On the Bandwidth-Power Tradeoff for Heterogeneous Wireless Networks with Orthogonal Bandwidth Allocation

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***Abstract*—One of the main tasks for future wireless systems is to reduce the environmental impacts of the wireless transmission under different network architectures, which motivates the research on the green radio. Traditional research focuses on study of the tradeoff relation in the homogeneous network architecture and the extension to the heterogeneous network is still open in the literature. In this paper, we shall investigate this open issue and derive the *closed-form* expression for the optimal bandwidth allocation scheme as well as the bandwidth-power tradeoff relation. The analytical result is then extended to the practical settings with the network layout of 19 hexagonal macro-cells. Both the analytical and numerical results show that the proposed bandwidth allocation scheme achieves the best bandwidth-power tradeoff in the heterogeneous network architecture, which is of great importance for the heterogeneous network deployment and the frequency planning. Moreover, we also show that the radius of the network and the power budget play an important role in the bandwidth-power tradeoff relation, which should be carefully considered in the heterogeneous network planning and optimization.**

***Index Terms*—green radio, bandwidth-power tradeoff, heterogeneous network, throughput**

I. INTRODUCTION

The popularity of the smartphones and other intelligent terminals makes the exponential growth of the wireless data traffics as well as the energy consumption of the wireless systems. It has been predicted that the information and communication technology (ICT) will be responsible for 4% of the global CO_2 emission by the year 2020. In order to make the sustainable development of the ICT industry and restrict the environmental impacts of the wireless transmission, Green Radio [1], which targets for the power saving and emission reduction, has been selected as a promising research direction for the wireless system evolution and supported by plenty of international research projects, including Mobile Virtual Centre of Excellence (MVCE) *Green Radio project* [2] and *Energy Aware Radio and neTwork tecHnologies* (EARTH) [3].

In the area of green radio research, a fundamental framework constructed by the four fundamental tradeoffs in the green wireless network has been proposed in [1], where different green technologies, such as resources management and energy efficient transmission technologies, have been linked together. For example, the spectrum efficiency-energy efficiency tradeoff [4] suggests that the energy efficient way to deliver the information bits is not transmitting at the maximum power of the base station(BS) and the delay-power tradeoff [5] prefers to schedule the delay insensitive user to transmit when the associated channel is in good condition.

Within the fundamental framework of green radio research, the bandwidth-power tradeoff becomes a hot research topic recently (see for example [6], [7] and references therein.). This is because of the following reasons. Firstly, the official organizations like International Telecommunication Union (ITU) and Federal Communications Commission (FCC) have approved to re-farm the spectrum of Global System of Mobile communication (GSM) for Universal Mobile Telecommunications System (UMTS) or Long Term Evolution (LTE) usage. Secondly, the UMTS/LTE standard start to investigate the bandwidth adjustment technologies such as carrier aggregation and dual carrier, which has attracted the industrial research attention. Thirdly, the technology evolution on the software defined radio and cognitive radio facilitates the dynamic usage of the spectrum. However, the theoretical research on the bandwidth-power tradeoff is still in the preliminary version and the following issues shall be addressed with the top priority.

- **Heterogeneous Network Topology** Heterogeneous networks serves as a promising solution to solve the non-homogeneous traffic distribution and a cost-effective way to improve the overall system capacity. Due to the heterogeneity of the network topology, there are a great amount of technical issues to be solved in the bandwidth-power tradeoff research. For example, how to define the throughput of the heterogeneous network and how to allocate the resources such as bandwidth between the heterogeneous cells are still open in the literature.
- **Critical Factors for Bandwidth-Power Tradeoff** Another important issue is to investigate the critical factors for the bandwidth-power tradeoff. In the homogeneous topology, the bandwidth-power tradeoff can be simply derived from the Shannon formula [1], while in the heterogeneous network topology, what are the most important factors from the theoretical point of view and how the tradeoff curve varies with those parameters are still left open.

