[ K_j > \tau \frac{\sum_{k=1}^{K_j} I_{k} + \sigma^2}{P x^{-\alpha}} \right] \]

\[ = \exp\left(-\frac{\tau}{P x^{-\alpha}} \right) \sum_{k=1}^{K_j} \left[ \exp\left(-\frac{\tau}{P x^{-\alpha}} I_{k} \right) \right] \]

\[ \exp\left(-\frac{\tau}{P x^{-\alpha}} \right) \sum_{k=1}^{K_j} \left( \tau P x^{-\alpha} I_{k} \right). \tag{26} \]

where \((\alpha)\) follows the assumption that channel fading \( K_j \) is exponential distribution (Rayleigh fading) and \((\theta)\) is given in Corollary 1.

By substituting (19) and substituting in (21), we can obtain the SINR coverage of non-hotspot user. By combining (24), (25) and (3) and then substituting in (20), we can obtain the SINR coverage of non-CoMP hotspot user. Using the SINR of CoMP hotspot user and by following the same steps in deriving (26), the CCDF of SINR can be written as

\[ P(\text{SINR} > \tau) = \exp\left(-\frac{\tau^2}{P x_1^{-\alpha} + P x_2^{-\alpha}} \right) \times \sum_{k=1}^{K_j} \left( \frac{\tau}{P x_1^{-\alpha} + P x_2^{-\alpha}} \right). \tag{27} \]

In this scheme, any hotspot user not only connects to its serving PBS, but also connects to its nearest MBS, i.e. all hotspot users operate in the CoMP mode. Non-hotspot user also connects to its nearest MBS. The following corollary provides the SINR coverage of non-hotspot user and hotspot user in this scheme.

**Corollary 1:** In FC scheme, the SINR coverage of non-hotspot user and hotspot user are given by

\[ S_1^{FC} = S_1, \tag{28} \]

(see (29))

where \( f_1(x) \) is given in Lemma 1 and \( L_{L_{12}}(s) \) is given in Theorem 1.

**Proof:** Non-hotspot user executes the same operation in FC and EACTC schemes. So, non-hotspot user has the same SINR coverage, i.e. \( S_1^{FC} = S_1 \). In our model, hotspot users gather around the PBS in the circular area of radius \( r \), the PDF of distance between a hotspot user and its serving PBS is \( f_1(x) = (2x/r^2) \).

In this scheme, hotspot user has less interference and more signal power than in EACTC scheme. The SINR coverage is better compared with the proposed scheme. However, spectrum, which BS can use is limited. With the increase of the number of CoMP hotspot user, user has much less spectrum to use. The energy efficiency of network will decline.

### 3.1.2 TNC scheme:

In this scheme, non-hotspot user always connects to its nearest MBS and hotspot user only served by its regular PBS. The following corollary provides the SINR coverage of hotspot user in this scheme.

**Corollary 2:** In traditional non-cooperation scheme, the SINR coverage of non-hotspot user and hotspot user are given by

\[ S_1^{TNC} = S_1, \tag{30} \]

\[ S_2^{TNC} = \int_0^\infty \exp\left(-\frac{\tau^2}{P x_2^{-\alpha}} \right) L_{L_{12}}(s) f_2(x) \, dx, \tag{31} \]

where \( L_{L_{12}}(s) \) is given in Theorem 1 and \( f_2(x) \) is given in Corollary 1.

**Proof:** Non-hotspot user always associates to MBS in TNC scheme. So, \( S_1^{TNC} = S_1 \). Using the results of Theorem 1, the SINR coverage of hotspot user can be obtained as in (20).

In this scheme, hotspot user has more interference and less signal power than EACTC scheme. However, user has more spectrum than proposed scheme. So, this scheme has better energy efficiency, but worse SINR coverage than proposed scheme.

### 3.2 Energy efficiency

We assume that user has a fixed-rate transmission, which called `Goodput` in [8]. Given a SINR threshold, the goodput of non-hotspot user is expressed as

\[ R_1 = S_1 \log(1 + \gamma_1), \tag{32} \]

where \( S_1 \) is the SINR coverage of non-hotspot user.
Using the property used in (18), the average hotspot user rate is given by

\[ R_{\text{hot}} = A_2 R_2 + A_c R_c \]
\[ = A_2 S_2 \log (1 + \tau_2) + A_c S_c \log (1 + \tau_c), \quad (33) \]

where \( R_2 \) and \( R_c \) are the goodput of hotspot user that operates non-CoMP and CoMP modes, respectively.

