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Enhancing Small Cell Capacity with In-Band Wireless Backhaul

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Abstract

In recent years, the wireless industry has been experiencing an explosion of cellular data traffic. Hyper-dense small cells deployment is one of the promising technologies that have been proposed to meet this challenge. It is expected to dramatically enhance the cellular networks capacity by increasing the small cells density (the number of small cells per square kilometre) . However, the capacity gain provided by hyper-dense small cells deployment may be limited by their connected backhauls, especially during heavy data traffic period. To overcome this limitation, in this paper, we propose an optimal scheme for the small cells to utilise the macrocell links as its in-band wireless backhaul. Our analysis and simulation results show that our proposed scheme can significantly improve the network performance in high traffic load scenarios.

1 Introduction

To address the explosive growth in data demands driven by the emerging smartphones, network operators will have to significantly increase the capacity of their networks. Hyper-dense small cells deployment has been considered as a key technology to offer high throughput and continuous coverage [1]. In hyper-dense small cells deployment, backhaul capacity becomes a limitation of the whole network capacity, as multiple small cell base stations (BSs) are connected to a same backhaul in order to reduce the deployment and operation cost [2]. Thus for each small cell its backhaul capacity is quite limited and its backhaul may overwhelm during a high traffic load period. On the other hand, as most of the user equipments (UEs) are served by the small cells in hyper-dense small cell networks, the radio resource of the macro-cell is not fully exploited and part of it is spare [1].

In [3], the authors proposed three strategies of small cell in-band wireless backhaul in massive MIMO systems to achieve throughput increase. The term in-band, means that the access link (BS-mobile station (MS) link) and backhaul link (BS-BS links or BS-network links) are on the same frequency band, compared with out-band wireless backhaul that is in a dedicated frequency band [4]. In this paper, we propose a scheme to utilise the in-band wireless backhaul to leverage the spare macro-cell radio resource to enhance the backhaul capacity of small cells, and thus improve the overall capacity of the hyper-dense small cells network. Our contributions are as following.

- We consider a multi-cell system model and inter-cell interference is considered in this paper, which is omitted in [3].
- We consider the influence of user density to the network performance and derive an optimal scheme which uses macro-cell link as in-band wireless backhaul for small cells to maximize their capacity.

2 System Model and Problem Formulation

The system model consists of a macro-cell with the BS at its centre and the small cells deployed according to a homogeneous spatial Poisson point process (SPPP) Φ of intensity ν in the Euclidean plane. We then randomly choose one small cell which is within the macro-cell for study. Without loss of generality, we assume the distance of the chosen macro BS and small cell is known as D. The UEs in a small cell are uniformly distributed. The backhaul capabilities for the macrocells are always profound and the small cells are connected to limited backhauls. The whole assess link bandwidth for a small cell is B and is divided into subchannels each with bandwidth b. We assume user requests take place following a Poisson process with rate λ and the service time of the users are assumed to be independent and exponentially distributed with mean μ. Then the system can be modelled as a M/M/N/N queue [5], where N represents the number of available subchannels in the network. If N servers are all busy, then any new arrival requests would be dropped.

We consider a channel model consisting of distance dependent path loss, multipath fading and shadowing. Thus the channel gain g of a link can be expressed as:

$$g = \kappa d^{-\alpha}\|h\|^2, \tag{1}$$

where κ is an environment related constant [6], α is the path loss distance exponent, d is the distance between the transmitter and receiver and h is the Rayleigh fading coefficient (coherence time is T_c).

For a small cell UE i, its SINR Υ_i is

$$\Upsilon_i = \frac{g_i P_s}{\sum_{j\in\mathscr{C}_i} g_{j,i} P_s + N_0}, \tag{2}$$

where P_s is the transmit power of small cell, g_i and $g_{j,i}$ are the channel gain (as defined in (1)) of the link from the small cell BS to the UE i and the inter-cell interfering links to the UE i, respectively, $\mathscr{C}_i$ is the set of inter-cell small BSs and N_0 is the additive white Gaussian noise (AWGN) power.