In this paper, we shall propose the way to measure the system throughput under the heterogeneous network architec-

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ture and formulate the optimization problem to achieve the maximum throughput. The *closed-form* expression for the optimal bandwidth allocation scheme as well as the bandwidth-power tradeoff relation is then derived to show that the optimal bandwidth allocation scheme is not a function of the total bandwidth budget. In addition, we extend the above results to the practical settings with the network layout of 19 hexagonal macro-cells. Interestingly, both the analytical and numerical results show that the proposed bandwidth allocation scheme achieves the best bandwidth-power tradeoff in the heterogeneous network architecture, which is of great importance for the heterogeneous network deployment and the frequency planning. We also show through numerical studies that the radius of the network and the power budget play an important role in the bandwidth-power tradeoff relation, which should be carefully considered in the heterogeneous network planning and optimization.

II. System Model

Consider a wireless network architecture with heterogeneous deployment as shown in Fig. 1. In this model, the network contains one macro-cell and one micro-cell with overlapping coverage and all the user terminals (UTs) are uniformly distributed within its coverage. The radius of the macro-cell and the micro-cell are given by R and r, and the total bandwidth and power shared by two cells are denoted by F and P respectively.

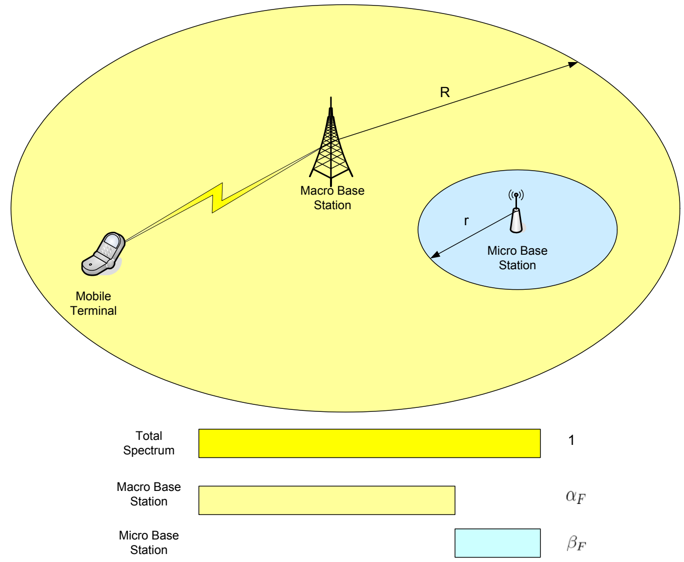

Fig. 1. Illustration example of a wireless network with heterogeneous deployment, containing one macro base station and one micro base station. The radius of the macro-cell is given by R and the radius of the micro-cell is given by r. We allocate α_F of the total bandwidth to the macro-cell and β_F of the total bandwidth to the micro-cell.

A. Channel Model

Followed by the conventional representation of additive white gaussian noise (AWGN) channel, the propagation model between the BS and the UT can be written as

$$y = hx + n \tag{1}$$

where y denotes the received signal at the UT side and n denotes the random noise with normalized variance. x denotes the transmitted signal at the BS side and the corresponding transmit power $p = \mathbb{E}[xx^*]$, where $\mathbb{E}(\cdot)$ denotes the mathematical expectation. h represents the channel condition between the BS and the UT and the variance of the channel condition, σ^2, can be determined through $\sigma^2 = \rho d^{-\theta}$, where d is the distance between the BS and the UT, θ is the path loss exponent and ρ is the corresponding coefficient.

