Performance Evaluation of Mobile Hotspots in Densely Deployed WLAN Environments

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***Abstract*—This paper presents a study of mobile wireless LAN (WLAN) hotspots which are used to provide cellular-WiFi tethering service to personal devices. A dense deployment scenario for fixed and mobile WLAN is described and potential performance problems due to interference are identified. An analytical model for coexisting fixed and mobile WLAN hotspots with heterogeneous traffic is presented. The model is used to evaluate the performance of a mobile WLAN as it transits through a set of densely deployed fixed access points (APs), and performance problems due to lack of frequency coordination are identified. An adaptive channel assignment (ACA) scheme for improving mobile AP performance is proposed and evaluated. It is shown that significant performance gains can be achieved with ACA with maximum absolute and percentage throughput gains up to 1.24 Mbps and 42.8% respectively. We also show that setting the scanning interval in ACA requires consideration of the speed at which the mobile WLAN is moving in order to compensate for the throughput losses during channel scanning.**

***Index Terms*—adaptive channel assignment, hotspots, mobile WLAN, WiFi tethering.**

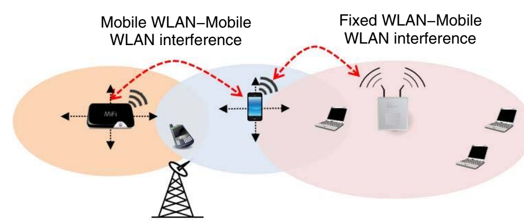
I. Introduction

Mobile hotspots enable cellular users to provide Internet connectivity to multiple WiFi enabled devices while on the move through WiFi tethering [1], [2]. Such mobile hotspots are increasingly feasible today due to the high Internet connectivity speeds (3-6 Mbps uplink and 10-20 Mbps downlink) available through 4G/LTE cellular service [3]. According to a recent industry report [4], such mobile hotspot services are expected to increase significantly in the next 3-5 years.

WiFi tethering through mobile hotspots is applicable to a variety of WiFi devices, such as laptops, tablets, cameras, portable gaming systems, MP3 players, medical devices [5], [6]. Since mobile WLANs operate in the already crowded unlicensed spectrum, deployment of mobile WLANs pose potential interference problems if any fixed access points (APs) are present along the travel path of the mobile AP; one such example scenario is illustrated in Fig. 1(a). It is also possible that multiple mobile WLANs may interfere with each other (intra-mobile WLAN interference) as illustrated in Fig. 1(b). Both these interference scenarios (fixed-mobile and intra-mobile) may reduce the throughput at both, fixed and mobile APs.

This motivates us to study the performance of mobile WLAN hotspots in typical urban environments which have a high density of fixed WLAN APs. The primary goal of this study is to gain a better understanding of the performance degradation experienced by mobile WLANs due to interference from fixed network APs.

(a) A user traveling with a mobile WLAN from point A to B can be in range of a varying number of fixed WLANs



(b) Intra-mobile WLAN and mobile WLAN-fixed WLAN interference.

Fig. 1. Co-existing scenario of fixed and mobile APs

In this paper, we focus on the throughput performance of a single mobile AP co-existing with multiple fixed APs. We also propose a technique to mitigate interference and increase the data throughput at mobile APs. We specifically consider the following unique characteristics of mobile WLANs in our simulation based study:

1) *Limited backhaul capacity at mobile APs due to limitations in 3G/4G/WiMAX backhaul connections.* For example, 4G/LTE provides a median uplink and downlink throughput up to 6 Mbps and 13 Mbps respectively [7].
2) *Small number of clients (typically between 1 and 5) and smaller distances between AP and clients than*

traditional WLANs. In contrast, commercial enterprise WLAN management techniques typically deal with large number of clients spread out at various distances from the AP locations.

3) *Dynamic nature of interference due to mobility of the AP.* Moving APs can stay in or go out of range of multiple fixed APs and/or other moving APs.

Related Works: There exists a rich literature on the subject of fixed AP networks, including topics such as performance analysis of the channel sharing mechanism of 802.11 [8], effect of AP density on the client throughputs [9], and interference between overlapping managed networks [10]. In contrast, there has only been a few limited studies on mobile WLANs. In [3] the authors focus on the problem of energy efficiency for mobile hotspots, while Hare et al. studied network characteristics, usage characteristics and deployment feasibility for vehicular WiFi hotspots in [11]. For quality-of-service (QoS) constrained applications using mobile hotspots, Ando et al. propose a QoS control mechanism based on TCP [12]. In this paper, we particularly focus on the interaction between fixed and mobile APs; a topic which has not been explored so far.

