Tradeoff Between Spectrum and Densification for Achieving Target User Throughput

Yanpeng Yang and Ki Won Sung
KTH Royal Institute of Technology, Wireless@KTH, Stockholm, Sweden
E-mail: yanpeng@kth.se, sungkw@kth.se

***Abstract*—Dense deployment which brings small base stations (BS) closer to mobile devices is considered as a promising solution to the booming traffic demand. Meanwhile, the utilization of new frequency bands and spectrum aggregation techniques provide more options for spectrum choice. Whether to increase BS density or to acquire more spectrum is a key strategic question for mobile operators. In this paper, we investigate the relationship between BS density and spectrum with regard to individual user throughput target. Our work takes into account load-dependent interference model and various traffic demands. Numerical results show that densification is more effective in sparse networks than in already dense networks. In sparse networks, doubling BS density results in almost twofold throughput increase. However, in dense networks where BSs outnumber users, more than 10 times of BS density is needed to double user throughput. Meanwhile, spectrum has a linear relationship with user throughput for a given BS density. The impact of traffic types is also discussed. Even with the same area throughput requirement, different combination of user density and individual traffic amount leads to different needs for BS density and spectrum.**

***Keywords*—Densification, spectrum, individual user throughput**

I. INTRODUCTION

Mobile wireless communication has experienced explosive growth during the last decades. The subscribers require high quality services such as high definition (HD) video and real time broadcasting which are supported by high user data rates. Consequently, an astounding 1000-fold increase in data traffic is expected in this decade [1], which pose a tremendous challenge to wireless research community. There is a general consensus that three fundamental ingredients are available for increasing wireless networks capacity: more spectrum, denser base stations (BSs), and better transmission technology [2][3]. Among those, we are interested in spectrum and BS density because these directly affect mobile operators' investment strategies. For any given access technology, an operator needs to make a decision on whether to increase BS density or acquire more spectrum in order to meet the soaring traffic demand.

Historically, densification of BSs has been the dominant source of capacity growth [2], and is still believed to serve as an important factor for the coming years [2][3][4]. Therefore, great interest has recently been drawn into the dense small cells. In [5], the authors give a holistic view of dense small cell networks and list the challenges of system design. The interference management problem in small cell networks is discussed in [6][7]. The dense deployment of small cells and their uncoordinated operation raise important questions on energy efficiency. Therefore, many works have been put in energy efficient design of small cell networks [8][9][10].

Radio spectrum, in terms of larger system bandwidth, has been another pillar of capacity increase [2]. Since spectrum is considered to be a scarce resource, there have been a lot of efforts to better utilize spectrum. For example, licensed shared access (LSA) approach show great promise in making spectrum sharing attractive for mobile operators [11][12][13]. Also, new frequency ranges such as millimeter-wave bands are investigated for mobile communication [14][15]. Spectrum aggregation technique has already been introduced to grasp available frequency bands [16].

In spite of abundant research in each ingredient, there has been little knowledge on the relationship between the BS densification and spectrum. An important question is which combination of BS density and bandwidth can satisfy a service requirement. When operators plan to deploy or upgrade networks, they are interested in how much resources are needed to meet their requirement, i.e., which is more efficient between deploying more BSs and acquiring more spectrum. Thus, it is crucial to identify the relation between spectrum and densification. The consensus in the industry is that the BS density and spectrum are linearly exchangeable for achieving area capacity increase [17]. The result of [18] also implies that both spectrum and BS density increases area capacity linearly under the assumption of saturated network, i.e., infinite user density. While the saturation assumption has been widely used for modeling macro-cellular networks, its applicability in denser networks is questionable. In very dense circumstances where the number of users is less than the number of BSs on average, the impact of densification may be overestimated. The effect of user density is introduced in [19], where it is argued that the densification has a diminishing return with the increasing user density. However, the performance metric of [19] is service probability which does not fully describe the experience of end users.

