Understanding Channel Selection Dynamics in Dense Wi-Fi Networks

Akash Baid and Dipankar Raychaudhuri

ABSTRACT

This paper aims to explain and analyze a growing problem in dense-urban wireless networks, that of co-existence between low-cost residential access points (APs) and actively-managed service provider APs in overlapping spatial, frequency, and time domains. Through detailed simulations and testbed experiments, the impact of increasing density of highly-adaptive service provider APs on the performance of typical residential APs is measured in terms of their respective channel assignment schemes. Simulation results with dense deployment of up to 500 APs/sq.km. show the benefits of centralized channel assignments, even in the presence of independent APs. In addition, it is shown that for a fixed AP density, an increase in the percentage of AP under the centralized scheme results in an increase in the throughput of surrounding independent APs. The broader implications of the simulation findings are discussed in order to develop a better macro-level understanding of dense Wi-Fi networks.

INTRODUCTION

Since their introduction in the early 2000s, the deployment of wireless local area networks (WLANs) has been constantly growing. While most urban residences and offices now already use WLANs, the recent spurt in WLAN density has been due to large-scale deployments by mobile operators and broadband Internet providers, collectively termed as service providers (SP) Wi-Fi [1]. This rapid rise in the number of Wi-Fi access points (APs) has led to an interesting mix of deployments where residential, enterprise, and SP APs operate on the same spectrum (and can thus interfere with each other), but enterprise and SP APs are actively managed and can usually adapt to interference much better than residential APs due to better and more expensive hardware and software. Figure 1 shows the combined percentage of enterprise and SP access points (of the total APs observed) in a representative 1 sq. km. area of four major US cities, as per the crowd-sourced WiGLE.net database [2]. A clear trend of an increasing percentage of "managed WLANs" can be observed, especially since the beginning of 2012.[1]

Since the coverage regions of the enterprise/SP APs often overlap with that of residential APs, this growth in actively managed APs can result in performance problems for the residential APs. An immediate example of the potential problem is the disparity between the channel selection schemes used in residential and managed WLANs. Most low-cost residential APs either operate on a fixed channel or change channels only upon power cycle, while most enterprise and SP APs incorporate centralized, adaptive channel assignment schemes. Thus in areas where both types of APs are present, the residential APs can potentially be cornered into higher interference channels, while the managed APs adapt their channels in response to interference. In this paper we target such mixed-deployment problems and build the understanding toward the key question: *What is the impact of the increasing density of highly-adaptive enterprise/service provider APs on the performance of typical residential APs and vice versa?*

In order to measure the performance of different types of APs in extremely dense networks, we extend Liew's Maximum Independent Set (MIS) model for channel share estimation [4]. In their seminal paper (which has since laid the foundation for throughput-optimal CSMA [5]), Liew *et al.* proposed an approximate but highly-accurate technique to calculate the channel share of an AP given the contention graph of the nodes surrounding that AP. Using the original MIS model for dense network graphs comprising hundreds of nodes runs into computational bottlenecks since the process involves finding all maximum independent sets of a graph, a classical NP-hard problem with a long standing bound of exponential complexity [6]. As such, in this paper we propose an approximation mechanism to parametrize the balance between computational complexity and desired accuracy.

Using this approximation technique, we measure the performance of a typical centralized channel assignment algorithm in the presence of a varying number of residential APs through dense-deployment simulations. The simulation scenarios are designed to reflect the current deployment mix in urban areas (5–25 percent managed and the rest residential), and also the possible continuation of the trends shown in Fig. 1, for example 50–75 percent managed APs. Different channel assignment schemes are assumed for the low-cost residential APs, in particular, static default, random, and least congested channel schemes. A key finding from the

Akash Baid and Dipankar Raychaudhuri are with Rutgers University.

Research supported by NSF EARS grant CNS-1247764.

[1] The percentage share of managed WLANs is calculated by matching the first three bytes of the logged MAC addresses with the IEEE OUI record of the top ten enterprise/SP WLAN vendors. Since there are other enterprise/service-provider WLAN vendors, the percentage share estimated here is a lower bound. See [3] for further details.

0163-6804/15/$25.00 © 2015 IEEE

simulations is that, while the trend of an increasing percentage of managed APs would improve the overall utilization of the ISM band, at high densities the existing managed APs would perform worse and the existing residential APs would perform better. The intuition behind this result is that, to an extent, the better performance of the managed APs over residential APs is because of the non-optimal choices made by the latter; and as more and more APs improve their resource-usage choices, the potential gains for managed APs is reduced due to the overall capacity of the spectrum being bounded.

The key contributions of this paper are:

- We propose a parametric approximation scheme to extend known channel estimation models for extremely dense network graphs. The key parameter in the model controls the tradeoff between accuracy and computation time.
- We study the performance of Wi-Fi APs in homogeneous as well as mixed settings, i.e. a fraction of APs in a region use simple static channels, while others are managed by a central controller.
- We highlight the issue of inverse correlation between the percentage of managed APs and their performance relative to non-managed APs through both simulation and experimental results.
- We discuss the broader implications of the observed results in terms of the performance of unlicensed band nodes in dense settings.