The key contributions of this paper are as follows:

1) *Heterogeneous traffic condition analysis*: In a simulation based study, we analyze the performance of a mobile AP in the presence of multiple fixed APs. We consider an unsaturated traffic model for mobile APs in order to reflect the limited backhaul capacity constraint.
2) *Adaptive Channel Assignment (ACA)*: We show that by adapting the channel assignment based on fixed-AP interference, the throughput at mobile APs can be significantly improved compared to static channel assignment.
3) *Effect of mobile speed*: We study the effect of the speed of the mobile device on the potential gains offered by ACA and suggest a technique to set the ACA scanning interval as a function of the speed at which the mobile is moving.

The paper is organized as follows: Section II provides a discussion on the fixed/mobile deployment scenarios under consideration, and explains the Markov chain model that is used to analyze the coexistence of fixed and mobile APs. Section III presents the adaptive channel assignment (ACA) technique and the corresponding effect of density of fixed APs. Section IV shows the effect of the mobile speed on the performance gains obtained through ACA. Finally, Section V outlines the conclusions and future directions.

II. Modeling coexistence of fixed & mobile AP

A. Deployment of fixed and mobile AP

In our MATLAB based simulation study, we consider a random deployment of multiple fixed APs in a 10 by 0.5 sq. km area. The density of APs is varied to emulate a range of real-world deployment scenarios including highways, residential, and commercial areas. A single mobile AP follows a random trajectory in the given area. We assume that each AP chooses one of the three orthogonal WiFi channels in the 2.4 GHz range and the channel assignment at fixed APs is random. Also, all APs operate in the 'greenfield' or 'non-legacy support' mode of 802.11g, i.e., it assumes that there are no 802.11b devices present [13]. The carrier sense threshold of all APs is fixed at 215 meters [10]. For each fixed AP, the clients connected to it can be present at arbitrary distances; thus the channel rate cannot be assumed to be the maximum in all cases and is set to 12 Mbps for simulation purposes, considering an average case. On the other hand, clients of mobile APs are usually located in close proximity of the AP which makes possible for the AP to transmit at the maximum channel rate of 54 Mbps. Since we are primarily interested in the downlink scenarios, performance of an AP is evaluated in terms of the throughput metric. Table I summarizes the important simulation parameters used in this study.

TABLE I
SIMULATION PARAMETERS OF FIXED AND MOBILE AP

Parameter	Fixed AP	Mobile AP
No. of APs	N	1
Traffic Model	Saturated	Unsaturated (backhaul limit: 6 Mbps)
WiFi type	802.11g (green mode)	802.11g (green mode)
Parameters for 802.11g		
Channel rate	12 Mbps	54 Mbps
Header rate	6 Mbps	6 Mbps
ACK frame rate	6 Mbps	24 Mbps
σ	$9\mu s$	$9\mu s$
SIFS	$10\mu s$	$10\mu s$
DIFS	$28\mu s$	$28\mu s$
Other parameters		
MAC header	24 Bytes	
PHY header	16 Bytes	
H	PHY header @ Header bit rate, μs	
ACK	14 Bytes + PHY header @ ACK frame bit rate	
Propagation delay	1 μs	
L, length of packet	1020 Bytes @ channel bit rate, μs	
T_s	$H + L + SIFS + t_p + ACK + DIFS + t_p$, μs	
T_c	$H + L + ACKTimeout$, μs	

B. Heterogeneous Network

As mentioned earlier, mobile APs use 3G/4G/LTE connection for backhaul, for which the average download throughput is typically capped around 6 Mbps. Due to such limited backhaul capacity, a saturated traffic model, in which the incoming packet buffer at APs always remain full, cannot be assumed for mobile APs. This leads to a heterogeneous network with a mix of saturated and unsaturated nodes when mobile and fixed APs coexist in a region [14], [15]. Malone et al. [14] presents a Markov chain model of CSMA/CA that relaxes the restriction of saturated traffic conditions given in Bianchi's model [8] and allows nodes to have any specified traffic arrival rate, λ packets/sec. We have adopted the model given in reference [14] for the mixed scenario of fixed APs (saturated node with $\lambda \rightarrow \infty$) and mobile AP (unsaturated node with $\lambda = 736$ packets/sec as per the parameters described in Table I). In addition, we have modified the model to accommodate the different channel rates at fixed and mobile