B. Bandwidth Allocation Model

In general, there are two ways to allocate the bandwidth in the heterogeneous network, namely the *orthogonal allocation* scheme and the *non-orthogonal allocation* scheme. For the orthogonal allocation scheme, the bandwidth allocated to the macro-cell and the micro-cell will not overlap with each other and for the non-orthogonal case, part of the bandwidth will be shared by the two cells. Denote $\alpha_F, \beta_F \in [0, 1]$ to be the share of the bandwidth in the macro-cell and the micro-cell, the mathematical representation of the above two bandwidth allocation schemes is hence given as follows.

$$\begin{aligned} \text{Orthogonal Allocation:} \quad & \alpha_F + \beta_F = 1. \\ \text{Non-orthogonal Allocation:} \quad & 1 < \alpha_F + \beta_F \le 2. \end{aligned}$$

In this paper, we focus on the study on the orthogonal bandwidth allocation case[1] as shown in Fig. 1, where the inter-cell interference can be eliminated due to the orthogonal frequency allocation.

III. Heterogeneous Network Throughput

In this section, we provide the definition of the heterogeneous network throughput and derive the optimal power and bandwidth allocation schemes to achieve the maximum throughput.

In the homogeneous network architecture, due to the symmetry of the network topology, the network throughput is simply given by the average throughput of each site times the number of sites in the network. However, the heterogeneous network architecture incurs the asymmetric property of the network topology and the conventional way to calculate the network throughput in the homogeneous network settings will no longer hold true. We first give the definition of the heterogeneous network throughput as follows and derive the optimal bandwidth and power allocation schemes thereafter.

Definition 1 (Heterogeneous Network Throughput): Given the orthogonal bandwidth allocation scheme α_F, β_F, the network throughput of the macro-cell and the micro-cell are defined to be the average data rates that can be reliably transmitted over the entire network. the network throughput of

[1]The results for the non-orthogonal bandwidth allocation case is reported in another paper due to the page limit.

the macro-cell $\mathcal{T}_{ma}$ and the micro-cell $\mathcal{T}_{mi}$ can be expressed as

$$\mathcal{T}_{ma}(\alpha_F) = \frac{\alpha_F F}{\pi R^2}\int_0^R \log(1+\frac{P_{ma}\rho d^{-\theta}}{\alpha_F F})2\pi d\mathrm{d}d \quad (2)$$

$$\mathcal{T}_{mi}(\beta_F) = \frac{\beta_F F}{\pi r^2}\int_0^r \log(1+\frac{P_{mi}\rho d^{-\theta}}{\beta_F F})2\pi d\mathrm{d}d \quad (3)$$

where P_{ma} and P_{mi} are defined to be the power budget of the macro-cell and the micro-cell respectively. The *heterogeneous network throughput* $\mathcal{T}(\alpha_F, \beta_F)$ is defined to be the total throughput of all the cells in the heterogeneous network, i.e.,

$$\mathcal{T}(\alpha_F, \beta_F) = \mathcal{T}_{ma}(\alpha_F) + \mathcal{T}_{mi}(\beta_F). \quad (4)$$

Based on Definition 1, we can achieve the optimal heterogeneous network throughput $\mathcal{T}^*$ by searching over all the possible power and bandwidth allocation schemes, i.e.,

$$\mathcal{T}^* = \max_{\alpha_F,\beta_F} \mathcal{T}(\alpha_F, \beta_F), \quad (5)$$
$$\text{subject to} \quad \alpha_F + \beta_F = 1, \quad \alpha_F, \beta_F \in [0,1].$$

In order to solve the optimization problem (5) , we first derive the network throughput of the macro-cell and the micro-cell as defined in (2) and (3), and summarize the main results in the following lemma.

Lemma 1 (Lower Bound on the Network Throughput): The lower bound of the network throughput of the macro-cell and the micro-cell are given by the following closed-form expression.

$$\mathcal{T}_{ma}(\alpha_F) = \alpha_F F\Big(\log\big(1+\frac{P_{ma}\rho R^{-\theta}}{\alpha_F F}\big)+\frac{\theta}{2} - \frac{\alpha_F F}{\alpha_F F + P_{ma}\rho R^{-\theta}}\Big). \quad (6)$$

$$\mathcal{T}_{mi}(\beta_F) = \beta_F F\Big(\log\big(1+\frac{P_{mi}\rho r^{-\theta}}{\beta_F F}\big)+\frac{\theta}{2} - \frac{\beta_F F}{\beta_F F + P_{mi}\rho r^{-\theta}}\Big). \quad (7)$$