In our model, we assume that each BS serves only one user and only one resource block (RB) can be used during a transmission interval. When MBS receives a request from non-hotspot user and a CoMP request from hotspot user at the same time, the probability that this RB allocate to hotspot user is \( \phi \). Based on this assumption, the average throughput per unit area is \( \lambda_1 (A_2 R_1 + (1 - \phi) A_c R_1) + \lambda_2 (A_2 R_2 + \phi A_c R_c) \). The total energy consumption per unit area is \( \lambda_1 (P_1 + P_{1l}) + \lambda_2 (P_1 + P_{2l}) \). Therefore, the expression of the energy efficiency in the EACTC scheme is as follows

\[ EE = \frac{\lambda_1 (A_2 R_1 + (1 - \phi) A_c R_1) + \lambda_2 (A_2 R_2 + \phi A_c R_c)}{\lambda_1 (P_1 + P_{1l}) + \lambda_2 (P_1 + P_{2l})}. \quad (34) \]

4 Numerical results and discussion

In this section, we compared the proposed EACTC scheme with FC scheme and traditional non-cooperation (TNC) scheme. The transmit power values of MBS and PBS are assumed to be \( P_1 = 40 \) W and \( P_2 = 0.1 \) W [20]. The static power values of MBSs and PBSs are \( P_{1l} = 130 \) W and \( P_{2l} = 6.8 \) W. The densities of MBSs and cluster are \( \lambda_1 = 0.000001 \) and \( \lambda_2 = 0.000001 \). The radiuses of cluster and hotspot region are \( R = 50 \) m and \( r = 10 \) m. To simplify calculate, we assume \( \sigma^2 = 0 \) and \( \alpha = 4 \) [21].

The user behaviour will be derived into two cases for discussion: Case 1: the number of hotspot regions in a cluster has change, but the amount of hotspot region does not change and Case 2: the radius of cluster has change, but the amount of hotspot region does not change.

4.1 Validation of analysis

In Fig. 2, we validate our analysis by comparing the SINR coverage for the proposed EACTC scheme obtained from both the analysis and Monte Carlo simulation. It can be seen that analytical results match the simulation results well, thus corroborating the accuracy of our theoretical analysis. Therefore, from now on, we use the analytical expressions to evaluate the system performance.

Fig. 3 illustrates the spatial aggregation coefficient for different density of cluster, where the analytical result approximately equals the simulation result. It corroborating the accuracy of (9) and we use it to describe user behaviour.

4.2 SINR coverage and energy efficiency

Fig. 4 shows the effect of varying the cooperation threshold for the EACTC, FC and TNC schemes. It can be seen that the EACTC scheme improves the SINR coverage of the hotspot user compared with the TNC scheme, but deteriorate the SINR coverage of the hotspot user compared to the FC scheme as the cooperation threshold increase. This result is consistent with our analysis. Using EACTC scheme, hotspot user who receives high interference from MBS increases the SINR, by increasing the received signal power and decreasing the interference power. As the increase of cooperation threshold, more hotspot users are served by two BSs and the SINR coverage of the proposed scheme approaches that of the FC scheme. When cooperation threshold is very big, the proposed scheme is same as FC scheme. On the other hand, the SINR coverage of non-hotspot user is not affected in increasing the threshold \( \beta \).
In Fig. 5, it can be seen the energy efficiency of the proposed scheme lies between the TNC and FC schemes. As the increases of cooperation threshold, more hotspot users are served by two BSs. However, BS only serves one user and only one RB can be used during a transmission interval. So, the energy efficiency of the proposed scheme is reduced gradually and the gap between the proposed EACTC and FC schemes increases. When $\beta \to \infty$, the proposed scheme is same as FC scheme.

4.3 Performance improvement compared with the FC scheme

From Figs. 4 and 5, we can see that the proposed scheme can improve the SINR coverage of hotspot user, but deteriorate the energy efficiency than FC scheme. There may be has a tradeoff between SINR coverage and EE in our proposed scheme. We assume that the hotspot user SINR coverage and network energy efficiency have equal status in network performance. Hence, the network performance improvement index can defined as follows:

$$K = \frac{EE_{\text{EACTC}} - EE_{\text{FC}} + S_{\text{EACTC}} - S_{\text{FC}}}{EE_{\text{EACTC}}},$$

(35)

where $EE_{\text{EACTC}}$ and $EE_{\text{FC}}$ are the energy efficiencies of the proposed EACTC and FC schemes, respectively. $S_{\text{EACTC}}$ and $S_{\text{FC}}$ are the SINR coverages of hotspot user of EACTC and FC schemes, respectively. The former part of $K$ is the increment of energy efficiency, which EACTC scheme relative to FC scheme. The latter part of $K$ is the negative increment of SINR coverage, which EACTC scheme relative to FC scheme. Hence, the network performance index can represent the improvement of energy efficiency while the SINR coverage is maintained at a certain level.

