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Placement of WiFi Access Points for Efficient WiFi Offloading in an Overlay Network

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***Abstract*—In order to alleviate a mobile data explosion problem, WiFi offloading has been proposed. The key issue is how many access points (APs) are needed to accommodate a proper number of users per WiFi AP without severe performance degradation. Although WiFi networks can provide higher throughput as more and more APs are deployed, it may not be a reasonable solution if we consider an increase in the corresponding capital and operational expenditure (CAPEX/OPEX). Therefore, it is important to investigate the minimum required number of WiFi APs which achieve a certain level of performance improvement. In this paper, we focus on the minimum required number of WiFi APs for efficient WiFi offloading. We first set the target average per-user throughput when a WiFi network can play a role as an offloading network of a given cellular network. Based on this criterion, we find the minimum required number of WiFi APs in an overlay network through mathematical analysis.**

I. Introduction

Mobile data traffic has recently increased very rapidly due to wide spread of smartphones. According to Cisco forecasts [1], monthly global mobile data traffic will surpass 10 exabytes in 2016 and global mobile data traffic will rise 18-fold between 2011 and 2016. However, the current capacity of cellular networks is not sufficient enough to accommodate such an exponential growth of mobile data. Moreover, considering the development of new mobile applications with large data traffic generation and an increasing number of smart device users, user traffic demands will soon exceed the capacity of the next generation networks (e.g. 3GPP Long Term Evolution (LTE) or WiMAX). Thus, it is imperative to find other approaches about how to effectively solve this critical problem.

Mobile data offloading is to utilize complementary network technologies for delivering data originally targeted for cellular networks. There are several possible offloading solutions and one of the leading candidates is WiFi offloading. WiFi technology has many advantages as a primary offloading technology. First of all, WiFi can provide comparable data rates with that of a cellular network and achieves higher energy efficiency than the cellular network does. Also, WiFi access points (APs) can be installed easily and quickly with a small amount of additional cost and millions of WiFi networks have already been deployed in residential areas and hotspots. In addition, since most smart devices have built-in WiFi capabilities, WiFi networks have an advantage of establishing a communication infrastructure over other wireless communication networks. With these features, WiFi networks have been widely used as a supportive network for mobile data offloading.

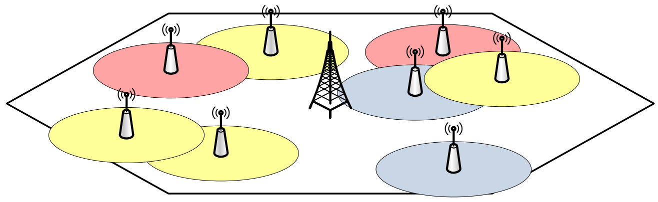

Fig. 1. An overlay network with the unplanned WiFi cell deployment

Many studies have shown the effectiveness of WiFi offloading. Lee *et al.* [2] showed that the existing WiFi networks have already offloaded about 65% of the total mobile traffic and save 55% of battery power without using any delayed transmission through their trace-driven simulation. Ristanovic *et al.* [3] designed two algorithms for delay-tolerant WiFi offloading. They showed that both solutions succeed in offloading a significant amount of traffic with a positive impact on battery lifetime. Deif *et al.* [4] proposed an architecture for deploying a WiFi offloading model into a heterogeneous network with IEEE 802.11 WiFi and UMTS. Aijaz *et al.* [5] showed that more than 65% of the cellular base station power consumption can be saved through WiFi offloading. Jung *et al.* [6] proposed a network-assisted user-centric WiFi offloading model in order to enhance the per-user throughput by utilizing the network information.

Most of current WiFi networks consist of randomly deployed WiFi cells since there is no regulation or policy on WiFi cell deployment, as shown in Fig. 1. The unplanned deployment of WiFi cells may cause the WiFi networks to be managed inefficiently. There have been some studies on WiFi cell deployment problems. Wang *et al.* [7] proposed WiFi deployment algorithms based on realistic mobility characteristics. Even though their algorithms significantly improve the continuous coverage for mobile users while reducing the required number of APs, they regarded WiFi as a separated network and did not consider the objective of mobile data offloading. Dimatteo *et al.* [8] quantified the number of APs required for WiFi offloading with different quality of service for data delivery. However, they just provided a feasibility study on such offloading solution through real mobility traces and did not perform any mathematical analysis of this problem.