Proof: In this proof, we focus on the study of the macro-cell, and we can follow the similar approach to prove the results for the micro-cell case. The network throughput of the macro-cell $\mathcal{T}_{ma}$, as defined in (2), can be derived based on the following steps.

$$\begin{aligned}\mathcal{T}_{ma}(\alpha_F) &= \frac{\alpha_F F}{\pi R^2}\int_0^R \log(1+\frac{P_{ma}\rho d^{-\theta}}{\alpha_F F})\mathrm{d}(\pi d^2) \\ &= \alpha_F F\log(1+\frac{P_{ma}\rho R^{-\theta}}{\alpha_F F})+ \\ &\quad \frac{\alpha_F F\theta}{R^2}\int_0^R \frac{P_{ma}\rho d^{-\theta+1}}{\alpha_F F+P_{ma}\rho d^{-\theta}}\mathrm{d}d \end{aligned} \quad (8)$$

where we have applied the integration by parts in the second equality and used the fact that $\lim_{d\to 0}\log(1+\frac{P_{ma}\rho d^{-\theta}}{\alpha_F F})d^2 = 0$ in the third equality.

We now process the integration term in the equation (8) as follows. $\int_0^R \frac{P_{ma}\rho d^{-\theta+1}}{\alpha_F F+P_{ma}\rho d^{-\theta}}\mathrm{d}d = \int_0^R d\mathrm{d}d - \int_0^R \frac{\alpha_F F d}{\alpha_F F+P_{ma}\rho d^{-\theta}}\mathrm{d}d = \frac{R^2}{2} - \int_0^{R^2} \frac{\alpha_F F}{\alpha_F F+P_{ma}\rho d'^{-\frac{\theta}{2}}}\mathrm{d}d' \geq \frac{R^2}{2} - \frac{\alpha_F F R^2}{\alpha_F F+P_{ma}\rho R^{-\theta}}$, where we use the fact that $\frac{\alpha_F F}{\alpha_F F+P_{ma}\rho d'^{-\frac{\theta}{2}}} \geq \frac{\alpha_F F}{\alpha_F F+P_{ma}\rho R^{-\theta}}$ for all $d \in [0,R]$. Substitute the above result into equation (8), we have Lemma 1. ■

Based on Lemma 1, we can explicitly show the expression of $\mathcal{T}^*$ as follows and the optimal bandwidth allocation strategy is summarized in Theorem 1.

$$\begin{aligned}\max_{\alpha_F,\beta_F} \quad & \alpha_F F\Big(\log\big(1+\frac{P_{ma}\rho R^{-\theta}}{\alpha_F F}\big)+\frac{\theta}{2} - \\ & \frac{\alpha_F F}{\alpha_F F+P_{ma}\rho R^{-\theta}}\Big) + \beta_F F\Big(\log\big(1+\frac{P_{mi}\rho r^{-\theta}}{\beta_F F}\big) \\ & +\frac{\theta}{2} - \frac{\beta_F F}{\beta_F F+P_{mi}\rho r^{-\theta}}\Big) \\ \text{subject to} \quad & \alpha_F+\beta_F = 1, \quad \alpha_F, \beta_F \in [0,1]. \end{aligned} \quad (9)$$

Theorem 1 (Optimal Bandwidth Allocation): The optimal bandwidth allocation scheme (α_F^*, β_F^*) to achieve the maximum heterogeneous network throughput is given by the following closed-form expressions.

$$\alpha_F^* = \frac{P_{ma}R^{-\theta}}{P_{ma}R^{-\theta}+P_{mi}r^{-\theta}}, \quad (10)$$

$$\beta_F^* = \frac{P_{mi}r^{-\theta}}{P_{ma}R^{-\theta}+P_{mi}r^{-\theta}}. \quad (11)$$

Meanwhile, the optimal bandwidth allocation scheme is unique.