The SINR Υ_m for the link between macro-cell BS and the small cell BS is

$$\Upsilon_m = \frac{g_m P_m}{\sum_{k\in\mathscr{C}_s} g_{k,s} P_s + N_0}, \tag{3}$$

where P_m is the transmit power of macrocell, g_m is the channel gain of the link from the macro BS to the target small cell, and $g_{k,s}$ are the channel gain (as defined in (1)) of interfering links from other small cells to the target small cell. $\mathscr{C}_s$ is the set of interfering small BSs. In this paper, we consider Shannon capacity. Denote R_i is the capacity of UE i. At time t, the total requests of a small cell is $N(t)$ and thus the total throughput (bits/s) of a small cell is

$$R_T = \sum_{i=0}^{N(t)} R_i = \sum_{i=0}^{N(t)} b\log_2(1+\Upsilon_i) \tag{4}$$

We consider a transmission time period T ($T \gg T_c$). We assume perfect interleaving is fulfilled under certain coherence time and delay restrictions and the receiver has perfect CSI, the fading channel can be transformed into an equivalent stochastic channel model, which is a strongly stationary process [7]. Thus we can use the ergodic capacity to represent the statistical expectation of the Shannon capacity over all fading states. In addition, $N(t)$ is a Poisson process which is also a strongly stationary process [8]. Thus the ergodic total throughput of the small cell can be expressed as:

$$R_C = \mathbb{E}[R_T] = \mathbb{E}[\sum_{j=0}^{N(t)} R_i] = \mathbb{E}[N(t)]\mathbb{E}[R_i]. \tag{5}$$

From [5], we have

$$\mathbb{E}[N(t)] = \rho(1-B(N,\rho)), \tag{6}$$

where $\rho = \lambda/\mu$ and $B(N,\rho)$ is Erlang-B loss formula [5]

$$B(N,\rho) = \frac{\rho^N/N!}{\sum_{k=0}^{N}(\rho^k/k!)} \tag{7}$$

As each small cell is connected to a limited backhaul, its backhaul capacity C_b might not be enough to sustain the total capacity R_C required of its radio access links, i.e., $C_b < R_C$. In this case, we shrink the bandwidth B of the small cell's RAN to $(1-\tau)B$ and use τB for in-band wireless backhaul with macro-BS ($0<\tau \le 1$). Thus, for a specific τ, we have $N = \lfloor (1-\tau)B/b \rfloor$. The average backhaul capacity the macro cell provides can be modelled as its ergodic capacity [3,9]. It's noted that for in-band wireless backhaul, the intra-frequency interference can be avoid, however, the interference from the communication between the target small cell with other macro BSs still exists and will be considered in the letter.

$$C_m = \mathbb{E}[\tau B \log_2(1+\Upsilon_m)] \tag{8}$$

Definition 1. *The total capacity of the small cell is defined as*

$$C_\tau = \min\{R_C, C_b + C_m\} \tag{9}$$

In this paper, we aim to maximise the capacity of the small cell

$$\text{OPT:} \qquad \arg\max_{\tau} C_\tau \tag{10}$$

$$\text{s.t.,} \qquad \tau \le \tau^\dagger \tag{11}$$

where $\tau^\dagger$ is the maximum portion of bandwidth can be utilised for in-band backhaul. We note $\tau^\dagger$ is determined by the traffic in macro cell and/or is controlled by the operator.

3 Solution

In this section, we provide the solution for *OPT*.

Theorem 1. *The ergodic capacity of a small cell UE $\mathbb{E}[R_i]$ is*

$$\mathbb{E}[R_i] = \int_{r>0} 2\pi\lambda r e^{-\pi\lambda r^2} \int_{t>0} e^{-\sigma^2\gamma r^\alpha(e^t-1)/P_s} \cdot \mathscr{L}_{I_r}(\gamma r^\alpha(e^t-1)/P_s)\,\mathrm{d}t\,\mathrm{d}r \tag{12}$$

where $\mathscr{L}_{I_r}$ is the Laplace transform of random variable I_r that is defined in [10].

Proof. See [10]. ■

Theorem 2. *The ergodic capacity C_m is:*

$$C_m = \frac{\tau B}{\ln 2}\int_{t>0} e^{\frac{-N_0\gamma D^{\alpha_m}(e^t-1)}{P_m\kappa}} e^{(-\pi\lambda(\frac{\gamma D^{\alpha_m}(e^t-1)P_s}{P_m\kappa})^{\frac{2}{a_s}}\frac{2\pi csc(\frac{2\pi}{a_s})}{a_s})}\mathrm{d}t \tag{13}$$

Proof.