AP, i.e., 12 and 54 Mbps respectively. A summary of the mathematical model is as follows:

$$
\begin{aligned}
P_{tr} &= 1-(1-\tau_1)^{n_1}(1-\tau_2)^{n_2};\\
P_{s1} &= \frac{\tau_1(1-\tau_1)^{n_1-1}(1-\tau_2)^{n_2}}{P_{tr}};\\
P_{s2} &= \frac{\tau_2(1-\tau_2)^{n_2-1}(1-\tau_1)^{n_1}}{P_{tr}};\\
\mathrm{E}[S] &= (1-P_{tr})\sigma + n_1P_{s1}P_{tr}T_{s1} + n_2P_{s2}P_{tr}T_{s2}\\
&\quad + ((1-\tau_2)^{n2} - 1 - P_{tr} - n_1P_{tr}P_{s1}) * T_{c1}\\
&\quad (1-(1-\tau_2)^{n_2} - n_2P_{tr}P_{s2})T_{c2};\\
S_i &= \frac{P_{s_i}L_i}{\mathrm{E}[S]};\\
S &= \sum_{i=1}^{n} S_i.
\end{aligned} \tag{1}
$$

where n_i is number of APs; τ_i is probability that AP transmits in randomly chosen time slot; P_{tr} is the probability at least one AP transmits in a given time slot; P_{si} is the probability that AP of type i successfully transmits in a given time slot; $\mathrm{E}[S]$ is the expected time per slot; T_{ci} is average time that channel is busy due to collision; T_{si} is average time that channel is busy due to successful transmission; S_i is the proportion of time that the medium used by node type i for successful transmission of data; L_i is the expected time spent transmitting payload data for node type i; S is the normalized throughput of the system. Here, index i assumes the values 1 and 2 for mobile and fixed APs respectively. In the modified model, T_{ci} is adjusted based on the source of packets (fixed or mobile or fixed-mobile) involved in a packet collision. The notations used are consistent to those used in Bianchi's model [8]. Also, for saturation conditions at all APs ($\lambda \to \infty$), the given model reduces to Bianchi's model.

C. Performance of Mobile APs

Using the given simulation parameters, we evaluate the downlink throughput performance of a single mobile AP based on a Markov chain model of CSMA/CA (refer to Eq. 1) as a function of the number of fixed APs $N = \{0, \ldots, 15\}$ where N fixed APs are present in carrier sense range of the mobile AP. From Fig. 2, it is observed that as the number of fixed APs increases, the throughput at the mobile AP decreases exponentially: from 4.18 Mbps for $N = 1$ to 0.26 Mbps for $N = 15$. We will use this preliminary results in the later sections.

III. Adaptive Channel Assignment

Unlike enterprise WLAN APs, commercially available mobile APs currently do not incorporate any dynamic channel adaptation schemes, possibly because of their simplified, small form-factor, and low-cost design. In this section, we study a basic frequency planning technique applicable to mobile APs, called 'Adaptive Channel Assignment' (ACA). Adaptive channel selection capability is incorporated in most fixed APs even though it not invoked very often; for example the popular least congested channel selection (LCCS) scheme on most Cisco-Linksys APs are only invoked when the AP is power cycled [16]. Under the ACA scheme, the mobile AP scans each channel from a candidate channel-set (here, orthogonal channels 1,6, and 11 in the 2.4 GHz band) and logs the number of unique beacons per channel. Based on the measurements, the AP changes to a less-crowded channel if the number of estimated APs on that channel is less than that of its current operating channel.

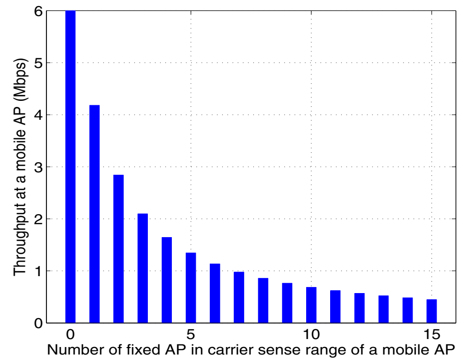


Fig. 2. Throughput at a mobile AP as a function of number of fixed APs in the carrier sense of the mobile AP.