In this paper, we aim to identify the relationship between spectrum demand and BS densification in order to meet the user throughput target. We consider a performance metric of individual user throughput because 'amazingly fast' data rate is one of the key user experiences needed for the future networks [20]. Moreover, it is not meaningful to consider area capacity in an ultra-dense scenario where most BSs remain idle due to higher number of BSs than users. We assume a limited number of users in an area and set a target individual user throughput. Then, we determine combinations of BS density and bandwidth which make at least 95% of the users achieve the target. A simulation framework is built

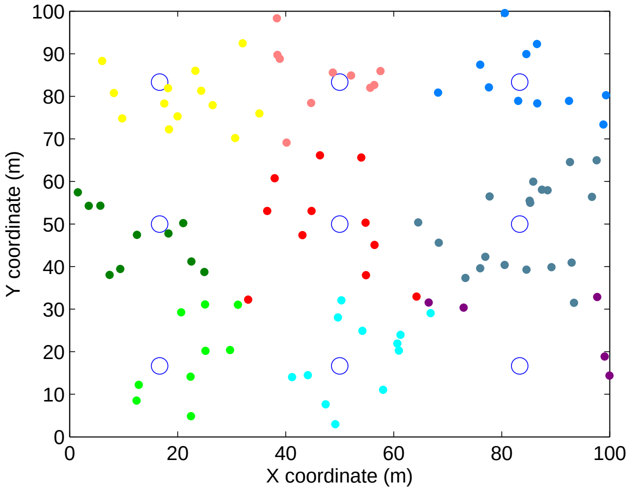


Fig. 1: Network Layout.

by adopting a feasible network load concept which relates cell resource utilization and interference-dependent resource demand generated by traffic [21, 22]. Therefore, we obtain system performance which is dependent on the number of users and individual traffic demand. Furthermore, we investigate how resource requirement changes in various traffic demand scenarios, including few users with extremely high throughput target and many users with low throughput target, which constitute the same area throughput. This will highlight the importance of specifying individual user demand in the dimensioning of wireless systems.

The remainder of this paper is organized as follows: The system model is explained in Section II. Then, we describe the simulation models in Section III. In Section IV, we present and analyze the numerical results. Finally, the conclusions are discussed in Section V.

II. SYSTEM MODEL

We consider a square grid deployed network with uniformly distributed BSs and users, which is illustrated in Fig. 1. The mobile users (dots) are associated with BSs (circles) according to highest SINR (expressed in different colors). The densities of BSs and users are λ_b and λ_u, respectively. Let user $i \in$ I connected with BS b_i. The link gain between user *i* and BS *j* is given by g_{ij}. For each BS, $\phi_k = \{i : b_i = k\}$ represent all the users connected to BS *k*. The BS load or resource utilization η_j is defined as the portion of time-frequency resource blocks (RB) that are allocated for cell *j*. The entire network load is given by a vector $\boldsymbol{\eta} = (\eta_1, \eta_2, \ ..., \ \eta_N)$, where N is the number of BSs and $\eta_j \in [0, 1]$. Then, for user *i* served by BS *k*, the average signal to interference plus noise ratio (SINR) is defined as

$$\gamma_i(\boldsymbol{\eta}) = \frac{g_{ik} \cdot P_k}{\sum_{j\neq k} \eta_j \cdot g_{ij} \cdot P_j + \sigma^2} \qquad (1)$$

where P_j is the transmit power of BS *j* and σ^2 is the non-zero noise power. In this case, cell load η_j can be viewed as a transmitting probability of BS *j*. Therefore, the co-channel interference is not received from all the other BSs simultaneously but can be considered as a statistical interference. Consequently, the effective data rate of user *i* as a function of the average SINR can be expressed as

$$r_i(\gamma_i(\boldsymbol{\eta})) = W \cdot \log_2(1 + \gamma_i(\boldsymbol{\eta})) \qquad (2)$$

where W denotes the system bandwidth.

A. Individual User Throughput Target

We assume that each user in the network has a homogeneous throughput target Ω. It can be interpreted as the average speed with which a user consumes a certain traffic demand in a given period. In this study, we consider individual user throughput as our performance metric rather than area throughput. Note that individual users may experience different data rates even with the same area throughput depending on the user density. Few users with a high throughput target represents a spatially bursty traffic situation whereas massive users with a low throughput target indicates a flat traffic scenario. The impact of different traffic type will be discussed in Section IV.