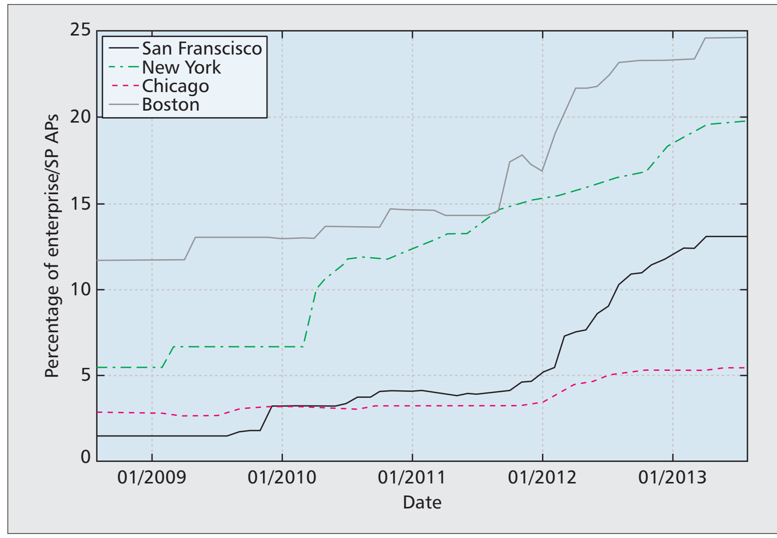

Figure 1. Percentage of APs from enterprise/SP WLAN vendors out of all observed APs from the WiGLE.net database [2].

Modeling AP Channel Share in Dense Deployments

The number of available channels in Wi-Fi is substantially less than what is required to build a conflict-free graph in dense settings. Hence all practical channel assignment schemes must assign the same channel to multiple APs in range of each other. A channel assignment scheme working with k available channels converts the distance-based graph, i.e. one in which an edge exists between two nodes if they are in carrier sense range of each other irrespective of the operating channel, to k derived-graphs. A node appears in derived-graph i if it has been assigned channel i, and a link in the original distance-based graph is transferred to the derived-graph i only if both its end-points are in i. Given such derived-graphs, a general model for the channel share of each AP as per the underlying CSMA protocol has proven to be extremely elusive, except for the case of a completely connected graph for which Bianchi's work provides an accurate model [7]. For a completely connected graph with N nodes, the channel share of each node comes to approximately $1/N$.

Liew's MIS Model

Liew *et al.* [4] proposed the following simple technique to calculate the approximate channel share of each node. Given a contention graph, first calculate its maximum independent sets (MISs). An independent set is a set of vertices, no two of which are connected by a link in the graph, and the maximum independent sets are such sets with the highest number of elements. The normalized throughput of each node in the graph is then given by the ratio of the number of MISs that node appears in to the total number of MISs. Performance results from experiments done with physical Wi-Fi devices have been shown to closely match the estimates given by this MIS model [4].

While being derived from a theoretical analysis of the underlying CSMA networks, the key intuition behind the accuracy of the MIS model is that among the 2^N possible states comprised of each node of a N node graph being on or off, the CSMA protocol largely favors the "greedy" states, i.e. the states that result in the maximum number of nodes transmitting simultaneously. Further, all such greedy states are equally probable, and thus the throughput of each node is dependent on how many greedy states it appears in, relative to the total number of such states.

Parametric Approximation of the MIS Model

Although simple to reason about, the problem with utilizing this MIS model is that computing all maximum independent sets of a graph is a classical NP-hard problem with a longstanding bound of exponential complexity [6]. As such, we propose the following approximation mechanism to parametrize the balance between computational complexity and desired accuracy.

Since computing the MISs of the complete graph is computationally expensive, we use the same MIS model per node over a neighborhood-graph centered around each node. The neighborhood-graph is defined by a parameter termed *span* which can range from 0 to the diameter of the graph. For a selected span s, the neighborhood-graph of a node i is formed of all the nodes at a graph-distance of less than or equal to s. For each node j at a distance exactly equal to s from node i, all directly connected nodes that are not already included in the neighborhood-