Fig. 6 shows the impact of increasing the cooperation threshold on the network performance improvement index. Two user behaviours in different spatial aggregation coefficient are considered. It can be seen that as the cooperation threshold increases, there has an optimal threshold $\beta$ which can maximise network performance improvement index $K$. It means that the proposed EACTC scheme has an optimal cooperation threshold which can maximise energy efficiency when SINR coverage gets a certain promotion compared with FC scheme. Different user behaviours have the same network performance improvement index unless spatial aggregation coefficient very little. When the spatial aggregation large enough, the distances between the service BSs and users are all very small. Different user distributions have not enough effect on the network performance. Hence, cases 1 and 2 have the same value of $K$ when $h_i = 0.28$ and $h_j = 0.71$. On the other hand, the optimal cooperation threshold diminishes and the network performance improvement index is increases, with the increases of spatial aggregation coefficient. This is due to the fact that PBSs have farther average distance in small spatial aggregation coefficient than that in big spatial aggregation coefficient. Therefore, user has less interference and network performance has more improvement.

5 Conclusions

This paper has investigated the cross-tier cooperation in non-uniform HetNets. A novel BS cooperation scheme for hotspot users was proposed depending on the interference from MBSs. A novel indicator of spatial aggregation coefficient was utilised to describe the spatial performance of hotspot regions. Based on the tool of stochastic geometry, the SINR coverage and energy efficiency are analysed theoretically. The proposed scheme was compared with the FC and TNC schemes. Numerical results have shown that the TNC scheme suffers from intolerable SINR coverage, and compared with the FC scheme, our proposed scheme can maximise the network energy efficiency by achieving an optimal cooperation threshold when SINR coverage is larger than a threshold. The user behaviours which we defined in this paper had little effect on the tradeoff between SINR coverage and energy efficiency unless spatial aggregation coefficient very small.

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7 References

1 Hu, R.Q., Qian, Y.: ‘An energy efficient and spectrum efficient wireless heterogeneous network framework for 5G systems’, IEEE Commun. Mag., 2014, 52 (3), pp. 94–101
2 Boccardi, F., Heath, R.W., Lozano, A., et al.: ‘Five disruptive technology directions for 5G’, IEEE Commun. Mag., 2014, 52 (2), pp. 74–80
3 Lee, D., Soo, H., Cheeks, B., et al.: ‘Coordinated multipoint transmission and reception in LTE-advanced: deployment scenarios and operational challenges’, IEEE Commun. Mag., 2012, 50 (2), pp. 148–155
4 Zhang, X., Zhang, J., Wang, W., et al.: ‘Macro-assisted data-only carrier for 5G green cellular systems’, IEEE Commun. Mag., 2015, 53, (5), pp. 223–231
5 Dhillion, H.S., Ganti, R.K., Baccelli, F., et al.: ‘Modeling and analysis of K-tier downlink heterogeneous cellular networks’, IEEE J. Sel. Areas Commun., 2012, 30, (3), pp. 550–560
6 Sakti, A.H., Hossain, E.: ‘Location-aware cross-tier coordinated multipoint transmission in two-tier cellular networks’, IEEE Trans. Wirel. Commun., 2014, 13, (8), pp. 4959–4973
7 Xia, P., Liu, C., Andrews, J.G.: ‘Downlink coordinated multi-point with overhead modeling in heterogeneous cellular networks’, IEEE Trans. Wirel. Commun., 2013, 12, (8), pp. 4025–4037
8 Zhao, P., Zhong, Y., Zhang, W.: ‘Base station cooperation for energy efficiency: a Gauss-Poisson process approach’, Signal and Information Processing Association Annual Summit and Conf. (APSIPA), 2013 Asia-Pacific, 29 October 2013–1 November 2013, pp. 1–7
9 Zhong, Y., Zhang, W.: ‘Multi-channel hybrid access femtocells: a stochastic geometric analysis’, IEEE Trans. Commun., 2013, 61, (7), pp. 3016–3026
10 Huang, Y., Zhang, X., Zhang, J., et al.: ‘Energy-efficient design in heterogeneous cellular networks based on large-scale user behavior constraints’, IEEE Trans. Wirel. Commun., 2014, 13, (9), pp. 4746–4757
11 Ganti, R.K., Haenggi, M.: ‘Interference and outage in clustered wireless Ad Hoc networks’, IEEE Trans. Inf. Theory, 2009, 55, (9), pp. 4067–4086
12 Deng, N., Zhou, W., Haenggi, M.: ‘Outage and capacity of heterogeneous cellular networks with intra-tier dependence’, Sixth Int. Conf. on Wireless Communications and Signal Processing (WCSP), 2014, October 2014, pp. 1–5
13 Andrews, J.G., Haenggi, M.: ‘A tractable approach to coverage and rate in cellular networks’, IEEE Trans. Commun., 2011, 59, (11), pp. 3122–3134