HetNets with Range Expansion: Local Delay and Energy Efficiency Optimization

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***Abstract*—In this paper, we explore the different per-user bandwidths available for each tier of heterogeneous networks (HetNets) and the corresponding downlink range expansion (RE, a key measure to boost small cell association). Based on the practical case of tier-specific path loss exponents, we derive the local delay of HetNets under the random discontinuous transmission scheme (DTX, employed to manage the interference and reduce energy consumption). Using such a new expression for local delay, we then analyze the corresponding energy efficiency (EE). These delay and EE expressions reveal that there exists an optimal value both for the RE bias factor and for the DTX mute probability. A closed-form optimum solution for the RE bias factor is also derived for the low rate regime.**

***Index Terms*—Range expansion, energy efficiency, local delay, random discontinuous transmission scheme, and heterogeneous networks.**

I. Introduction

With the explosive growth of wireless data traffic, ultra dense heterogeneous networks (HetNets) have become a powerful solution. However, the heterogeneity of HetNets may not be fully utilized if the maximum received signal strength (RSS) association rule is always employed, as most of the users may be associated with the macro cells due to their higher transmission power. To this end, the range expansion (RE) scheme can be adopted at BSs [1]. As a main strategy to boost small cell association, range expansion (RE) increases the coverage of small cells (i.e. the boundary of small cells in Fig.1) by using a biased handover threshold. As a result, RE can make small cells serve more end users, hence offloading more traffic off macrocells. Many works have recently been conducted on RE, but these existing results (e.g. [2], [3] and the references therein) normally employ optimization methods to improve the network performances without any closed-form expressions. For example, in [2], the maximization problem of a logarithmic utility function was formulated and solved. However, the procedure is based on iteration, whose complexity and efficiency depend upon the number of iterations needed before reaching convergence. In comparison, the corresponding analysis based on closed-form solutions (such as those in this paper) is clearly more efficient and convenient. Furthermore, as an emerging effective tool, stochastic geometry has been employed to investigate the HetNets. For example, the data rate and outage performance of HetNets with RE were analyzed in [3] by using the Poisson point process (PPP).

In HetNets, small cells can offer a relatively larger per-user bandwidth than macrocells, due to the smaller number of users that they serve, which can significantly improve the end-user data rate. Therefore, letting an end-user associate with the small cells as much as possible via RE can make better use of bandwidth resources and improve the performances of HetNets (both for the uplink and for the downlink), such as the local delay and energy efficiency, which will be analyzed in this paper. On the other hand, users offloaded to small cells may well suffer from a higher level of interference from the macro cell base stations. In reality therefore, there exists a tradeoff between the bandwidth resources and the allowed RE of small cells. To our best knowledge, this has not been addressed in the literature (e.g. [2] and [3]). It is another motivation of this paper to examine such a tradeoff.

In wireless HetNets, transmitting data packets successfully within a specified time is closely related to the quality of service. The local delay was therefore defined as the average time taken until the data packet has been transmitted successfully. The analytical framework of local delay was provided in [4] and [5]. In addition, the local delay was extended to a K-tier HetNet with the same per-user bandwidths in [6] and [7]. Obviously, the per-user bandwidths in each tier of HetNets can be very different. More importantly, each tier of HetNets may well have a different path-loss exponent instead of the same path-loss exponent as assumed in [7].

Energy efficiency is another key indicator of system performances in ultra dense HetNets. Many strategies to improve energy efficiency have been proposed. For instance, energy saving can enjoy a huge improvement by jointly optimizing cell activation, RE and multicell multiuser channel assignment according to [8]. Though the cell-specific RE bias is better in

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improving energy efficiency, it is hard to formulate and as such a per-tier bias scheme will be employed in this paper. In [9], energy efficiency was analyzed by introducing an additional bias factor to enlarge the range of all small cells.

Different from the above works, we in this paper employ the discontinuous transmission (DTX) scheme to manage the interference and improve the energy efficiency. DTX has proved to be a powerful strategy in managing network interference and in improving network energy efficiency [6] [10].