As shown in the previous studies, it is obvious that cellular traffic load is partially reduced(offloaded) if we use both cellular and WiFi together. The key issue is how many APs are needed to accommodate a proper number of users per WiFi AP while satisfying a given performance requirement. The WiFi network can achieve higher throughput as more and more APs are deployed. However, it may not be a good solution if we consider an increase in the corresponding capital and operational expenditure (CAPEX/OPEX). Therefore, it is important to investigate the minimum required number of WiFi APs which achieve a certain level of performance improvement. In this paper, we focus on the minimum required number of WiFi APs in a cellular/WiFi overlay network for efficient WiFi offloading. We first set the target average per-user throughput when a WiFi network plays a role as an offloading network of the cellular network. Based on this criteria, we find the minimum required number of WiFi APs in an overlay network through mathematical analysis.

The rest of this paper is organized as follows. We introduce a system model and the target throughput in Section II. In Section III, we analyze the throughput of the overlay network and find the minimum required number of WiFi APs. Numerical results are presented in Section IV. Finally, we draw conclusions in Section V.

II. System Model

The object of this paper is to find a minimum required number of WiFi APs for WiFi offloading in a cellular/WiFi overlay network. In this section, we describe a system model and set the target average per-user throughput that a WiFi network should achieve through more efficient WiFi offloading. This target average per-user throughput will be used as a criterion for finding the minimum required number of WiFi APs in the overlay network.

A. An Overlay Network

We consider the overlay network coverage, A_{OV}, which consists of a single cellular base station (BS) and K WiFi APs. N_{OV} users are uniformly distributed within this coverage and each user has an identical and saturated traffic demand. The WiFi cells are deployed based on a regular hexagonal cell (RHC) architecture and three non-overlapping channels (channel 1, 6, and 11 for IEEE 802.11 WLAN in the 2.4GHz band) are allocated in the manner of minimizing the co-channel interference, as shown in Fig. 2. We assume that the users offload data traffic based on the *on-the-spot* WiFi offloading model [2], in which users use spontaneous connectivity to WiFi and transfer data on the spot. When the users move out of the WiFi coverage, they discontinue the offloading and transfer their traffic through the cellular network. This means that the users within the coverage of WiFi APs are always served by WiFi and the users outside the coverage of WiFi APs are necessarily served by the cellular network. In the conventional RHC architecture, a WiFi AP covers the whole area of the hexagon, however, in our system model, we assume that the coverage of a WiFi AP can be adjusted between zero and the area of a hexagon, denoted by A_{hex}, based on the power control. Using this WiFi power control, we can control the proportion of users served by WiFi denoted by η. η is expressed as follows:

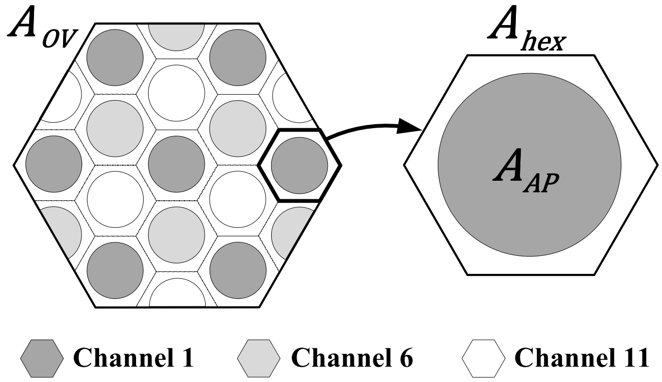

Fig. 2. An overlay network based on a regular hexagonal cell architecture

$$\eta = \frac{N_W}{N_{OV}} = \frac{\lambda A_W}{\lambda A_{OV}} = \frac{A_W}{A_{OV}} = \frac{KA_{AP}}{KA_{hex}} = \frac{A_{AP}}{A_{hex}}, \quad (0 < \eta < 1), \qquad (1)$$

where N_W, λ, A_W, and A_{AP} represent the number of active WiFi users, the active user density of the uniformly distributed users, the overall coverage of WiFi APs, and the coverage of a WiFi cell, respectively. Note that η does not depend on the number of WiFi APs, K. This implies that once the value of η is fixed, the overall coverage of WiFi APs (A_W) does not change even if the number of WiFi APs (K) changes. Therefore, we can control the number of users per WiFi AP while accommodating the total number of users served by WiFi by adjusting K for fixed η. Since the throughput of WiFi depends on the number of contending users in a WiFi cell, we can achieve a certain level of throughput by adjusting K.