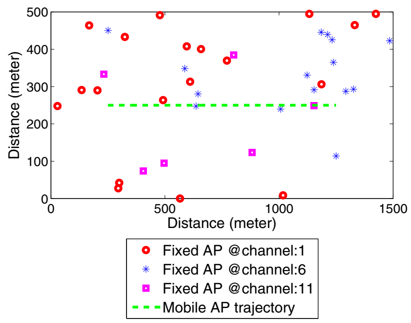
A. Increase in throughput at mobile AP

Performance of Adaptive Channel Assignment (ACA) at a mobile AP is illustrated by considering one instance of the deployment of fixed APs as shown in Fig. 3(a). In this scenario, the mobile AP follows a specific trajectory (as per Fig. 3(a)) of length 1 km with a pedestrian speed of 2 m/s. For the results presented in this section, ACA scanning and switching interval is fixed at 1 sec, but we study the effect of varying the inter-scan interval in Section IV. Fig. 3(b) and 3(c) show the quasi-static throughput performance of mobile APs due to ACA compared to the case when mobile APs are statically connected to one of the three WiFi channels. Since ACA continuously updates the WiFi channel to the one which results in the least amount of interference at the mobile AP, it shows significant improvement in the throughput performance of mobile AP over the traversed distance. Thus, we can infer that mobile APs need frequent updates in the selection of WiFi channel as they change their positions.

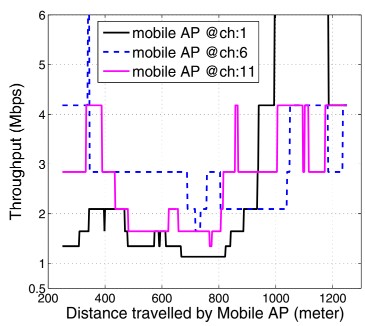
B. Effect of density of fixed APs

The performance of mobile APs using ACA is compared with the case when a static channel is assigned at mobile APs and throughput at mobile APs is averaged over 3 possibilities of static channel assignments with varying density of fixed APs. For this simulation, we consider the same trajectory length of 1 km, and mobile speed of 2 m/s (4.5 miles/hr) as described in the Sec. III-A. The number of fixed APs is varied from 10 to 120 APs/km^2. Results are calculated for 20,000 runs of simulation for each density.

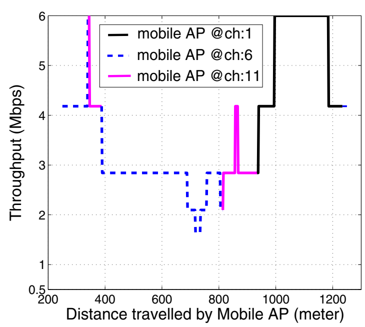
Fig 4(a) plots the average throughput at the mobile AP for static and adaptive channel assignments, where the throughput



(a) Random deployment of Fixed APs and the trajectory of the mobile AP.

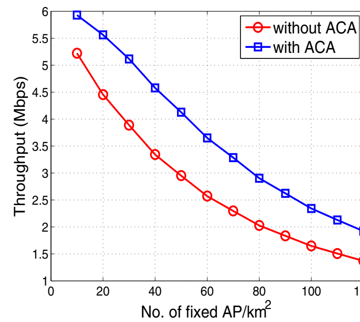


(b) Throughput at mobile AP with static channel assignment

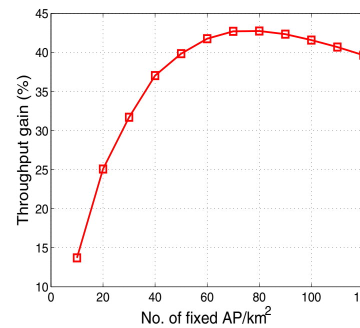


(c) Throughput at mobile AP with ACA

Fig. 3. Application of Adaptive Channel Assignement (ACA)



(a) Throughput (Mbps) at mobile AP with and without application of ACA



(b) Percentage improvement in throughput at mobile AP due to ACA

Fig. 4. Increase in throughput at mobile AP due to Adaptive Channel Assignment (ACA) as a function of the number of fix APs/km^2

values are averaged over the trajectory distance. The results show that average throughput at the mobile AP with static channel assignment is in the range of 1.37 to 5.22 Mbps for the AP densities under consideration. With the application of ACA, these throughput values increase to 1.92 and 5.93 Mbps respectively, achieving a maximum gain in throughput of 1.24 Mbps. The percentage throughput increase as a function of AP density is shown in Fig.4(b). For lower density values, the interference offered at a mobile AP due to fixed APs is already low; thus the gain due to ACA is low as well. But as the density of fixed APs increases, interference at the mobile AP becomes significant and gains due to ACA are relatively large. The percentage gain in throughput, however saturates around 42% at the density of 70 APs/km^2. At this density, all channels are so congested that adapting the channel does not provide increasing benefit. Further increase in the density, thus results in lower gains.