Contributions: This paper has derived the expressions for local delay and energy efficiency of K-tier HetNets under RE and DTX by using stochastic geometry (assuming tier-specific path-loss exponents). The relative per-user bandwidths are employed to change the length of time slots in each tier of HetNets. Based on the derived new expressions, the local delay and energy efficiency with respect to the RE bias factor and the mute probability have been analyzed, revealing the existence of an optimum value for both the RE bias factor and the mute probability. In particular, in the low-rate regime, the optimal bias factor was obtained in a closed form.

II. System Model

A. Heterogeneous Networks Model

We consider a downlink HetNet (as depicted in Fig.1), which comprises K independent network tiers of BSs with $\mathcal{K} = \{1, 2, ..., K\}$ and a typical mobile user at origin $o \in \mathbb{R}^2$. The set Φ of the all BSs consists of all the subset Φ_i of the BSs in each tier. In each tier, the BSs are equipped with a single antenna with density λ_i and BS locations follow a homogeneous Poisson point process (PPP). Correspondingly, the transmission power and per-user bandwidth of BSs within Tier i are respectively P_i and w_i. In addition, the range extension bias factor B_i is employed to adjust (i.e. enlarge) the coverage of small cell BSs. As shown in Fig. 1, small cells with positive RE (i.e. $B_i > 0$dB) can serve more users than with the traditional "strongest received signal strength" indicator and therefore can off-load more traffic off macro cells. Assume that the location of a BS in the ith tier is x_i. Moreover, we adopt a distance-dependent path loss model, $l(x_i) = \|x_i\|^{-\alpha_i}$, where $\|x_i\|$ is the distance between the BS at x_i and the typical user and α_i ($\alpha_i > 2$) is the tier-specific path-loss exponent for the ith tier. Furthermore, we adopt the assumption that the power fading coefficients h_x follow the exponential distribution of unit mean and are spatially and temporally independent. Finally, we neglect the noise as interference is the main problem in dense HetNets.

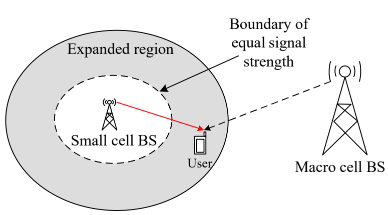

Fig. 1. Range Expansion of small cells in downlink HetNets by using a bias factor.

As in all the existing literature, the average biased received signal strength (RSS) is employed as the association criterion in this paper. The index of the serving BS, assuming in the kth tier, is expressed by

$$k = \arg\max_{i\in\mathcal{K}} P_i B_i \|x_{i,0}\|^{-\alpha_i}, \quad (1)$$

where $x_{i,0}$ is the location of the BS in the ith tier offering the strongest biased RSS. Using the bias factor B_i, the small cell BSs can have a larger coverage range (i.e. serve more users) and reduce the loads of macro cells.

In this paper, time is divided into discrete slots, and the random discontinuous transmission (DTX) scheme is employed in each time slot at the BS, due to DTX being an effective measure to manage the network interference [6]. The ith-tier BSs transmit the data packets with the probability of $1 - \zeta_i$ in each time slot, i.e., it keeps mute with the probability of $\zeta_i \in [0, 1)$. Letting $\Phi_{i,t}$ denote the set of active BSs in the ith tier in Time slot t, the aggregate interference at the typical user is

$$I_t = \sum_{i\in\mathcal{K}} \sum_{BS(x_i)\in\Phi_i\setminus\{BS(x_{k,0})\}} P_i h_x \|x_i\|^{-\alpha_i} \mathbf{1}(BS(x_i) \in \Phi_{i,t}), \quad (2)$$

where $BS(x_i)$ is the BS located at x_i and $\mathbf{1}(\cdot)$ is the indicator function. The received signal-to-interference-ratio (SIR) at the typical mobile user can then be calculated:

$$\mathrm{SIR}_{k,t} = \frac{P_k h_x \|x_{k,0}\|^{-\alpha_k}}{I_t}, \quad (3)$$

where $x_{k,0}$ is the location of the serving BS, as expressed in (1).

B. Performance Metrics

Inspired by [6] and for completeness and comparison, we consider two main performance metrics: local delay and energy efficiency.