We define user utilization τ_i^k as the proportion of resources at BS *k* to serve user *i*. In order to achieve the throughput target Ω,

$$\tau_i^k = \frac{\Omega}{r_i(\gamma_i(\boldsymbol{\eta}))} \qquad (3)$$

When τ_i^k is less than 1, the system can afford the user with target throughput. Otherwise if τ_i^k turns out larger than one, it means the solution is infeasible and user *i* is not able to meet the throughput requirement. When it happens during the simulation procedure, we set τ_i^k to 1 and count the respective users as 'outage' which belongs to the 5th percentile parts. Besides, we have the relationship between user utilization and cell load as follows:

$$\sum_{i\in\phi_k} \tau_i^k = \eta_k. \qquad (4)$$

B. Feasible Load Concept

Combining (1)-(4), we have the following formula:

$$\eta_k = \sum_{i\in\phi_k} \frac{\Omega}{W \log_2(1 + \frac{g_{ik}\cdot P_k}{\sum_{j\neq k} \eta_j\cdot g_{ij}\cdot P_j + \sigma^2})}. \qquad (5)$$

Eq. (5) represents the iterative load coupling relation between BSs due to the fact that the loads of other BSs have an impact on the SINR of cell *k*. This is illustrated as a feasible load problem (FLP) in [21] and [22]. The objective of the FLP is to find a load vector $\boldsymbol{\eta}$ that balances the cell utilizations, which can be denoted by a compact nonlinear equation:

$$\boldsymbol{\eta} = f(\boldsymbol{\eta}). \qquad (6)$$

It is proven in [22] that (6) has at most one solution $\boldsymbol{\eta}^*$. Meanwhile, the unsolvable case is avoided in our simulation because we set the infeasible τ_i^k to 1. Therefore we adopt the interpolation search algorithm proposed in [21] to obtain the only $\boldsymbol{\eta}^*$.

III. DENSIFICATION-SPECTRUM TRADEOFF PROBLEM

Our objective is to find out a set of resource combinations of BS density λ_b and system bandwidth W to satisfy the user throughput target Ω. Since the actual throughput differs in every user due to different SINR and BS load, we need to find out (λ_b, W) tuples with which most of users in the system can fulfill Ω. In wireless networks, 95% availability is generally considered to be a reasonable performance target [20]. Thus, our research question can be written as

$$\text{Find } (\lambda_b, W) \tag{7}$$

$$\text{Subject to } \boldsymbol{F}_{5\%}[r_i(\gamma_i(\boldsymbol{\eta}^*))] \geq \Omega, \tag{8}$$

where $\boldsymbol{F}_{5\%}[\cdot]$ is the 5*th* percentile of the CDF of the variable in the bracket, i.e. it provides us with the smallest user throughput threshold such that at most 5% of all users in network experience an average throughput lower than the target Ω.

In this framework, we can also investigate a network upgrading problem, i.e., to find out additional resource requirement in order to increase, say double, the throughput target. User density λ_u should also come into play. Assume that a system is dimensioned for a certain area throughput target. Since the area throughput is $\lambda_u\Omega$, different user density gives different individual throughput for the same area throughput. We can say that few users with high Ω represents a spatially bursty traffic situation whereas massive users with low throughput target indicates a flat traffic scenario. Therefore, the impact of user density or traffic demand types is of interest.

Note that the solution of the above problem is not one, but continuum of resource combinations depending on the tradeoff between λ_b and system bandwidth W. From (5), we can observe that both λ_b and W influence our performance metric Ω. The impact of spectrum is straightforward because Ω is proportional to W while λ_b is fixed. This means that spectrum has a linear relationship with user throughput for a given BS density. The impact of BS densification can be explained twofold. Firstly, the densification implies fewer mobile users served by one cell, i.e. ϕ_k in (4) has fewer elements. Thus, each user can have higher user utilization τ_i^k, which promises higher throughput target with the same utilization level in (3). Secondly, the relative distance between the desired and interfering BSs is increasing, i.e., g_{ik}/g_{ij} ratio is increasing, which permits higher Ω as well. As discussed, the effect of BS densification is rather complex, and difficult to be parameterized. Thus, we perform Monte Carlo simulations based on the feasible load concept in order to answer our research question.

Although the impact of BS densification is complicated, it is obvious that the throughput target Ω is a monotonic increasing function of both spectrum W and BS density λ_b when λ_u is fixed. We study a set of scenarios with different BS densities $[\lambda_b^1, \lambda_b^M]$. For each scenario, the minimum required spectrum W^i can be obtained empirically by performing simulations with the algorithm proposed in [21]. The corresponding spectrum vector $[W^1, W^M]$ and BS density vector λ_b^i and W^i are the resource pairs for the network planning. In network upgrading, we set a higher throughput target and obtain the resource requirement. By comparing the new resource requirement with the previous one, we can decide the cost efficient way to upgrade the network. For different traffic types, we hold the same area throughput requirement with different combinations of user density and individual traffic amount.