IV. Adaptive Channel Assignment with High Mobility

In Section III the throughput evaluations considered a quasi-static model where the mobile AP was considered to move at a pedestrian speed of 2 m/s. But in general, mobile APs may move with much higher speeds, especially in the case of vehicular mobile hotspots. Also, in the previous sections we showed that the frequent updates of the WiFi channel can mitigate interference at mobile AP, which subsequently improves the performance at mobile AP. But this involves overheads due to channel scanning and reassignment which needs to be considered for a more accurate evaluation of the performance with ACA. The channel switching time for the 802.11 hardware chips is usually low (for example less than 1ms for the Atheros AR9462 chip [17]), but scanning multiple channels and measuring the number of beacons on each channel results in a significant overhead in the system.

During channel scanning, channel load can be estimated by two methods: (1) dwelling on each channel long enough to estimate the channel free and channel busy fractions and (2) listening for beacons from co-channel APs. The method of load estimation depends on the sensing deployment system; thus the scanning time would vary from system to system. To simplify the analysis, we assume that the total scanning time required to estimate the load on all channels and connect on the channel with the least load is 200 ms. Since the AP cannot scan channels and transmit data at the same time, the throughput at the mobile AP is considered to be zero during this duration. For example, let us consider the earlier example where the channel was scanned for ACA every second. At this scanning interval, the average throughput at the mobile AP gets reduced by 20% because of the scanning overhead. Thus, in order to better understand this tradeoff between the throughput loss due to scanning and the throughput gain due to changing to a better channel, we measure the performance of the ACA scheme while varying the scanning period (i.e. the time period between two successive scans).

In this simulation study, the average throughput of a mobile AP is evaluated over a 10km trajectory with varying ACA channel scanning period between 1 and 20 seconds. For each value of the scanning period, the resulting throughput values are averaged over 10, 000 simulation runs. Results are plotted for four mobility speeds, s, 16.2, 32.4, 64.8 and 97.2 km/hr (10, 20, 40 and 60 miles/hr respectively) as shown in Fig. 5, keeping the density of fixed APs constant at 50 APs/km^2.

If ACA is not used and instead the channel assignment is done at random, average throughput at mobile AP is 2.94 Mbps. This can be considered as a baseline for comparison with ACA results with varying scanning periods. For all considered values of mobility speed, a common trend is observed for the relation between the average throughput at a mobile AP and the ACA scanning period. As the scanning period increases, the throughput at the mobile AP increases as the loss in throughput during the scanning time of 200 ms decreases. The throughput values attain a local maxima at certain values of the scanning periods (which depends on the speed of the mobile AP), and then starts a gradual decline. This reduction in throughput stems from the fact that with longer scanning periods, the mobile AP is using a non-optimal channel for longer durations.

We note that local optima of average throughput is obtained at different value of scanning interval for given values of s. For $s = \{16.2, 32.4, 64.8, 97.2\}$ km/hr, local optima is observed at scanning intervals $10, 7, 5, 4$ seconds respectively. This can be explained by the fact that at higher speeds, the mobile AP moves a greater distance between scans, each channel assignment ceases to be optimal more quickly. Thus, we conclude that scanning interval in ACA needs to be updated depending on mobility speed.

V. Conclusion and Future Work

In this paper, we have presented a model for mobile WLAN performance in presence of densely deployed fixed WLAN access points. It is shown that the throughput at mobile APs may degrade significantly due to interference from fixed APs and that performance can be improved using adaptive channel assignment techniques. The coexistence scenario of fixed and mobile APs needs to be further extended considering factors such as mobility, mobile node density and mutual interference between fixed and mobile APs. We are currently working on experimental validation of the analytical framework presented in this paper, and on studying other resource allocation problems in the light of mobile APs.

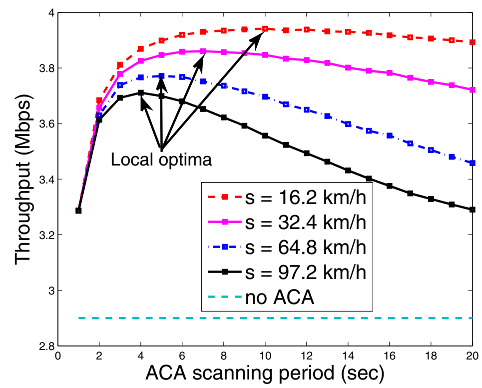


Fig. 5. Throughput at mobile AP (Mbps) when ACA is applied, as a function of ACA scanning period (sec) for a fixed density of 50 APs/km^2

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