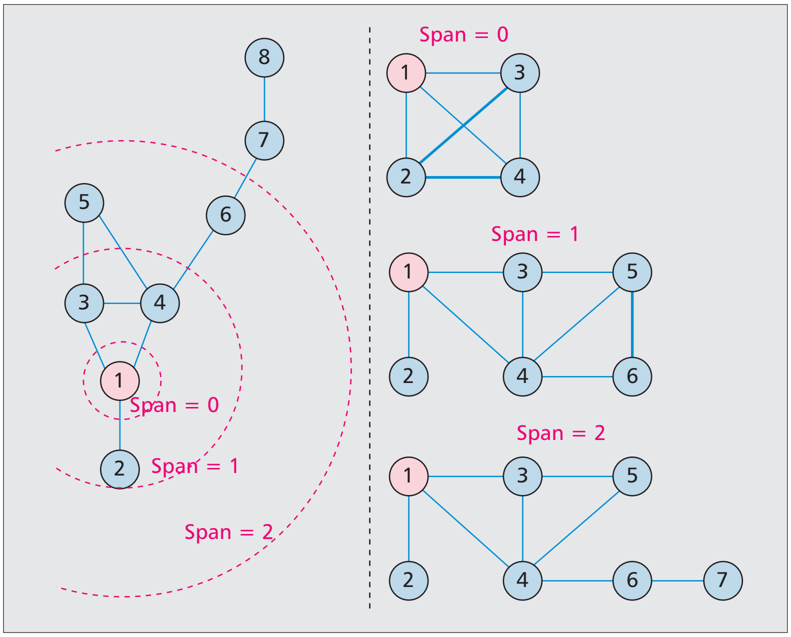

Figure 2. Formation of the neighborhood-graph for approximating the MIS model.

graph of i are added to it but the connectivity between such nodes is assumed to be a clique. The process is illustrated in Fig. 2, which shows the process for building neighborhood-graphs of different spans around node 1. Note that for the span 0 graph, nodes 2, 3, and 4 are included but links 2–3 and 2–4 are added even though they are not present in the original graph.

The intuition behind the step of clique-formation at the edge of the span is to invoke the standard $1/N$ model beyond the point of the neighborhood-graph. This results in the computed channel share to be exactly equal to that found through the $1/N$ model for span 0 and equal to that derived from the MIS model for maximum span. Figures 3a and 3b show the mean error compared to maximum span, and the time required for computation respectively when varying the span from 0 to 2 and the number of nodes in the graph from 20 to 50. All values are averaged over 100 random initiations of the graph. As is clear from these plots, while computing the span 0, i.e. the $1/N$ model is extremely fast, it can result in large errors; increasing the span decreases the error but results in a corresponding increase in the computation time. For a given application, the value of the span parameter should be chosen according to the requirements of accuracy and computation time. For all the simulation results presented next, we use a value of $span = 2$ since for the size of the graphs considered, a higher span results in prohibitively larger computation times.

Analyzing Channel Assignments in Mixed Deployments

The approximate MIS model defined earlier provides a scalable mechanism to estimate the saturation throughput of APs given the deployment topology and the channel assignment. In this section, we use that model to study the performance of different channel assignment mechanisms under different assumptions about the mix of residential vs. enterprise/hotspot APs.

Simulation Description

All results presented in this section are based on MATLAB simulations of dense AP deployments in a 1 sq. km. area. To exactly model the performance perceived by clients in a realistic deployment, the simulation must consider, at the least:

- Environment-dependent pathloss, shadowing, and multipath, including wall losses.
- The number, placement, and capabilities of client devices.
- The offered load and its variation for each client.
- The policy of the AP for scheduling multiple backlogged clients (note that this is not specified by the 802.11 standard).
- Capture effect, based on relative signal strength and timing of interfering signals.

Accounting for all these factors can make the simulations extremely intractable, especially when simulating extremely dense deployments. As such, we consider a much simplified simulation setting that retains the qualitative nature of the tradeoffs involved but admittedly misses some of the finer nuances involved in wireless communications.

In order to focus on node-starvation and similar network-level effects, we limit the granularity of simulations to APs, i.e. measuring the throughput achieved at each AP instead of each client. This relieves us from the task of modeling AP load-distribution policy, client locations, and capabilities. We assume a downlink saturation scenario, which translates to the assumption of each AP always having one or more connected clients whose data demand is enough to prevent the AP from being idle when it gets access to the channel. We consider a purely distance-based interference model. If two APs are within carrier sense range (assumed to be 100 meters), there exists a link between them in the contention graph. Each channel assignment scheme is assumed to be working with three orthogonal channels, as in the 2.4 GHz band. Similar results can be obtained for a regime with more channels or with non-orthogonal channels by considering a channel overlap dependent sharing model [8].

Metrics: Normalized Throughput and Starved Nodes — We use two key performance metrics throughout this study. The first metric is mean normalized throughput received by an AP. As mentioned above, the throughput "received by an AP" reflects the combined throughput that all clients connected to the AP would be expected to receive. The term normalized is used to indicate that all throughputs are expressed as a fraction between 0 and 1; an AP with a normalized throughput of 1 gets access to the channel 100 percent of the time, whereas a normalized throughput of 0 indicates that the AP never sees the channel free for transmission. This is calculated using the approximate MIS model described earlier. The other metric we focus on is the percentage of starved nodes, as estimated from the MIS model. A channel