IV. NUMERICAL RESULTS

We consider downlink of a network with square grid layout in an area of $100 \times 100\text{m}^2$. In each cell, a BS with omnidirectional antenna is placed in the cell center. Wrap-around technique is adopted in order to reduce the boundary effect in the simulation. The BS density ranges from 0.01 to 100 times of the user density which includes extremely sparse and dense scenarios. The thermal noise density is -174 dBm/Hz and noise figure is 9 dB. We assume that transmit power of BSs is adjusted according to the BS density such that the cell edge SNR always equals to 30 dB. The standard power loss propagation model $P_r = C \times P_t \times d^{-\alpha}$ is applied with the constant C and the path loss exponent α of 2, 3 and 4. A log-normal shadow fading with 3 dB standard deviation is used.

A. Network planning

The relationship between spectrum and BS density for network planning with the three pathloss exponents is illustrated in Fig. 2. The throughput target Ω is 100 Mbps for the 100 randomly distributed users in the area. In a circumstance with high propagation loss, we need fewer resources to achieve throughput target because of the lower interference. Another observation is that we can approximately divide the figure into two parts on the basis of density ratio, which is circumscribed by the logarithmic density ratio *0*. We roughly define the left side as sparse network where $\lambda_b < \lambda_u$ and the right side as dense networks where $\lambda_b \geq \lambda_u$.

In sparse networks, the slope of the curve is sharp while in dense region the slope is quite flat. This indicates that deploying more BSs in sparse network can save large amount of spectrum. However in dense network, densification becomes less effective. The phenomenon can be explained by Fig. 3, which shows average cell utilization in different scenarios. In sparse network, most of BSs are in service, and thus the average utilization is high. Adding more BSs can relieve the burden of current BSs, which is directly converted into the throughput increase of the users. This also means that BS densification is an effective substitute for spectrum in sparse regime. However, the densification hardly affects the network due to the low cell utilization in dense networks. Only a portion of BSs is active in dense regime because BSs outnumber the mobile users. Thus, the average cell utilization remains quite low. A further densification will add even more idle BSs which are not effective, though slightly helpful, for the throughput increase.

B. Network upgrading

Fig. 4 depicts how much resource is required to improve the user throughput doubly from 50 Mbps to 100 Mbps with the pathloss exponent of 3. As shown in the figure, we can reach the upper line (100 Mbps) by moving either vertically, i.e. providing more spectrum or horizontally, i.e. increasing the BS density. We observe that twice spectrum can always double the throughput as clearly illustrated in (5). However, the

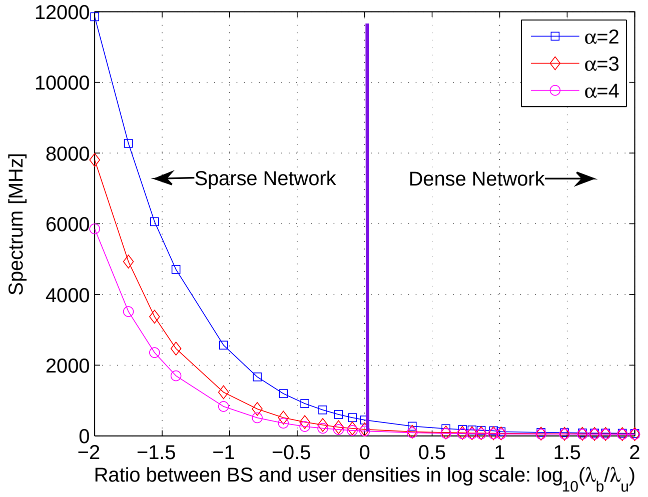


Fig. 2: Relationship between spectrum and BS densification.

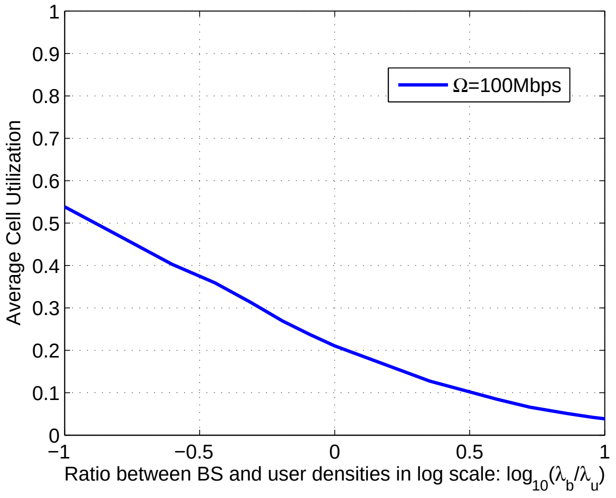


Fig. 3: Cell utilization versus densification.

required increment in BS density varies depending on sparse or dense regime. We can divide Fig. 4 into two parts for further comparison and elaboration, which are presented in Fig. 5a and Fig. 5b, respectively.