1) Local Delay: This paper considers the case where a successful transmission happens when the received SIR at the user is larger than some specific SIR threshold θ, otherwise a retransmission will be conducted. Hence, the conditional probability of a successful transmission event $\mathcal{C}_\Phi$ is given by

$$\mathbb{P}(\mathcal{C}_\Phi) = (1 - \zeta_k)\mathbb{P}(\mathrm{SIR}_{k,t} > \theta \mid r, \Phi), \quad (4)$$

where r is the associated distance, and $1-\zeta_k$ means that the serving BS must be active when the data packet is transmitted. The local delay is defined as the average number of time slots for a successful transmission over the wireless link. The associated local delay can be expressed by

$$D_k = \mathbb{E}_{r,\Phi}[\frac{1}{\mathbb{P}(\mathcal{C}_\Phi)}], \quad (5)$$

where $\mathbb{E}_{r,\Phi}[\cdot]$ is the mean over r and Φ. To examine the effect of per-user bandwidth on the local delay without changing the unit of the local delay, we now consider the normalized bandwidth. According to the law of total probability, the average local delay is given by

$$D = \sum_{k\in\mathcal{K}} \frac{\mathcal{A}_k D_k}{W_k}, \quad (6)$$

where $\mathcal{A}_k$ is the probability of the typical mobile user being associated with the kth-tier BS [13] and W_k is the kth-tier normalized per-user bandwidth, which can be calculated by

$$W_k = \frac{w_k}{w_1}, \quad k \in \mathcal{K}. \tag{7}$$

In cellular step-up, the bandwidth allocated to a user depends on the cell load which further depend on the biasing factor. We assume that W is the total bandwidth of BS and the per-user bandwidth in the kth tier can be calculated as

$$w_k = \frac{W\lambda_k}{\mathcal{A}_k \lambda_u}, \tag{8}$$

where λ_u is the density of users, sampled from homogeneous PPP, so the average numbers of users per BS in each tier can be expressed as $\frac{\mathcal{A}_k\lambda_u}{\lambda_k}$. Specially, we have $W_1 = 1$, implying that 1st-tier (macro cells) bandwidth is regarded as the reference. The normalized bandwidth ensures that the unit of the local delay in (6) is still time slot. Furthermore, when $\{\alpha_k\} = \alpha$, the normalized bandwidth can be expressed by

$$W_k = \frac{w_k}{w_1} = \frac{(P_1 B_1)^{2/\alpha}}{(P_k B_k)^{2/\alpha}}, \tag{9}$$

which indicates that the normalized per-user bandwidth will decrease when the bias factor increases. Here, P_i and B_i are the same as in (1).

2) Energy Efficiency: The energy efficiency η of HetNets is defined as the ratio of average area network throughout to average area power consumption [6]. The linear power consumption model in [11] is employed for each-tier's BSs, which is given by

$$P_{c,i} = \begin{cases} P_{i,a} + \beta_i P_i, & if \quad BS(x_i) \in \Phi_{i,t} \\ P_{i,m}, & if \quad BS(x_i) \notin \Phi_{i,t}, \end{cases} \tag{10}$$

where $P_{i,a}$ and $P_{i,m}$ are respectively the static power of the active BS and the mute BS, and β_i is the slope of power consumption for the ith-tier BSs. Therefore, the energy efficiency [6], with unit nats/J/Hz, is expressed by

$$\eta = \frac{D^{-1}\log(1+\theta)\sum_{i=1}^{K}(1-\zeta_i)\lambda_i}{\sum_{i=1}^{K}\lambda_i[(1-\zeta_i)(P_{i,a}+\beta_i P_i)+\zeta_i P_{i,m}]}. \tag{11}$$

III. Local Delay

This section will explore characteristics of the local delay with respect to key parameters.

A. General Case and Main Results

Based on the above definitions, we have the following results on the local delay.

Theorem 1: The local delay in a K-tier PPP distributed HetNet with RE and random DTX is given by

$$D = \sum_{k=1}^{K}\int_0^\infty \frac{2\pi\lambda_k}{(1-\zeta_k)W_k}\exp\left\{-\pi\sum_{i=1}^{K} r^{\frac{2\alpha_k}{\alpha_i}}\lambda_i(\widetilde{P}_i\widetilde{B}_i)^{\frac{2}{\alpha_i}} \Big(1-(1-\zeta_i)\mathcal{Z}(\zeta_i,\alpha_i,\theta,\widetilde{B}_i)\Big)\right\} r dr, \tag{12}$$