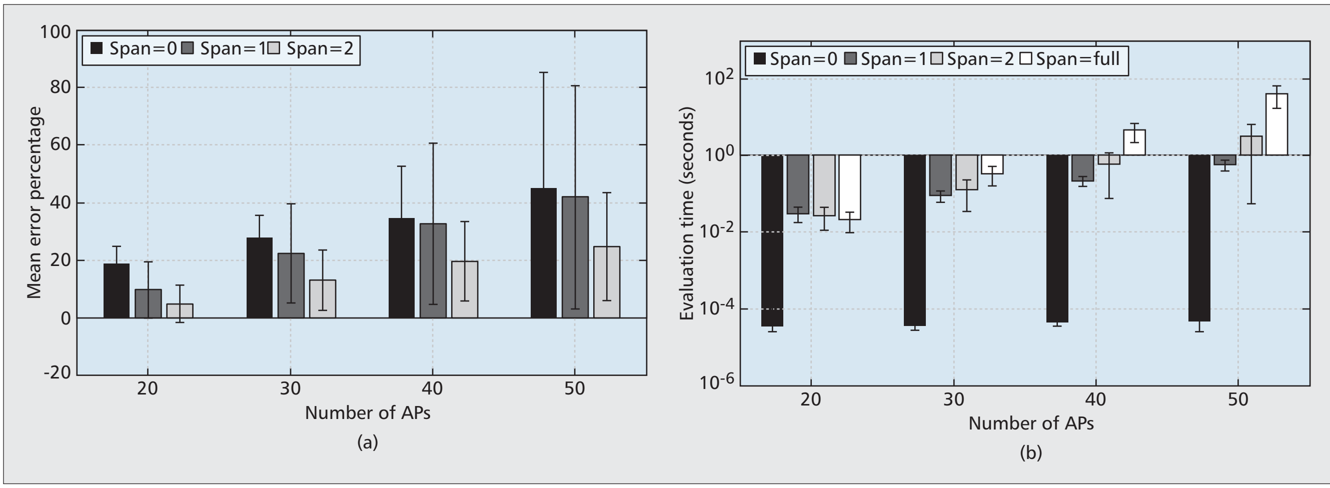

Figure 3. Performance of the approximation algorithm for different spans: a) error percentage compared to max span; b) evaluation times for different spans.

assignment scheme can result in a starved node if the neighborhood contention graph around the node is such that the node receives a much smaller share of the channel. We want to emphasize that although the MIS model would estimate a zero throughput for such a node, it is only applicable in scenarios where all nodes have saturation traffic over a long period of time. Since in reality some nodes may be intermittently idle, these starved nodes might get access to the channel during the idle-times of other nodes. Nonetheless, from a deployment perspective, the starved nodes identified by the model would be topologically vulnerable to performance problems and would offer very low throughput to connected clients during times of peak traffic, i.e. near-saturation load.

Simulation Results: Homogeneous Settings

We first benchmark the performance of three channel assignment strategies in homogeneous settings, i.e. all nodes follow the same algorithm:
- Random channel: each AP independently selects one of the three available channels respectively.
- Local selection: APs are deployed sequentially, and each AP selects the least congested channel from a local viewpoint.
- Centralized assignment: a single entity assigns the channel for all APs using a commonly used, greedy graph coloring heuristic [9].

In most real-world scenarios the number of available channels are far fewer than that required for completely conflict-free coloring. Thus this heuristic employs a multi-pass approach in which every pass involves identification of the most "saturated" node, i.e. the node with the largest number of already colored neighbors, and then assigns it a color that is least used among its neighbors. These three strategies are an extremely small subset of a vast trove of research as well as production algorithms for channel selection in wireless networks, including distributed schemes that specify optimal decisions for individual APs without the need for explicit cooperation [10]. However, these can serve as simplified representative strategies that occupy very different points in the space of possible channel assignment algorithms.

Figure 4a shows the mean normalized throughput at an AP for the three channel assignment schemes listed above. Each point shown in the plots is the average of 1000 simulations runs with AP locations chosen from a uniform random distribution within the simulation area of 1 sq. km. for each run. An interesting insight from this result is that a simple random channel selection performs reasonably well, especially in extremely dense settings since the gains from an optimal choice of channel is vastly reduced if all channels are almost equally crowded. However, in moderate densities (100–200 APs/sq.km), the centralized algorithms result in sizable gains of up to 30 percent. The gains from the centralization can be seen more prominently in terms of the starved node metric. Figure 4b shows the mean percentage of starved nodes (out of all nodes in the simulation) for varying densities. The performance of the random and local assignment schemes as per this metric generally follows the same trends as observed in Fig. 4a. However, the centralized assignment results in substantially fewer starved nodes at all densities.