In Fig. 5a which denotes the sparse network, around 2.2 times densification brings about doubled data rate. For this case, user throughput is almost linearly increasing with the BS density. This corresponds with the conclusion in [18] because BS density is smaller than user density, where it is likely to have at least one user per BS. Since the amount of spectrum to meet the high user throughput is large in Fig. 5a, densification is the key solution in sparse networks to enhance the performance. However, in the dense network, the increase rate of user throughput diminishes as the BS density increases. As illustrated in 5b, much more than 2 times densification, even more than 20 times in the extremely dense situations, is needed to achieve the double data rate. Contrarily, required amount of spectrum is relatively small, which implies that the spectrum is an effective resource to invest in dense situation. Acquiring a few more spectrum may have a huge impact and save the required BS deployment.

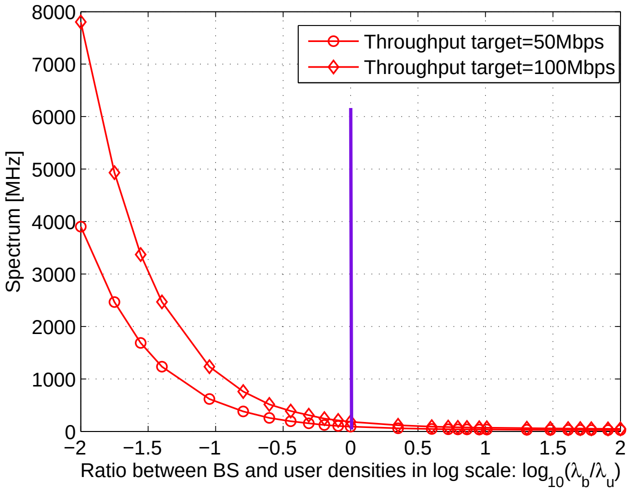
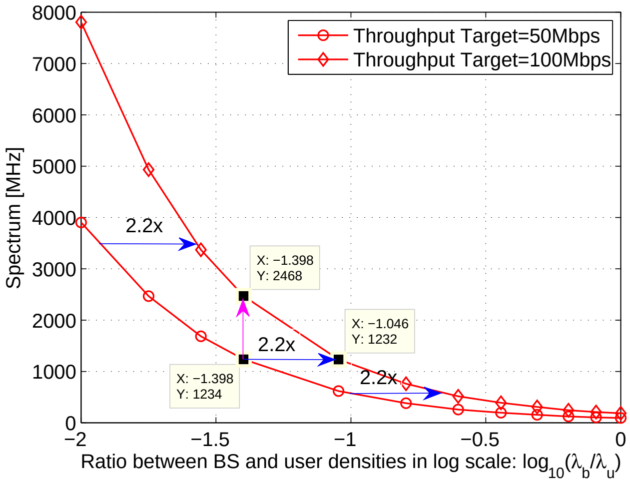


Fig. 4: Resource requirement to double the throughput target.

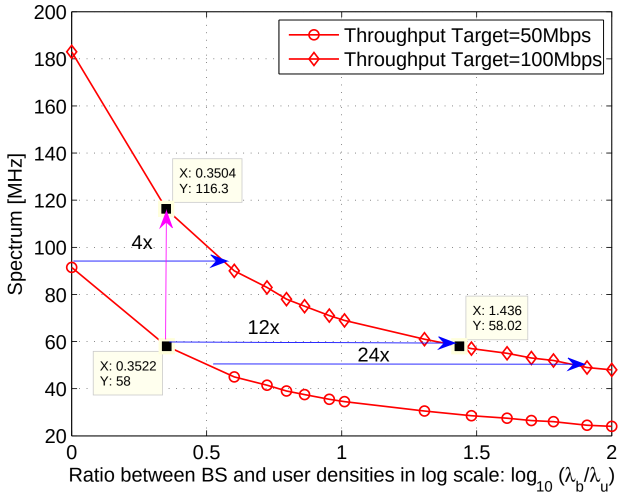
C. *Impact of Traffic Type*

In this subsection, we consider various individual throughput target meanwhile keeping the total traffic requirement in the network, i.e. area capacity demand (100 users × 100 Mbps/user = 1 Mbps/m^2) same for comparison. For instance, when twice higher throughput target is set, half of users are distributed in the network. We consider a extremely bursty scenario with 10 users and 1 Gbps target, a flat traffic scenario with 1000 users and 10 Mbps target, and medium scenarios inbetween.