where $\widetilde{P}_i = P_i/P_k$, $\widetilde{B}_i = B_i/B_k$ and $\mathcal{Z}(\zeta_i,\alpha_i,\theta,\widetilde{B}_i) = C(\alpha_i)\theta^{\frac{2}{\alpha_i}}\widetilde{B}_i^{-\frac{2}{\alpha_i}}\zeta_i^{\frac{2}{\alpha_i}-1} - \frac{1}{\zeta_i}{}_2F_1(1,\frac{2}{\alpha_i};1+\frac{2}{\alpha_i};-\frac{\widetilde{B}_i}{\theta\zeta_i})$ with $C(\alpha_i) = 1/\mathrm{sinc}(2/\alpha_i)$ and ${}_2F_1(\cdot)$ denotes the Gauss hypergeometric function. The proof is given in the Appendix.

From Theorem 1, we observe that larger per-user bandwidth will indeed reduce the local delay. RE of small cells can ensure more users to be served with the larger available per-user bandwidth. Therefore, the per-user bandwidth advantage of small cell BSs can be utilized fully by increasing the bias factor. Moreover, a sufficient condition is that the bias factors satisfy $(1-\zeta_i)\mathcal{Z}(\zeta_i,\alpha_i,\theta,\widetilde{B}_i) < 1$, $\forall i,k \in \mathcal{K}$, ensuring that RE leads to a finite local delay.

The local delay expression in (12) can be simplified in some special cases. First, if we assume that BSs in each tier have the same path-loss exponent $\{\alpha_i\} = \alpha$ and mute probability $\{\zeta_i\} = \zeta$ and use the equation $\int_0^\infty 2re^{-cr^2}dr = 1/c$, Theorem 1 can be simplified as

$$D = \frac{1}{(1-\zeta)}\sum_{k=1}^{K}\frac{\lambda_k}{W_k}\frac{1}{g_k}, \tag{13}$$

where $g_k = \sum_{i=1}^{K}\lambda_i(\widetilde{P}_i\widetilde{B}_i)^{\frac{2}{\alpha}}(1-(1-\zeta)\mathcal{Z}(\zeta,\alpha,\theta,\widetilde{B}_i))$.

B. Analysis of Range Expansion

Proposition 1: In the low-rate regime ($\theta \to 0$), the optimal bias factor that maximizes the local delay is given by

$$B_k^* = \frac{1}{P_k}\Big(-\frac{b_0}{b_2}+\sqrt{\frac{b_0^2}{b_2^2}+\frac{b_1}{b_2}}\Big)^{\frac{\alpha}{2}}, \tag{14}$$

where $b_2 = \lambda_k$, $b_1 = \sum_{i=1,i\neq k}^{K}\lambda_i v_i^2$, $b_0 = \sum_{i=1,i\neq k}^{K}\lambda_i v_i$, and $v_i = (P_i B_i)^{2/\alpha}$.

Proof: In the low-rate regime ($\theta \to 0$), we have $g_k = \sum_{i=1}^{K}\lambda_i(\widetilde{P}_i\widetilde{B}_i)^{\frac{2}{\alpha}}$ and the local delay can be approximated as

$$D \sim \frac{\sum_{k=1}^{K}\lambda_k v_k^2}{\sum_{i=1}^{K}\lambda_i v_i}. \tag{15}$$

Through derivative of the local delay in (15) with respect to v_i, we obtain $\frac{\partial D}{\partial v_k} \sim 2\lambda_k v_k\sum_{i=1}^{K}\lambda_i v_i - \lambda_k\sum_{i=1}^{K}\lambda_i v_i^2$. Therefore, the optimal v_k^* can be calculated as

$$v_k^* = -\frac{b_0}{b_2}+\sqrt{\frac{b_0^2}{b_2^2}+\frac{b_1}{b_2}}. \tag{16}$$

Then, the optimal bias factor can be obtained immediately. □

Formula (14) shows that the optimal bias factor B_k^* decreases when the kth-tier density and transmission power of BSs increase. This is because increasing density and transmission power can already expand the coverage of small cells, reducing the need for RE. Specifically, when $\lambda_k \to \infty$, the optimal bias factor tends to zero dB. That is, in the extremely dense scenario of small cells, the typical user will be associated with small cells without having to employ RE. From (11), we can observe that the optimal bias factor in (14) can maximize energy efficiency. In addition, the sufficient condition restricting the bias factor to ensure a finite local delay becomes $\frac{B_k}{B_i} < (2\theta/(\alpha-2))^{-1}$. Therefore, when the data rate increases, the bias factor of small cell BSs should decrease. The reason is that the threshold θ restricts the effectively-serving range of the BS.