Simulation Results: Mixed Settings

Next we consider deployments where different APs in range of each other use different channel assignment schemes. In reality, the number of different channel selection algorithms is bounded only by the number of different vendors (we observed more than 500 different vendors in the WiGLE.net dataset used in Fig. 1, and hence a myriad of scenarios with various permutations of AP locations and channel assignment schemes can arise). To make this analysis tractable for simulations, we compare the scenarios in which all APs under consideration either set channels based on a single centralized scheme or follow a different scheme independently. In practice, this assumption translates to the case of a single regional service assigning channels to all APs in

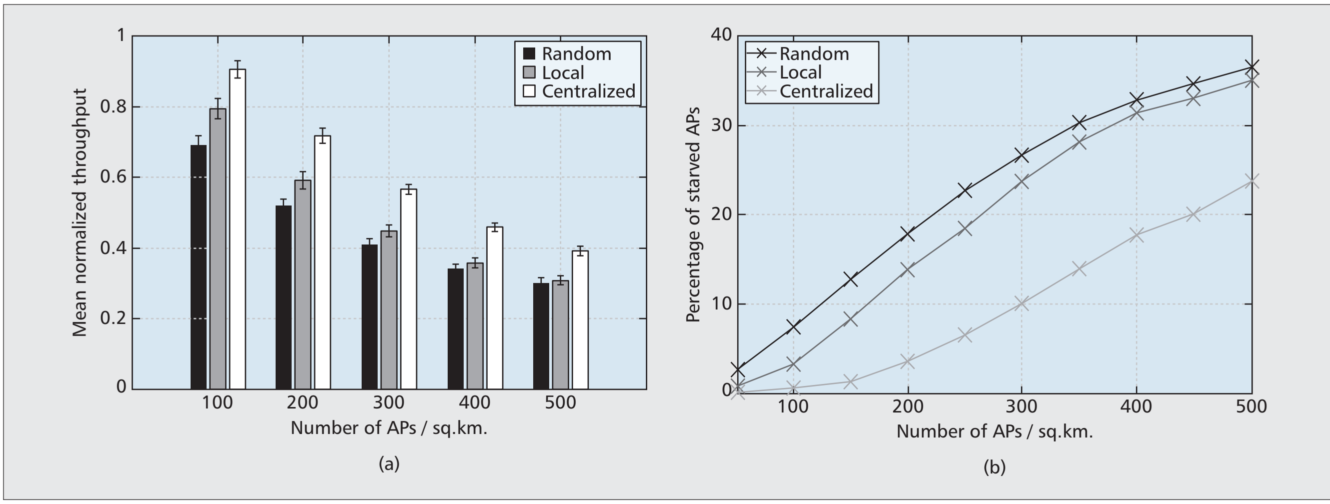

Figure 4. Comparison of channel assignment schemes in homogeneous settings: a) normalized throughput; b) starved nodes.

the region, except for a varying number of non-subscribers. Alternatively, this is also applicable when the same fraction of APs implement a distributed version of a centralized algorithm by cooperating through a database service such as the TV White Space database [11].

The ratio of the number of APs following an independent scheme to those under the centralized scheme is varied from all APs belonging to one camp to all APs belonging to the other camp in step size of 5 percent of the total APs in consideration. For each ratio, 1000 simulation runs are performed where APs are deployed randomly and the independent group is chosen at random after the deployment. The centralized algorithm described above is used for the single centralized group, while three different assumptions are made for the independent group: random, local assignment, and same (all APs choose the same channel, for example channel 6 by default). Since the local assignment scheme involves scanning all channels locally for counting the number of neighboring APs on each channel, additional assumptions need to be made about the order in which the centralized and local assignments occur. For this, we assume that the APs in the independent group are turned on sequentially after the centralized group has fixed its channels. However, since we want the independent and centralized groups to reflect the behavior of low-cost residential APs and actively-managed hotspot APs, respectively, we assume that the local assignments, once made, remain fixed, while the centralized assignments are re-computed after the deployment of the local group.

Figure 5 shows both metrics described for the cases of random, local, and same channel assignments for the independent group. For each plot in these figures, the averages are computed over all the APs in the simulation, i.e. APs from the independent group and the centralized group together, and the shaded regions show the standard deviation around the mean values. The trends across all the cases are similar. There is a gradual increase in performance, in terms of both throughput and number of starved nodes as the ratio of APs acting independently is decreased. In other words, when deployment scenarios evolve from completely independent operation to a completely cooperative regime, throughput gains of the order of 40 percent and 15 percent are possible for the random and local assignments, respectively. The gains in terms of alleviating starved nodes are more pronounced, approximately 4x and 3x, respectively, for the same scenarios as above. Another interesting point to note here is that the performance of the centralized algorithm falls very gracefully in the presence of an increasing number of APs that are outside its control, as observed from the smooth nature of all curves. The extreme scenario of all independent nodes choosing the exact same channel is shown in Figs. 5e and 5f. As can be expected, the gains from all nodes using a centralized algorithm compared to individual operation are more here, approximately 2x in terms of mean throughput and 9x in terms of percentage of starved nodes.