The impact of the traffic types is shown in Fig. 6. Intuitively, different resources are required even though the total area throughput is the same. Furthermore, we can see that spectrum has a significant impact in the bursty situation while the densification plays a more important role with the flat traffic. With the same BS density, the bursty traffic requires more spectrum. By increasing the BS density by 4 times, we can save $3 \sim 4$ times of required spectrum in the flat situation whereas the saving is only 2 times in the bursty scenario. In the bursty scenario, the average number of users sharing one BS is low which makes the users utilize high portion of the BS resources. In this case, spectrum will determine the system performance and putting more BSs has a less effect. However in the flat traffic situation, the bottleneck lies in the cell utilization when large amount of users sharing a few BSs. As a result, the densification can release part of the users to new deployed BSs, which has a significant impact. Fig. 6 suggests that the area throughput is not a good metric for network dimensioning decisions. Individual user performance should be taken into account for making a right choice of resource planning.



(a) Sparse Network



(b) Dense Network

Fig. 5: Tradeoff in sparse and dense network regime.

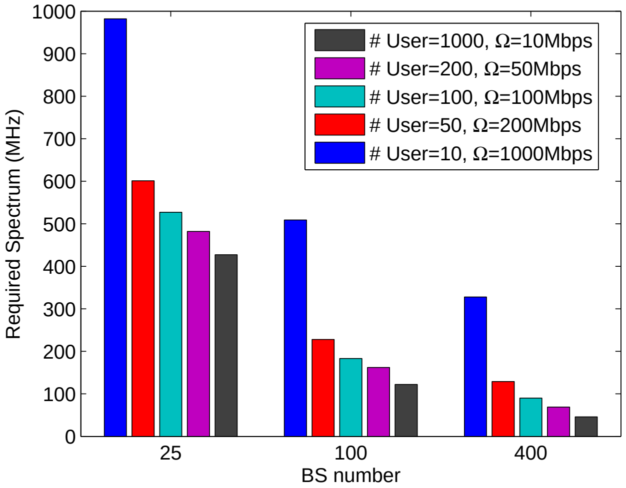


Fig. 6: Resource requirement in different traffic demands.

V. CONCLUSION

In this paper, we have investigated the tradeoff between BS density and spectrum configuration in wireless networks in order to achieve individual user throughput target. We adopted a feasible load concept which takes into account service- and load-dependent network performance. It was illustrated that we can approximately divide the networks into two regimes according to the ratio between BS and user densities: sparse network with more BSs than users and dense network otherwise. As indicated from the numerical results, BS densification performs well in sparse network. User throughput increases almost linearly with the BS density in this regime. On the contrary, further densification is not effective in dense networks. More than 10 to 20 times of BS density is needed to double user throughput when the BS density is already very high. Meanwhile, twice spectrum always guarantees twofold increase in the user throughput for a given BS density. Spectrum is shown very effective in dense deployment where acquiring few more spectrum gives significant reward on user throughput. We also demonstrated the importance of specifying user demand in the dimensioning of wireless networks by showing that different resources are needed in different traffic demand types even with the same area throughput. Spectrum has significant impact in a situation with few users and high individual requirements while densification plays a more important role in flat traffic conditions with many users. Our findings indicate that spectrum demand is a non-linear function of network deployment, subject to active user density and individual user requirement.

This study was based on the assumption of a full frequency reused regular grid BS deployment, with a simplified path loss model and no network coordination in an open environment. Besides, the results only holds for high capacity demand networks. Future work should consider more realistic scenarios of BS deployment and various technologies(e.g. MIMO, Beamforming, CoMP).

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REFERENCES

[1] Qualcomm Incorporated (2013, June), "The 1000x Data Challenge," [Online]. Available: http://www.qualcomm.com/1000x/

[2] Real Wireless, "Strategies for Mobile Network Capacity Expansion," White Paper, 2010.