B. A Cellular Network

Users outside the WiFi coverage are served by a cellular network. We assume that all the users are fairly scheduled and all the resources are fairly allocated to all users in the cellular network. Moreover, the resource of the cellular network is fully utilized by the cellular users regardless of how many users are served by the cellular BS and how the effective cellular coverage changes. The area of the effective cellular coverage, A_C, varies as η varies, whereas it does not change when K varies, as mentioned in Sub-section II-A. On the other hand, the shape of the effective cellular coverage changes with the number of overlaid WiFi APs (K), as shown in Fig. 3. Therefore, the area and the shape of the effective cellular coverage change when η and K vary, and they affect the system capacity of the cellular network. However, through simulations, we observe that the effect of η and K on the system capacity of the cellular network is negligible, Thus, we regard the system capacity provided by the cellular BS, S_C, as a constant regardless of the values of η and K in our analysis.

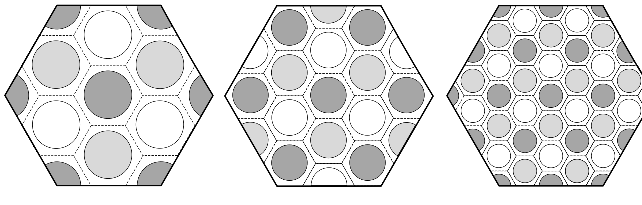

Fig. 3. An overlay network for different values of K and fixed η

C. WiFi Networks

The users within the coverage of WiFi APs are served by WiFi networks. We assume that all the WiFi users have a single data rate and the transmit power of an AP is equal to that of a mobile station while the antenna gain of an AP is also equal to that of a mobile station. The effect of the hidden node problem and the exposed node problem is not considered in our analysis.

In the WiFi offloading, the WiFi network is used as an offloading network of the cellular network. Therefore, the WiFi network should provide at least the same average per-user throughput as the cellular network does. Based upon this constraint, we set the target average per-user WiFi throughput as follows:

$$S_W^{user} \geq S_C^{user} = S_W^{user*}, \tag{2}$$

where S_W^{user}, S_C^{user} and S_W^{user*} represent the average per-user WiFi throughput, the average per-user cellular throughput, and the target average per-user WiFi throughput, respectively.

In Section III, we will find the minimum required number of WiFi APs, K^*, which achieves the target average per-user WiFi throughput (S_W^{user*}) in Eqn. (2). The mathematical expression of the meaning of K^* can be express as follows:

$$\begin{aligned} K^* &= \arg\min_K S_W^{user} \\ &\textit{such that } S_W^{user} \geq S_C^{user}. \end{aligned} \tag{3}$$

III. Analysis of the Minimum Required Number of WiFi APs

The system capacity of a WiFi network varies as the number of WiFi APs (K) and the proportion of offloaded users (η) vary. In this section, we will find the minimum required number of WiFi APs (K^*) to meet the target average per-user WiFi throughput (S_W^{user*}) as shown in the previous section.

A. Average Per-user Cellular Throughput

The average per-user cellular throughput can be expressed as:

$$S_C^{user} = \frac{S_C}{N_C} = \frac{S_C}{(1-\eta)N_{OV}}, \tag{4}$$

where S_C and N_C represent the system capacity provided by the cellular BS and the number of active cellular users, respectively. From Eqn. (4), N_C is equal to $N_{OV} - N_W = (1-\eta)N_{OV}$.