$$\begin{aligned} C_m =& \tau B(\mathbb{E}(log_2(1+\frac{P_m h\kappa D^{-\alpha_m}}{N_0+I_r})) && (14)\\ =& \frac{\tau B}{\ln 2}(\int_{t>0}\mathbb{E}(exp(-\frac{\gamma D^{\alpha_m}}{P_m\kappa}(N_0+I_r)(e^t-1))\,\mathrm{d}t) && (15)\\ =& \frac{\tau B}{\ln 2}\int_{t>0} e^{\frac{-N_0\gamma D^{\alpha_m}(e^t-1)}{P_m\kappa}}\mathscr{L}(\frac{\gamma D^{\alpha_m}(e^t-1)}{P_m\kappa})\,\mathrm{d}t && (16)\end{aligned}$$

The Laplace transform of interferenced can be expressed as follows:

$$\mathscr{L}_{I_r}(s) = \mathbb{E}_{I_r}[exp(-sI_r)] \tag{17}$$

$$= \mathbb{E}_{\mathscr{C}_s,h_{k,s}}\left[exp(-sP_s\sum_{k\in\mathscr{C}_s} h_{k,s}d_{k,s}^{-\alpha_s})\right] \tag{18}$$

$$= \mathbb{E}_{\mathscr{C}_s,h_{k,s}}\left[\prod_{k\in\mathscr{C}_s} \mathscr{L}_{h_{k,s}}(-sP_s d_{k,s}^{-\alpha_s})\right] \tag{19}$$

$$= \mathbb{E}_{\mathscr{C}_s}\left[\prod_{k\in\mathscr{C}_s} \mathbb{E}_h[exp(-sP_s h d_{k,s}^{-\alpha_s})]\right] \tag{20}$$

$$= \exp\left(-2\pi\lambda\int_0^{+\infty}(1-\mathscr{L}_{h_{k,s}}[(-sP_s v^{-\alpha_s})])v\mathrm{d}v\right) \tag{21}$$

$$= \exp\left(-2\pi\lambda\int_0^{+\infty}(\frac{1}{1+(sP_s)^{-1}v^{\alpha_s}})v\mathrm{d}v\right) \tag{22}$$

$$\tag{23}$$

Employing a change of variables $u = \left(\frac{v}{(sP_s)^{\frac{1}{\alpha_s}}}\right)^2$, the integral can be expressed as:

$$\int_0^{+\infty}(\frac{2}{1+(sP_s)^{-1}v^{\alpha_s}})v\mathrm{d}v = (sP_s)^{2/\alpha_s}\int_0^{+\infty}\frac{1}{1+u^{\alpha_s/2}}\mathrm{d}u \tag{24}$$

The Laplace transform of interference is :

$$\mathscr{L}(\frac{\gamma D^{\alpha_m}(e^t-1)}{P_m K_m})$$
$$= \exp\left(-\pi\lambda(\frac{\gamma D^{\alpha_m}(e^t-1)P_s}{P_m K_m})^{2/a_s}\frac{2\pi csc(\frac{2\pi}{a_s})}{a_s}\right) \tag{25}$$

■

Proposition 1. *The solution τ^* to* OPT *is the solution τ_s of the following equation*

$$R_C = C_b + C_m, \tag{26}$$

if $\tau_s \leq \tau^\dagger$, otherwise $\tau^* = \tau^\dagger$, where R_c is in (12), C_b is the backhaul capacity, and C_m is in (13).

Proof. It is easy to prove that C_m defined in (13) (Theorem 2) strictly increases with τ. In addition, with Theorem 1 and (5), we have R_C strictly decreasing with τ. Thus when $\tau < \tau_s$, $C_m + C_b < R_C$ and $C_\tau = C_m + C_b$, while $\tau > \tau_s$, $C_m + C_b > R_C$ and $C_\tau = R_C$. We then know that C_τ increases with τ for $\tau \in [0, \tau_s]$ and decreases with τ for $\tau \in [\tau_s, 1]$. With these discussions, we conclude that C_τ reaches its maxima at τ_s. Thus we know $\tau^* = \tau_s$ if $\tau_s < \tau^\dagger$, otherwise $\tau^* = \tau^\dagger$. ■

We note that, (26) can be efficiently solved by numerical algorithms, such as Brent's method [11].

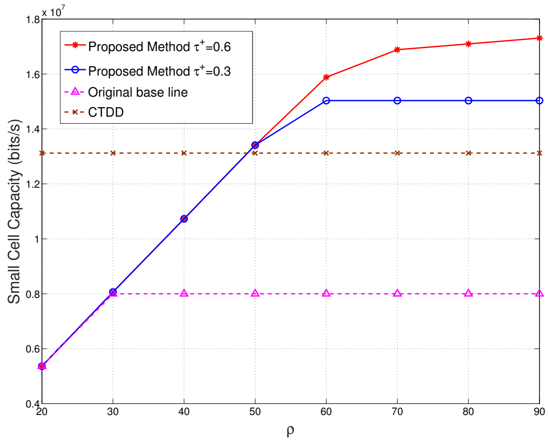

Figure 1. Simulation results

4 Simulation and Results

We uses the simulation scenario in [10]. The transmit power of small cells and macro cells are 23dBm and 46dBm, respectively. The othe major parameters utilised in the simulations can be found in [6, Table A.2.1.1.2-3].