From Theorem 1, we find several interesting results as listed below. (1) The optimal bandwidth allocation scheme is NOT a function of the total bandwidth, F. In other words, once we fix the power budgets for the macro-cell and the micro-cell, we can uniquely identify the optimal bandwidth allocation scheme regardless of the total amount of bandwidth. (2) If we increase the power budget of the macro-cell or the micro-cell (P_{ma} or P_{mi}), the bandwidth allocation (α_F or β_F) shall be be increased as well. (3) If the radius of the macro-cell and the micro-cell are the same, i.e., $R = r$, the optimal way to allocate the bandwidth is proportion to the power budget of the two cells. Fig. 2 shows the heterogeneous network throughput comparison under different bandwidth allocation schemes. The optimal bandwidth allocation α_F^* remains unchanged when we adjust the total bandwidth F from 4.7 MHz to 5.3 MHz. However, if we reduce the power budget of the micro-cell from 5w to 1w, the optimal bandwidth allocation α_F^* increases significantly as predicted in the above result (2).

IV. Bandwidth-Power Tradeoff Relations

In this section, we focus on characterizing the power-bandwidth tradeoff relations under the same heterogeneous network throughput requirement, followed by the discussions of the tradeoff curves with respect to the system parameters, such as the network size and the bandwidth allocation schemes.

Based on Theorem 1, we can find the maximum heterogeneous network throughput under the optimal bandwidth

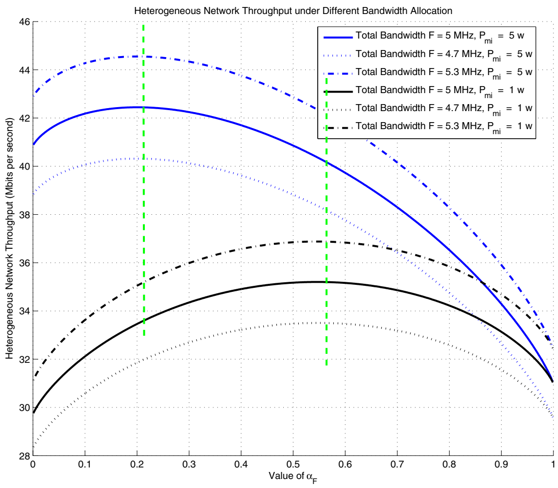

Fig. 2. The numerical results of the heterogenous network throughput versus different bandwidth allocation schemes. The power budget for the macro-cell is fixed to $P_{ma} = 20$ w, the pathloss exponent θ is equal to 3 and the corresponding normalized pathloss coefficient $\rho = -20$ dB. The radiuses of the macro-cell and the micro-cell are $R = 0.25$ km and $r = 0.1$ km, respectively.

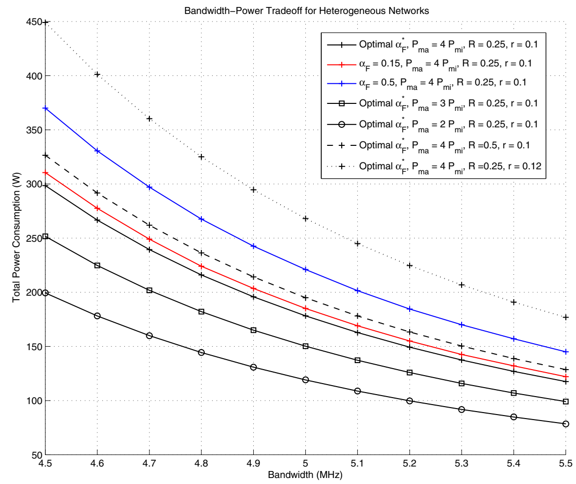

Fig. 3. The bandwidth-power tradeoff for the heterogeneous network architecture with one macro-cell and one micro-cell. The pathloss exponent θ is equal to 3 and the corresponding normalized pathloss coefficient $\rho = -20$ dB. The target throughput of the heterogeneous network is 40 Mbps.