B. Average Per-user WiFi Throughput

We use the Markov chain model in [10] for throughput analysis of a WiFi network. In the WiFi network, users within the carrier sensing range are coordinated by the basic access method of the DCF mechanism. According to Eqns. (11)-(13) in [10], P_{tr} denotes the probability that there is at least one transmission in the expected slot time, P_s denotes the probability of a successful transmission, and S_W^{AP} denotes the normalized system throughput for a single WiFi AP. P_{tr}, P_s, and S_W^{AP} are expressed, respectively, as follows:

$$P_{tr} = 1 - (1-\tau)^n, \tag{5}$$

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}}, \tag{6}$$

$$S_W^{AP} = \frac{P_s P_{tr} E[P]}{(1-P_{tr})\sigma + P_s P_{tr} T_s + (1-P_s) P_{tr} T_c}, \tag{7}$$

where n, τ, $E[P]$, σ, T_s, and T_c denote the number of users per WiFi AP, the transmission probability of a user, the average packet length, the duration of an empty slot time, the successful transmission time, and the collided transmission time, respectively. Note that P_{tr} and P_s are functions of n. Since $n = \frac{N_W}{K} = \frac{\eta N_{OV}}{K}$ from Eqn. (1), S_W^{AP} in Eqn. (7) can be expressed as a function of K, η, and N_{OV}, i.e. $S_W^{AP}(K, \eta, N_{OV})$. Then, the average per-user WiFi throughput can be calculated as:

$$S_W^{user} = \frac{K S_W^{AP}(K, \eta, N_{OV})}{N_W} = \frac{K S_W^{AP}(K, \eta, N_{OV})}{\eta N_{OV}}. \tag{8}$$

C. Minimum Number of WiFi APs

The average per-user WiFi throughput S_W^{user} is determined by K, η and N_{OV}, as shown in Eqn. (8). When we consider the fixed η and N_{OV}, we can find K which makes the WiFi network provide at least the same average per-user throughput of the cellular network as in Eqn. (2). Therefore, this value K, denoted as K^*, can be interpreted as the minimum required number of WiFi APs to meet the target average per-user throughput under given η and N_{OV}. From Eqns. (2), (4) and (8), this condition can be expressed as:

$$\frac{K S_W^{AP}(K, \eta, N_{OV})}{\eta N_{OV}} \geq \frac{S_C}{(1-\eta)N_{OV}}. \tag{9}$$

Then, we can obtain

$$\begin{aligned} K^*(\eta, N_{OV}) &= \arg\min_K f(K, \eta, N_{OV}) \\ &\textit{subject to } f(K, \eta, N_{OV}) \geq 0, \end{aligned} \tag{10}$$

where

$$f(K, \eta, N_{OV}) = (1-\eta) K S_W^{AP}(K, \eta, N_{OV}) - \eta S_C. \tag{11}$$

In the following section, we will show the graphical meaning of Eqn. (10) through numerical results.

TABLE I
SYSTEM PARAMETERS

Parameters	Values
BS cell radius	$R_C = 500\ m$
Path loss at $d_0 = 1\ m$	$\alpha = (\frac{c}{4\pi f_c d_0})^2 = 9.895 \times 10^{-5}$, $(f_c = 2.4\ GHz, c = 3 \times 10^8\ m/s)$
$CW_{\min}$	15
Retry limit	4
Packet size	300 $bytes$
Basic rate	6 $Mbps$
Channel rate	30 $Mbps$
Slot time	9 μsec
SIFS	16 μsec
DIFS	34 μsec
Propagation, δ	1 μsec
PHY overhead, H	24 $bits$
ACK length	158 $bits$

IV. NUMERICAL RESULTS AND DISCUSSIONS

In the previous section, we proposed a mathematical approach to find the minimum required number of WiFi APs. In this section, we present numerical results by using MATLAB and explain the graphical meaning of the proposed minimum required number of WiFi APs. The typical parameter setting in our analysis is shown in TABLE I. The system parameters of the overlay network are based on the specification of 3GPP LTE and IEEE 802.11n standard.