In Figure 1, we demonstrate the capacity of a small cell versus the Erlang-B normalised ingress load $\rho = \lambda/\mu$. We can see that our proposed method can significantly improve the capacity of small cell when the traffic load exceeds the capacity of the small cell backhaul and the improvement is more significantly as the traffic load increases. When the traffic is extremely high (i.e., $\rho = 90$ in Figure 1), the improvement reaches 125% with $\tau^\dagger = 0.6$. We also note that, a more strict restriction on the ratio of the band that can be utilised for in-band backhaul (i.e., $\tau^\dagger$) will not significantly downgrade the small cell capacity. This shows that the in-band wireless backhaul can effectively improve the small cell capacity without consuming a large amount of macro cell resources. The CTDD in [3] did not consider the traffic load in a small cell, thus it remains constant in Figure 1. We can see from Figure 1, compared to our method, when the traffic load in the small cell is light (i.e., $\rho < 50$), CTDD actually wastes the radio resources of macro cell, as the capacity of its in-band wireless backhaul exceeds the actual data demand. Then in a high traffic load scenario (i.e., $\rho > 50$), CTDD provides less capacity then our proposed method, because it dose not consider the backhaul capacity of the small cell.

5 Conclusion

In this paper, a strategy to utilize in-band wireless backhaul to maximize the network throughput is proposed. The simulation results show that our proposed method performs much better than the existing CTDD [3]. In addition, the system throughput increases with backahul limitation $\tau^\dagger$ increase. The future topics may include: 1) optimise the in-band wireless backhaul scheme for multiple small cells;

and 2) Maximise the whole network capacity instead of the capacity of small cell as discussed in this paper.

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References

[1] I. Hwang, B. Song, and S. S. Soliman, “A holistic view on hyper-dense heterogeneous and small cell networks,” *IEEE Communications Magazine*, vol. 51, no. 6, pp. 20–27, Jun. 2013.

[2] D. Lopez-Perez, A. Valcarce, G. de la Roche, and J. Zhang, “Ofdma femtocells: A roadmap on interference avoidance,” *IEEE Communications Magazine*, vol. 47, no. 9, pp. 41–48, September 2009.

[3] B. Li, D. Zhu, and P. Liang, “Small cell in-band wireless backhaul in massive mimo systems: A cooperation of next-generation techniques,” *IEEE Transactions on Wireless Communications*, vol. 14, no. 12, pp. 7057–7069, 2015.

[4] R. Taori and A. Sridharan, “Point-to-multipoint in-band mmwave backhaul for 5g networks,” *Communications Magazine, IEEE*, vol. 53, no. 1, pp. 195–201, 2015.

[5] D. Gross, J. F. Shortle, J. M. Thompson, and C. M. Harris, *Fundamentals of Queueing Theory*, 4th ed. New York, NY, USA: Wiley-Interscience, 2008.

[6] G. TSG-RAN, “Further advancements for e-utra physical layer aspects,” 3GPP Technical Report, 3G TR 36.814 v9.0.0, Mar. 2010.

[7] J. G. Proakis and M. Salehi, *Digital Communications*. McGraw-Hill Higher Education, 2007.

[8] A. Papoulis and S. Pillai, *Probability, Random Variables, and Stochastic Processes*, ser. McGraw-Hill series in electrical engineering: Communications and signal processing. Tata McGraw-Hill, 2002.

[9] X. Kang, Y.-C. Liang, A. Nallanathan, H. K. Garg, and R. Zhang, “Optimal power allocation for fading channels in cognitive radio networks: Ergodic capacity and outage capacity,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 940–950, Feb 2009.

[10] J. G. Andrews, F. Baccelli, and R. K. Ganti, “A tractable approach to coverage and rate in cellular networks,” *IEEE Trans. on Commun.*, vol. 59, no. 11, pp. 3122–3134, November 2011.

[11] R. P. Brent, *Algorithms for minimization without derivatives*, ser. Prentice-Hall series in automatic computation. Englewood Cliffs, N.J. Prentice-Hall, 1973.