[3] Nokia Solutions and Networks, "Looking ahead to 5G," White Paper, Dec. 2013.

[4] N. Bhushan, J. Li, D. Malladi, R. Gilmore, D. Brenner, A. Damnjanovic, R. T. Sukhavasi, C. Patel, and S. Geirhofer, "Network Densification: The Dominant Theme for Wireless Evolution into 5G," *IEEE Commun. Mag.*, vol.52, no. 2, pp. 82-89, 2014.

[5] I. Hwang, B. Song, and S. S. Soliman, "A Holistic View on Hyper-Dense Heterogeneous and Small Cell Networks," *IEEE Commun. Mag.*, vol.51, no. 6, pp. 20-27, 2013.

[6] J. Huang, H. Zhang, W. Xu, and H. Zhang, "Grouping based inter-cell interference coordination in LTE-A dense small-cell networks," *IEEE 5th International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications (MAPE)*, Oct. 2013.

[7] Y. Zhang, S. Feng, P. Zhang, L. Xia, Y. Wu, and X. Ren, "Inter-Cell Interference Management in LTE-A Small-Cell Networks," *IEEE Vehicular Technology Conference (VTC Spring)*, June. 2013.

[8] C. Li, J. Zhang, and K. B. Letaief, "Energy efficiency analysis of small cell networks," *IEEE International Conference on Communications (ICC)*, June. 2013.

[9] Y. Soh, T. Q. S. Quek, M. Kountouris, and H. Shin, "Energy Efficient Heterogeneous Cellular Networks," *IEEE Journal on Selected Areas in Communications*, vol.31, no. 5, pp. 840-850, 2013.

[10] R. Razavi, and H. Claussen, "Urban small cell deployments: Impact on the network energy consumption," *IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, Apr. 2012.

[11] Ericsson White Paper, "Spectrum Sharing," Oct. 2013.

[12] M. Matinmikko, M. Palola, H. Saarnisaari, M. Heikkila, J. Prokkola, T. Kippola, T. Hanninen, M. Jokinen, and S. Yrjola, "Cognitive Radio Trial Environment: First Live Authorized Shared Access-Based Spectrum-Sharing Demonstration," *IEEE Vehicular Technology Magazine*, vol. 8, no. 3, pp. 30-37, 2013.

[13] P. Ahokangas, M. Matinmikko, S. Yrjola, M. Mustonen, H. Posti, E. Luttinen, A. Kivimaki, "Business models for mobile network operators in Licensed Shared Access (LSA)" *IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Apr. 2014.

[14] Z. Pi and F. Khan, "An Introduction to Millimeter-wave Mobile Broadband Systems," *IEEE Commun. Mag.*, vol.49, no. 6, pp. 101-107, 2011.

[15] T. S. Rappaport et al., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work," *IEEE Access J.*, vol. 1, pp. 335-349, 2013.

[16] H. Lee, S. Vahid, K. Moessner, "A Survey of Radio Resource Management for Spectrum Aggregation in LTE-Advanced," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 2, pp. 745-760, 2014.

[17] J. Zander, and P. Mähönen, "Riding the Data Tsunami in the Cloud: Myths and Challenges in Future Wireless Access," *IEEE Commun. Mag.*, vol.51, no. 3, pp. 145-151, 2013.

[18] J. G. Andrews, F. Baccelli, and R. K. Ganti, "A Tractable Approach to Coverage and Rate in Cellular Networks," *IEEE Transactions on Wireless Communications*, vol. 59, no. 11, pp. 3122-3134, 2011.

[19] S. M. Yu, and S. L. Kim, "Downlink Capacity and Base Station Density in Cellular Networks" *11th International Symposium on Modeling & Optimization in Mobile, Ad Hoc & Wireless Networks (WiOpt)*, May. 2013.

[20] METIS deliverable D1.1: Scenarios, requirements and KPIs for 5G mobile and wireless system, Apr. 2013.

[21] I. Siomina, A. Furuskąğar, and G. Fodor, "A mathematical framework for statistical QoS and capacity studies in OFDM networks," *IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Sept. 2009.

[22] I. Siomina, and D. Yuan, "Analysis of Cell Load Coupling for LTE Network Planning and Optimization," *IEEE Transactions on Communications*, vol. 11, no. 6, pp. 2287-2297, 2012.