The results above suggest that if the deployment trends shown in Fig. 1 continue, i.e. the percentage of more actively managed cooperating APs increases, the overall performance of APs will improve. However, when the same results are broken into the performance of the independent APs and the cooperating APs measured separately, a more nuanced view emerges. Figure 6a shows the breakup of the mean throughput between the two groups for a particular simulation: a mix of centralized and same channel APs with a density of 200 APs/sq. km. This shows that for a given density, as the percentage of independent APs decreases, the performance of the centralized APs also decreases, whereas that of the independent APs increases. This somewhat counter-intuitive result arises from the fact that when only a few APs make a smart choice about the channel in the presence of many "dumb" APs, they get more room to optimize the channel selection process. In other words, the worse performance of the independent APs in a setting with mostly independent APs is partially due to inefficient crowding of these APs onto certain channels, leaving more channels open to those APs that can sense and decide, whereas when only a few APs make sim-

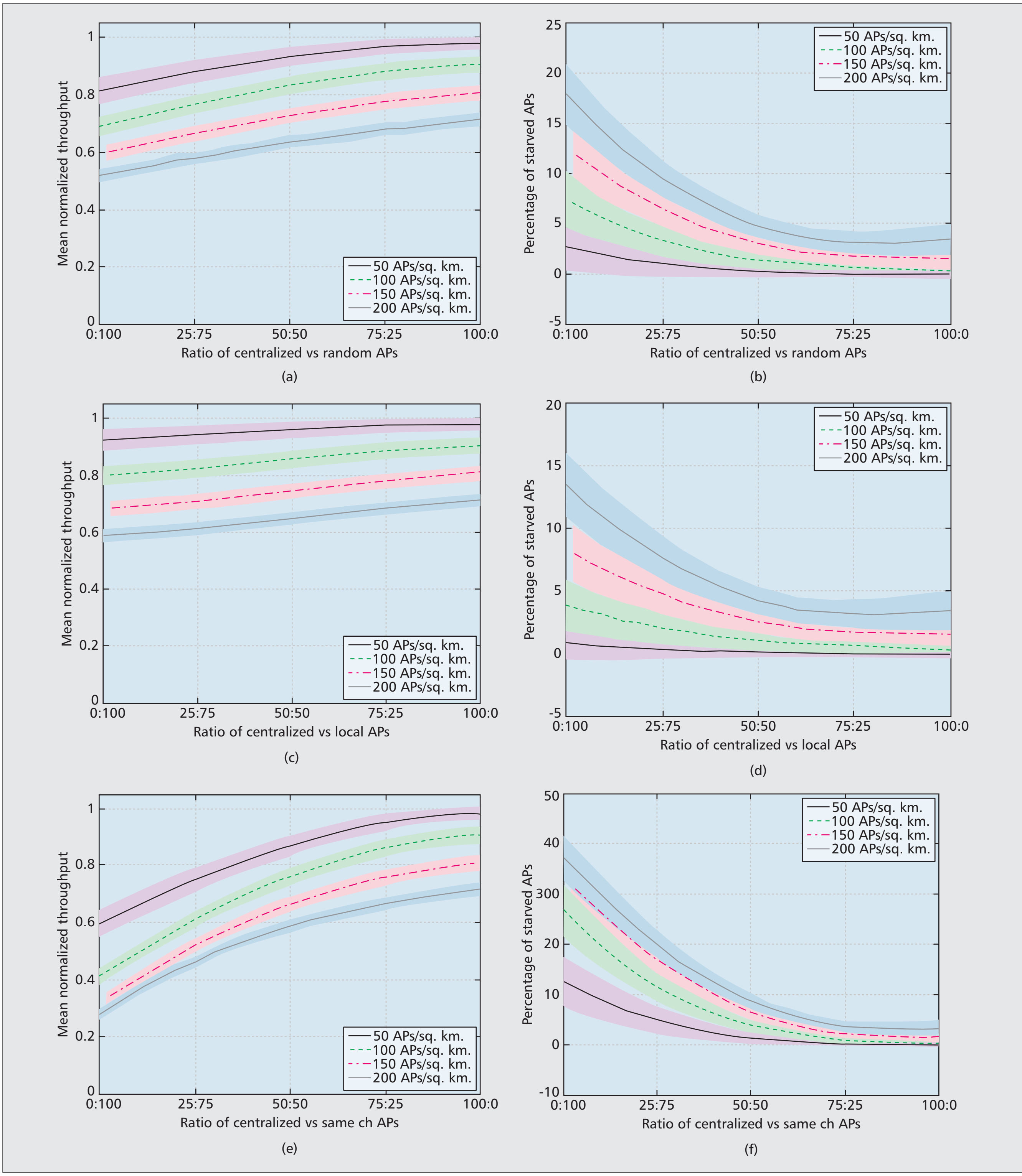

Figure 5. Performance under mixed deployment scenario. Figures a) and b): centralized vs. random; c) and d): centralized vs local; e) and f): centralized vs. same.

ple, static choices, the penalty of those choices is less severe since the centralized APs can sense and adjust their own channels accordingly.