Fig. 4 shows the average per-user WiFi throughput S_W^{user} for varying N_C when $\eta = 0.7$. The integer value of K right above the intersection point of the target average per-user throughput, S_W^{user*}, and the average per-user WiFi throughput, S_W^{user}, is the minimum required number of WiFi APs, $K^*(\eta, N_{OV})$. We observe that the average per-user WiFi throughput increases as the number of WiFi APs, K, increases. Thus, we can achieve the higher average per-user WiFi throughput than S_W^{user*} by deploying more WiFi APs than $K^*(\eta, N_{OV})$. The effect of WiFi offloading decreases as N_{OV} increases for a fixed K since S_W^{user} decreases as the number of contending users increases. Therefore, more WiFi APs are needed to achieve S_W^{user*} as N_{OV} increases.

Fig. 5 illustrates the minimum required number of WiFi APs, $K^*(\eta, N_{OV})$, for varying N_{OV} when $\eta = 0.7$. As N_{OV} increases, $K^*(\eta, N_{OV})$ also increases to compensate for the throughput degradation of WiFi induced due to an increase in the number of contending users.

Fig. 6 shows the average per-user WiFi throughput, S_W^{user}, for varying η when $N_{OV} = 200$. Similar to the result in Fig. 4, the integer value of K right above the intersection point of S_W^{user*} and S_W^{user} is the minimum required number of WiFi APs, $K^*(\eta, N_{OV})$. In this case, S_W^{user*} increases rapidly as η increases since the number of active cellular users decreases. This decreasing number of cellular users causes an increment in the average per-user cellular throughput, and, thus, the target average per-user WiFi throughput also increases. However, the average per-user WiFi throughput decreases as the proportion of offloaded users, η, increases when K is fixed. This is because the number of users per WiFi AP increases as η

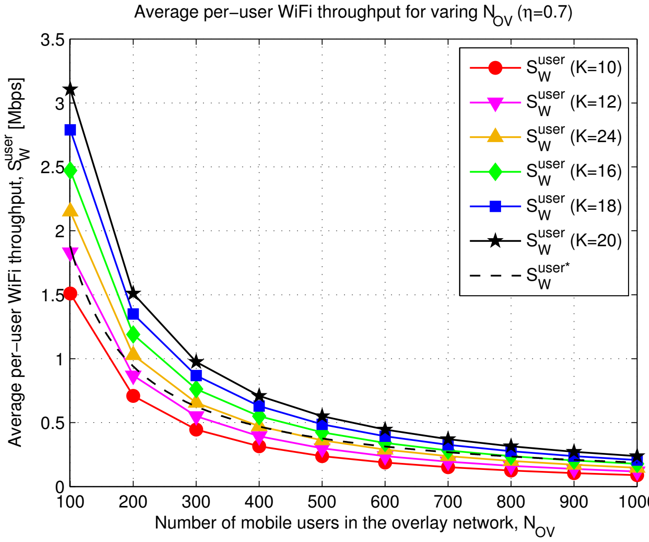

Fig. 4. Average per-user WiFi throughput for varying N_{OV} $(\eta = 0.7)$

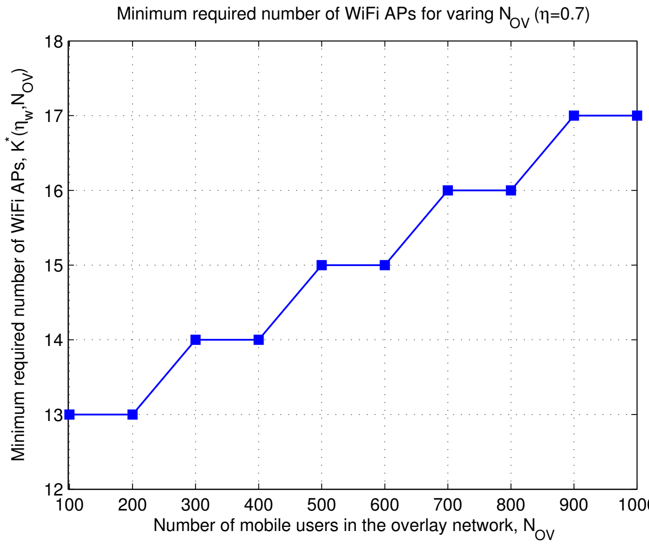

Fig. 5. Minimum required number of WiFi APs for varying N_{OV} $(\eta = 0.7)$

increases for a fixed K.