IV. Numerical Results

In this section, we carry out numerical analyses of the local delay and energy efficiency to verify and complement the above analysis. A two-tier HetNet structure, consisting of macro cells (Tier 1) and pico (small) cells (Tier 2), is used. We focus on the RE and the random DTX scheme of pico cells according to (11) and (12). In addition, the related parameters are $P_1 = 20W$, $P_2 = 0.13W$, $P_{1,a} = 130W$, $P_{2,a} = 6.8W$, $P_{1,m} = 0.75P_{1,a}$, $P_{2,m} = 0.75P_{2,a}$, $\beta_1 = 4.7$, and $\beta_2 = 4.0$ [11], which are similar to the actual base station parameters and have now been widely adopted for simulations.

In Fig. 2, the local delay and energy efficiency as a function of the mute probability are shown. For $\zeta_1 = 0.5$ and $\zeta_1 = 0.9$, we can observe that the local delay and energy efficiency of biased HetNets (using RE in small cell BSs: $B_2 = 3$dB) under the random DTX scheme show better performances than unbiased HetNets ($B_2 = 0$dB) and homogeneous network, which only consists of macro cells. Nevertheless, the local delay and energy efficiency with the RE of small cells perform poorly when $\zeta_1 = 0.1$ (meaning a higher interference from the macro BSs). The reason is that the larger inter-cell interference the active macro cells generate, the poorer performance the small BS users in the extended range will have to suffer from. Moreover, there exists a trade-off between the minimum local delay and the maximum energy efficiency.

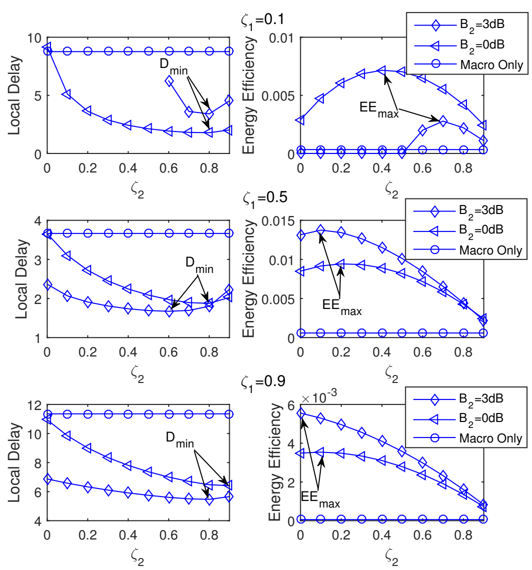

Fig. 2. The local delay and energy efficiency as a function of the mute probability, where $\alpha = 4$, $B_1 = 0$dB, $\theta = 1$, $\lambda_1 = 1/(\pi 500^2)$, $\lambda_2 = 10\lambda_1$.

In Fig. 3, the local delay and energy efficiency as a function of the bias factor are shown. For $\lambda_2 = 5, 10, 15\lambda_1$, the performances of the local delay and the energy efficiency improve first with the increase of the bias factor. The reason is that with the bias factor increasing, the user has a high probability of associating with small cells owning a higher per-user bandwidth. On the other hand, the SIR of the user at the edge of small cells decreases with the bias factor, leading to increase of the local delay and decrease of the energy efficiency. As a result of such a trade-off, an optimal bias factor exists and needs to be determined to minimize the local delay and maximize the energy efficiency. For the low-rate regime, we have obtained the optimal bias factor's expression. In addition, with the increase of picocells' density, the optimal bias factor in terms of the local delay and the energy efficiency will decrease. When the density of picocells tends to infinity (i.e. an extremely dense scenario), the bias factor becomes useless. The physical meaning here is that in extremely dense HetNets users generally are associated with small cells anyway (i.e. unlikely with a macro-cell), eliminating the role of RE.