allocation scheme (α_F^*, β_F^*) as follows,

$$\mathcal{T}^* = F\Bigg(\log(1 + P_{ma}\rho R^{-\theta} + P_{mi}\rho r^{-\theta}) + \frac{\theta}{2} - \frac{1}{1 + P_{ma}\rho R^{-\theta} + P_{mi}\rho r^{-\theta}}\Bigg) \qquad (12)$$

where we have substituted the results (10) and (11) into (9). Equivalently, the optimal bandwidth allocation scheme (α_F^*, β_F^*) also achieves the best power-bandwidth tradeoff relation for the given throughput requirement $\mathcal{T}^*$. We summarize the optimal bandwidth-power tradeoff relation in the following theorem.

Theorem 2 (Optimal Bandwidth-Power Tradeoff): The optimal bandwidth-power tradeoff for the given heterogeneous network throughput requirement $\mathcal{T}^*$ under the high signal-to-noise ratio (e.g. $P_{ma}\rho R^{-\theta} + P_{mi}\rho r^{-\theta} \gg 1$) is given by,

$$\frac{P_{ma}}{R^\theta} + \frac{P_{mi}}{r^\theta} = \frac{2^{(\frac{\mathcal{T}^*}{F} - \frac{\theta}{2})} - 1}{\rho} \qquad (13)$$

Proof: The proof of Theorem 2 is rather straight-forward. Since $P_{ma}\rho R^{-\theta} + P_{mi}\rho r^{-\theta} \gg 1$, $\frac{1}{1+P_{ma}\rho R^{-\theta}+P_{mi}\rho r^{-\theta}}$ is approximately close to zero. Divide by F of both two sides and with some basic mathematical manipulations, we have the expression (13). ■

Theorem 2 provides the explicit relationship between the bandwidth and the power, which gives an important guideline to perform the network planning and optimization for the heterogeneous network topologies. The main principles regarding the effects of the bandwidth allocation, the network size and the power relation, are summarized in the following remarks.

Remark 1 (Effect of Bandwidth Allocation): Bandwidth allocation schemes may greatly change the bandwidth-power tradeoff curves and the optimized bandwidth allocation scheme provides the best bandwidth-power tradeoff curve. As shown in Fig. 3, the total power consumption will be reduced by 20% (e.g. from 370 w to 300 w for the total bandwidth $F = 4.5$ MHz case), if we changed the bandwidth allocation scheme from the equal allocation scheme ($\alpha_F = 0.5$) to the proposed optimized bandwidth allocation scheme.

Remark 2 (Effect of Network Size): The radius of the network is another important factor for the bandwidth-power tradeoff relations. If we enlarge the network size of the macro-cell and the micro-cell, the bandwidth-power tradeoff relation will become worse. Fig. 3 gives some numerical results regarding the effect of the network size, e.g. if we double the radius of the macro-cell, the total power consumption will be increased by around 50%.

Remark 3 (Effect of Power Relation): The relationship between the power budget of the macro-cell and the micro-cell will also directly impact the bandwidth-power tradeoff curves. If we relax the power ratio of the micro-cell[2], e.g. from $P_{ma} = 4P_{mi}$ to $P_{ma} = 2P_{mi}$, the bandwidth-power tradeoff curve will be improved as shown in Fig. 3.

V. Numerical Results

In this section, we extend the above results to the practical cellular layout, which contains 19 macro-cells arranged around a central macro BS. The inter-site distance of the macro BSs is 1732m according to the LTE standard [8] and the radius of the macro-cells R is 1000m. The micro BS is deployed at a fixed distance $R/2$ from the central macro BS with the radius r given by 300m. We consider the inter-cell interference

[2]In the practical systems, the power budget of the cell will also be determined by the coverage of the control signal and the capability of the base station equipments. However, in this analysis, we focus on the theoretical scaling relation, while leave the study of other factors for future research.

from other macro BSs in this experiment and the pathloss coefficient ρ is normalized to -140 dB at the distance of 1 km and the noise figure for the signal processing is 10 dB. Table I summarizes the values of the parameters used in the simulation.