Experimental Validation of Results

We performed a set of experiments with eight hardware nodes in order to verify the relation between the percentage of centralized nodes and their performance, observed in Fig. 6a. We use an eight-node attenuator system available as a part of the ORBIT lab facility [12]. This measurement system consists of eight Linux boxes, each of which has an Atheros 5212/5213 mini-PCI card and an Intel 6250 mini-PCIe 802.11/802.16 card. The nodes are enclosed in an RF enclosure that provides 80 dB of isolation,

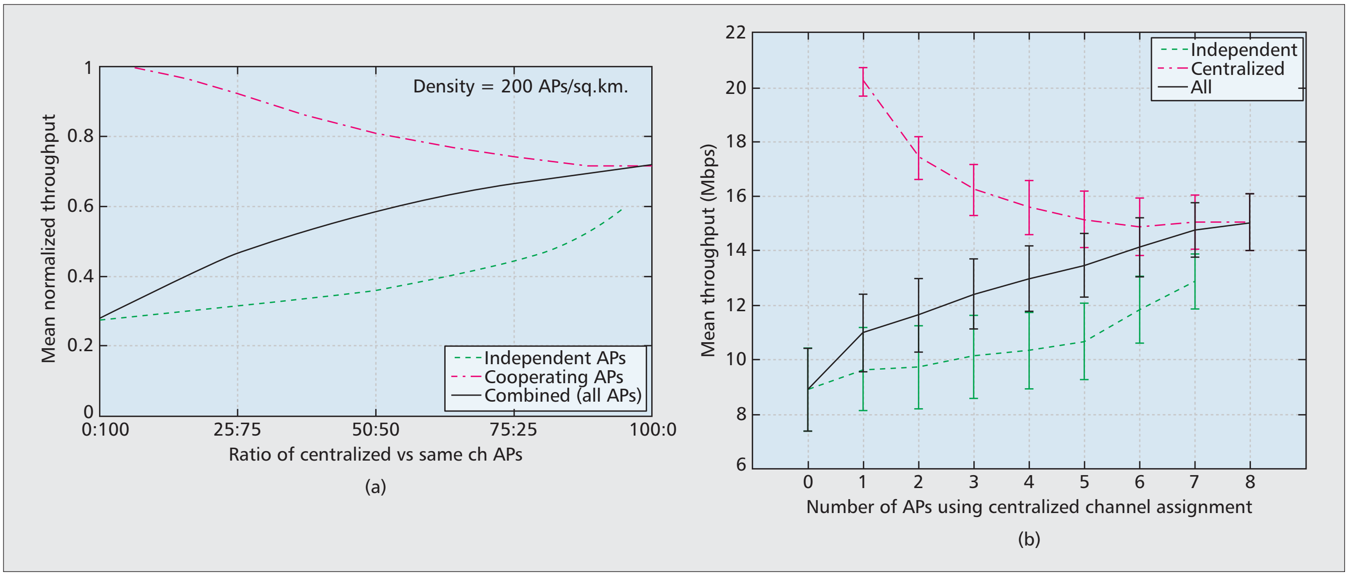

Figure 6. Breakdown of the performance gain — increasing percentage of centralized APs leads to increasing performance of the independent APs: a) simulation results; b) experimental validation.

whereas all the input/output ports of the wireless cards are connected through a programmable attenuator. This setup provides a way to create arbitrary topologies (within the operating range of the attenuators) in a stable manner. Further details about this setup are available at [13].

For these experiments, we first randomly select 100 topologies out of the 11,117 connected topologies that are possible in a graph of exactly eight nodes [14]. The reason for this subsampling is that each experiment takes a considerable amount of time and the error margins obtained by averaging over 100 topologies seemed within acceptable bounds. For each topology, we run nine different experiments in which we vary the number of APs, choosing a constant fixed channel from 0 to 8 in increments of 1. Channels for the remaining APs in each experiment are assigned using the centralized-MIS scheme.

Figure 6b shows the performance of independent nodes, centralized nodes, and that of all nodes combined. As observed in the simulation results, this figure indicates that as the fraction of nodes that are under centralized control increases, the room for improvement in their performance decreases. Specifically, across 100 different topologies, the throughput obtained by a single "smart" AP in presence of seven other APs, all of which select the same channel, is on average 20 Mbps, whereas when all eight APs are under the same centralized channel assignment scheme, the average throughput of each AP is about 15 Mbps, indicating a ~25 percent drop in performance.

Implications and Discussions

In this paper we have highlighted the problem of co-existence between low-cost residential APs and actively-managed service provider APs in dense urban deployments. While several past works on heterogeneous radios have focussed on the interaction of different transmission technologies such as Wi-Fi, Bluetooth, and ZigBee, we study one specific difference that arises within Wi-Fi APs: the manner in which their channels are set. The vast difference in the cost and complexity of different APs poses a problem of unequal and unfair distribution of resources, especially in dense settings where performance is largely dependent on the number and type of other devices in the vicinity. We provide a detailed description of the simulation setup in order to encourage further studies of macro-level characteristics in dense wireless networks. Such simulations require abstraction of a number of finer aspects of the wireless medium, but enables the study of inter-linked mechanisms that can sometimes reveal counter-intuitive results. The simulation results presented in this paper lead to the following broader perspective and discussion points.