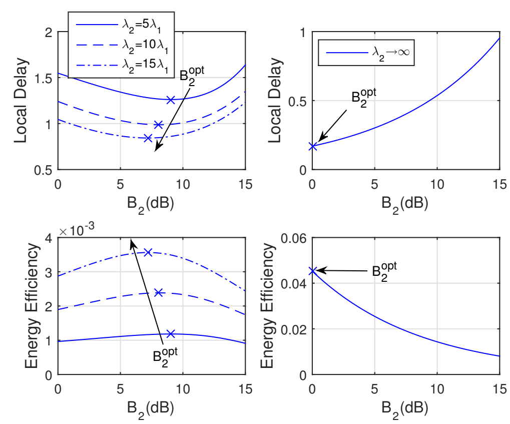

Fig. 3. The local delay and energy efficiency as a function of bias factor, where $\theta = 0.1$, $\alpha = 4$, $B_1 = 0$dB, $\zeta_1 = \zeta_2 = 0.5$, $\lambda_1 = 1/(\pi 500^2)$.

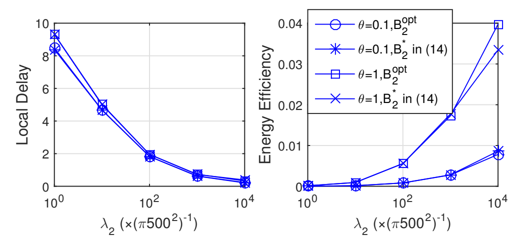

Fig. 4. The optimal local delay and energy efficiency as a function of pico cells' density, where $\alpha = 4$, $B_1 = 0$dB, $\zeta_1 = \zeta_2 = 0.9$, $\lambda_1 = 1/(\pi 500^2)$.

In Fig. 4, we show that the local delay and energy efficiency as a function of pico cells' density. We compare the optimal bias factor B_{opt} from the numerical results with the optimal bias factor B_2^* in (14). The local delay and the energy efficiency match well between the two cases, which verify the accuracy of (14). Furthermore, any increase in pico cells' density can make the local delay decrease and the energy efficiency increase with the optimal bias factor. The reason is that, when the density of small cell increases, the association distances between BSs and users decrease. Users also tend to connect to small cells with larger bandwidth resources, so the local delay decreases. The results under different λ_1 values (macro BS density), although omitted here, have shown similar trends.

V. Conclusion

In this letter, the local delay and energy efficiency of HetNets with RE under the random DTX have been derived by employing different per-user bandwidth in the each tier. The results indicated that the local delay and energy efficiency of HetNets can be optimized with respect to the mute probability and the bias factor. As a result, utilizing the bandwidth advantage of the small cell BSs, the optimal bias factor in the low-rate regime was obtained as a closed form. Future works include the scenarios of user mobility and clustered BS distribution.

Appendix

Proof of Theorem 1

Proof: Using the probability generating functional of the PPP [12], the associated local delay conditioned on the distance r is given by

$$D_k(r) = \frac{1}{1-\zeta_k}\exp\left[\sum_{i=1}^{K}\pi\lambda_i(1-\zeta_i) \left(\frac{P_iB_i}{P_kB_k}\right)^{\frac{2}{\alpha_i}} r^{\frac{2\alpha_k}{\alpha_i}}\mathcal{Z}(\zeta_i,\alpha_i,\theta,\hat{B}_i)\right]. \tag{17}$$

Based on the association rule of the strongest biased RSS, the probability distribution function of the associated distance r between the user and its associated BS is

$$f_k(r) = \frac{2\pi\lambda_k}{\mathcal{A}_k}\exp\left[-\pi\sum_{i=1}^{K}\lambda_i\left(\frac{P_iB_i}{P_kB_k}\right)^{\frac{2}{\alpha_i}} r^{\frac{2\alpha_k}{\alpha_i}}\right]r. \tag{18}$$

According to the integral of $D_k(r)$ with respect to r and the law of total probability in (6), the local delay in (12) can be determined by

$$D = \sum_{i=1}^{K}\frac{\mathcal{A}_k}{W_k}\int_0^\infty D_k(r)f_k(r)dr. \tag{19}$$

□

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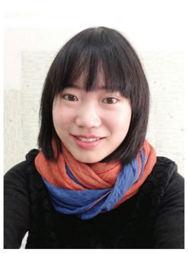

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