Fig. 7 illustrates the minimum required number of WiFi APs, $K^*(\eta, N_{OV})$, for varying η when $N_{OV} = 200$. Compare to the result in Fig. 5, we can observe that $K^*(\eta, N_{OV})$ increases more rapidly. The main reason of this tendency is that S_W^{user*} decreases when N_{OV} increases, whereas increases when η increases.

V. CONCLUSIONS

In this paper, we proposed a mathematical approach to find the minimum required number of WiFi APs for efficient WiFi offloading, which is a critical parameter for both of the performance and the CAPEX/OPEX of a WiFi network. We first set the target average per-user throughput which a WiFi network should achieve as an offloading network of the cellular network. Based on this criterion, we found the

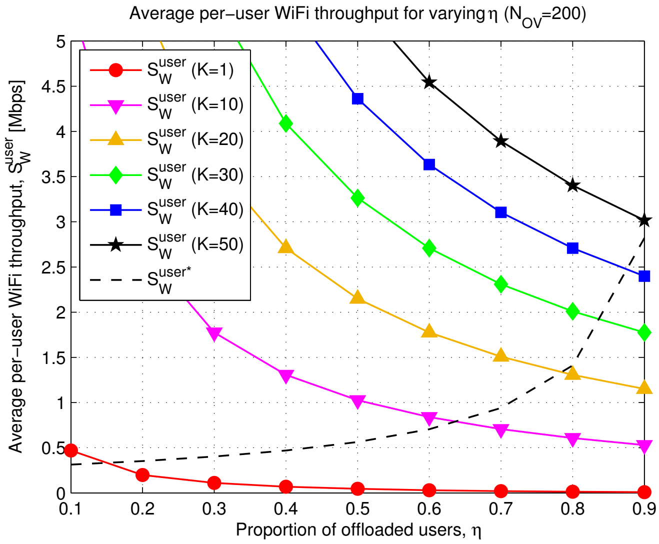

Fig. 6. Average per-user WiFi throughput for varying η ($N_{OV} = 200$)

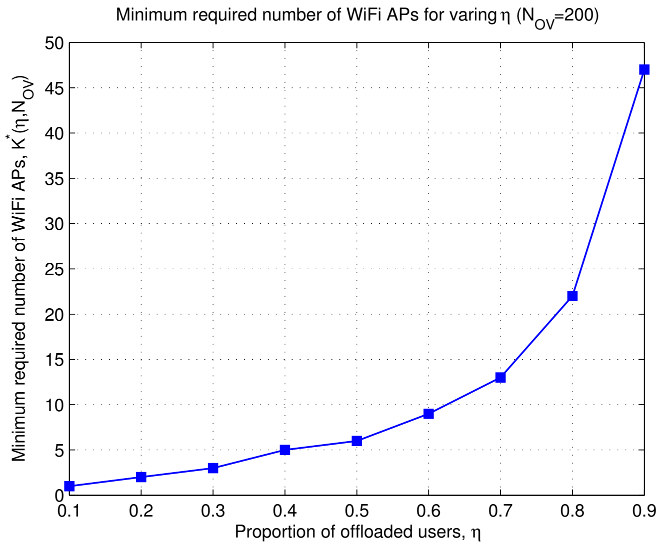

Fig. 7. Minimum required Number of WiFi APs for varying η ($N_{OV} = 200$)

minimum required number of WiFi APs in an overlay network. The numerical results presented in this paper graphically showed the proposed minimum required number of WiFi APs. We note that the criterion proposed in this paper, the target average per-user WiFi throughput, is just an example and it can be adjusted if we employ other performance evaluation metrics such as energy efficiency or delay. Although the results of this paper are based on several assumptions for simplicity of analysis, it provides intuitive results and basic guidelines to establish a WiFi cell deployment strategy.

For further work, we will consider the performance degradation due to hidden and exposed node problems and investigate the impact of practical traffic patterns and multiple modulation and coding scheme (MCS) levels on WiFi cell deployment.

ACKNOWLEDGMENT

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