TABLE I
SIMULATION PARAMETERS

Parameters	Value
Traffic Model	Downlink Full Buffer
Scheduling	Round Robin
Inter-Site Distance	1732 m
Freq. Reuse Factor	3
Pathloss Exponent	3
Pathloss Coefficient	- 140 dB @ 1 km
Noise Power	- 174 dBm/Hz
Carrier Freq.	2.0 [GHz]
Noise Figure	10 dB

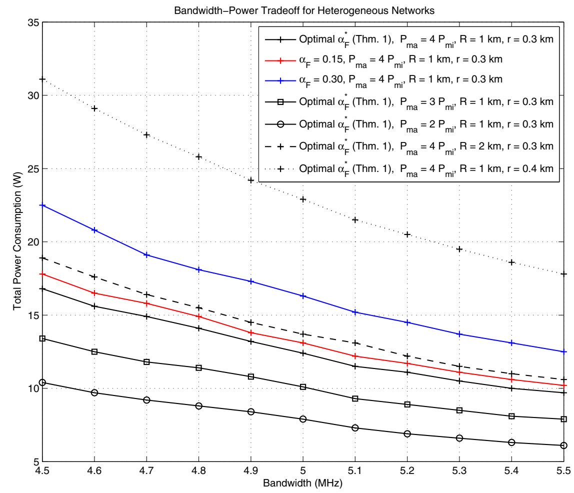

Fig. 4. The bandwidth-power tradeoff for the heterogeneous network architecture with one micro-cell and 19 macro-cells. The target throughput of the heterogeneous network is 16 Mbps.

Fig. 4 shows the empirical results regarding the bandwidth-power tradeoff relations. The optimal bandwidth allocation α_F^* is derived based on Theorem 1. By comparing different curves in Fig. 4, we can draw the following conclusions from the numerical examples. (1) The optimal bandwidth allocation α_F^* based on Theorem 1 provides a useful guideline for the frequency planning with practical network layout, which gives a better bandwidth-power tradeoff relation than the artificially selected α_F. (2) The main principles regarding the effects of the bandwidth allocation, the network size and the power relation as illustrated in the above three remarks still hold true under the practical network settings. (3) The bandwidth-power tradeoff relation is more sensitive to the radius of the micro-cell, e.g. if we increase the radius by 33%, the required power budget is nearly doubled. In other words, to make the micro-cells small is a promising solution to improve the bandwidth-power tradeoff.

VI. CONCLUSION AND FUTURE DIRECTIONS

In summary, we have investigated the bandwidth-power tradeoff relation under the heterogeneous network architecture. In order to obtain the design insights of the frequency planning as well as the network planning and optimization, we formulate the bandwidth allocation problem as an optimization problem to achieve the best bandwidth-power tradeoff relation. The closed-form expressions for the optimal bandwidth allocation scheme and the achievable bandwidth-power tradeoff are derived and the dedicated attentions are paid to obtain the main principles for the network planning with respect to the system parameters, such as the bandwidth allocation and the network size. In addition, we perform the system-level simulations to co-verify that the proposed frequency planning scheme and the design insights derived therein are important guidelines for the practical heterogeneous network planning.

The following directions are quite interesting and will be considered in the future research. Firstly, the effect of the services types with different quality of service (QoS) requirements is an important effect in the heterogeneous network. How to analyze the bandwidth-power tradeoff relation under different services requirements is still an challenging task in the heterogeneous network systems. Secondly, the antenna height, the antenna tilt and other effects like the shadowing, result in different propagation models of wireless links, and the bandwidth-power tradeoff under more practical channel conditions will be an interesting topic for future study. In a nutshell, the bandwidth-power tradeoff relation in the heterogeneous network has plenty of open issues in the heterogeneous network architecture design and the green radio research, and hence requires continuous research efforts in both academic and industrial areas.

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