- Liew's MIS model for the channel share of a CSMA node, and the approximation of that model, shows that the performance of Wi-Fi APs can be greatly affected by the specific topology that happens to have formed due to other APs in its vicinity. The presence or absence of a single AP a few hops away can change the maximum independent sets of the graph and consequentially the channel share of an AP. Limiting the *span* around each node in the model can reduce the computation time but leads to larger approximation errors.
- In dense wireless network studies, starved nodes, i.e. nodes that are topologically vulnerable to performance problems, could be an important metric of interest. While under realistic traffic conditions these nodes might achieve nonzero throughput, the system design should aim at minimizing the number of such nodes since they will be prone to low channel share as and when traffic nears saturation.
- Increasing density of APs leads to substantial reduction in the average performance of channel selection schemes, and at 400-500 APs/sq.km. there are no benefits of a local chan-

nel selection strategy since random selection works equally well. Centralized channel assignment, on the other hand, helps at all densities, especially in terms of the starved node metrics.

• While the increase in the number of APs leads to lower performance for all APs, the residential APs would in fact be better off if new APs in their vicinity use a centralized infrastructure for channel planning, as compared to the new APs also being residential APs with fixed/local channel selection schemes.

An important extension of the problem as well as the simulation setup would be to consider multiple disjoint networks, each using the same or different centralized channel assignment algorithms. In general, it is not obvious to predict whether performance will still be close to the case of a single central agency, or will resemble that of local independent selections. Further work in this regard can also consider other radio resource allocation problems such as rate control, power control, and client-AP association optimization.

REFERENCES

[1] S. Gundavelli *et al.*, Service Provider Wi-Fi Services over Residential Architectures, IETF Internet Draft, draft-gundavelli-v6ops-community-wifi-svcs-06.txt, Apr. 2013.

[2] WiGLE: Wireless Geographic Logging Engine, http://www.wigle.net/.

[3] Visualization of Wi-Fi Deployment over the Years for Different Cities in the US, http://www.winlab.rutgers.edu/baid/apViz.html.

[4] S.-C. Liew *et al.*, "Back-of-the-Envelope Computation of Throughput Distributions in CSMA Wireless Networks," *IEEE Trans. Mobile Computing*, vol. 9, no. 9, 2010, pp. 1319–31.

[5] L. Jiang and J. Walrand, "A Distributed CSMA Algorithm for Throughput and Utility Maximization in Wireless Networks," *IEEE/ACM Trans. Net.*, vol. 18, no. 3, June 2010, pp. 960–72.

[6] I. M. Bomze *et al.*, "The Maximum Clique Problem," H*andbook of Combinatorial Optimization*, Kluwer Academic Publishers, 1999, pp. 1–74.

[7] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE JSAC*, vol. 18, no. 3, 2000, pp. 535–47.

[8] A. Mishra, S. Banerjee, and W. Arbaugh, "Weighted Coloring based Channel Assignment for WLANs," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 9, no. 3, July 2005, pp. 19–31.

[9] J. Riihijarvi, M. Petrova, and P. Mahonen, "Frequency Allocation for WLANs Using Graph Colouring Techniques," *Proc. 2nd Annual Conf. Wireless On-demand Network Systems and Services (WONS)*, 2005, pp. 216–22.

[10] D. Leith and P. Clifford, "A Self-Managed Distributed Channel Selection Algorithm for WLANs," *4th Int'l. Symp. Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, Apr. 2006, pp. 1–9.

[11] "In the Matter of Unlicensed Operation in the TV Broadcast Bands: Third Memorandum Opinion and Order," Federal Communications Commission, Apr. 2012.

[12] D. Raychaudhuri *et al.*, "Overview of the ORBIT Radio Grid Testbed for Evaluation of Next-Generation Wireless Network Protocols," *Proc. IEEE WCNC*, 2005, vol. 3, pp. 1664–69.

[13] Sandbox 4 at ORBIT, http://bit.ly/1eeYi2w.

[14] Information System on Graph Classes and Their Inclusions, http://www.graphclasses.org/smallgraphs.html#nodes5.

BIOGRAPHIES

AKASH BAID (baid@winlab.rutgers.edu) is a network software engineer at Tarana Wireless. This work was part of his Ph.D. research at the Wireless Information Network Laboratory (WINLAB) at Rutgers University. He received his B.Tech degree in electronics and communications engineering from the Indian Institute of Technology Guwahati in 2008, and the M.S. and Ph.D. degrees in electrical and computer engineering from Rutgers University in 2010 and 2014, respectively.

DIPANKAR RAYCHAUDHURI [F] (ray@winlab.rutgers.edu) is a distinguished professor of electrical & computer engineering, and director of WINLAB (Wireless Information Network Lab) at Rutgers University. Dr. Raychaudhuri has previously held corporate R&D positions in Iospan Wireless, NEC USA C&C Research Laboratories, Broadband Communications Research, and Sarnoff Corp. He obtained his B.Tech (Hons) from the Indian Institute of Technology, Kharagpur in 1976, and the M.S. and Ph.D. degrees from SUNY, Stony Brook in 1978 and 1979, respectively.

While the increase in the number of APs leads to lower performance for all APs, the residential APs would in fact be better off if new APs in their vicinity use a centralized infrastructure for channel planning, as compared to the new APs also being residential APs with fixed/local channel selection schemes.