

# Understanding the Effectiveness of a Co-located Wireless Channel Monitoring Surrogate System

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**Abstract**—In Wireless Local Area Networks (WLANs), channel management is important in achieving reliable data communications and satisfying QoS requirements. The key aspects of wireless channel management are monitoring the channel quality and adapting quickly to the network conditions by switching to a better channel. We propose a wireless channel monitoring system with co-located monitoring surrogates. Our system works on multi-radio Access Points (APs) where a co-located surrogate radio monitors the condition of various channels while the master radio serves the clients for data communication. Although we have designed our system for generic WLANs, we believe it will be most useful for IEEE 802.11n networks where there are a large number of channels and dynamic frequency selection is required. Our system enables intelligent, fast channel adaptation, reduces service disruption time, and consequently helps realize the performance potential of 802.11n. We present our multi-radio co-located wireless channel monitoring surrogate system and evaluate its effectiveness on our IEEE 802.11n network testbed. We also perform case studies to demonstrate the benefit our system brings compared against the existing schemes.

## I. INTRODUCTION

With the advance of wireless communications and networking technology, the popularity and the deployment of WLAN are still increasing. People not only expect wireless coverage, but also high bandwidth and uninterrupted service for applications such as video conferencing and live media streaming. One of the main challenges in providing high performance wireless networks is overcoming the variation of the wireless channel condition. In order to provide reliable connectivity and QoS, the wireless APs and clients switch the channel when the system performance degrades or a military radar is detected in the UNII-2 band. When selecting a new channel, the quality of all available channels must be scanned. As a wireless radio can only transmit or receive on one channel, during the channel scanning, data communication must stop, and this leads to disruption of connectivity and service.

The IEEE 802.11n [1] is gaining momentum as it provides improved capacity and coverage over the legacy 802.11a/b/g. 802.11n networks are deployed mostly in the 5 Ghz band as the 2.4 Ghz band is crowded with the legacy 802.11b/g and Bluetooth devices, and microwave signals. Channel management is very important in reaching the potential of 802.11n

systems, especially in the 5 Ghz band due to a large number of channels<sup>2</sup> and the Dynamic Frequency Selection (DFS) [2].

We propose a wireless channel monitoring system with co-located monitoring surrogates. Our system works on multi-radio APs [3], [4] where the co-located surrogate radio monitors the condition of various channels while the master radio(s) serve the clients for data communication. We do not require the clients to be equipped with multiple radios.

Most current multi-radio network channel management solutions intersperse channel monitoring between data communications; all radios are primarily used for data communication and must cease data communication when scanning the channels. Hence, they suffer from long service disruption time when switching the channels. Moreover, increasing the number of radios increases the capacity, but does not reduce the disruption time. Other solutions [5] deploy a dedicated monitoring infrastructure that is separate from the service infrastructure. As the monitoring sniffer is not co-located with the communication radio, the measured channel quality could be different from that of the actual data link.

Our co-located surrogate wireless channel monitoring system reduces the service disruption time and provides fresh information of all available channels that are essential when selecting a channel. Our system also enables role reversal between the master and the surrogate radios that further reduces the disruption time.

Our contributions are: (i) we measure and analyze the various components that add to the service disruption time during channel migration, (ii) propose a channel monitoring system that reduces the service disruption time from the order of minutes to milliseconds, (iii) present 802.11n testbed results that show the link qualities measured by the co-located radios are mostly within 2 dB difference, and (iv) perform two case studies to evaluate the throughput and disruption time tradeoff of our system.

The rest of the paper is organized as follows. We present our co-located wireless channel monitoring surrogate system in Section II. We study the effectiveness of our system on our 802.11n testbed in Section III. Case studies are presented in Section IV and related work is surveyed in Section V. We conclude in Section VI.

This work was performed when Sungjoon Choi was an intern at HP Labs, prior to his employment at Microsoft.

<sup>2</sup>In the US, there are 24 orthogonal channels in the 5 Ghz band and 3 orthogonal channels in the 2.4 Ghz band. The AP scanning time of all 27 channels is at least 2.7 seconds with a 100 ms beacon period.

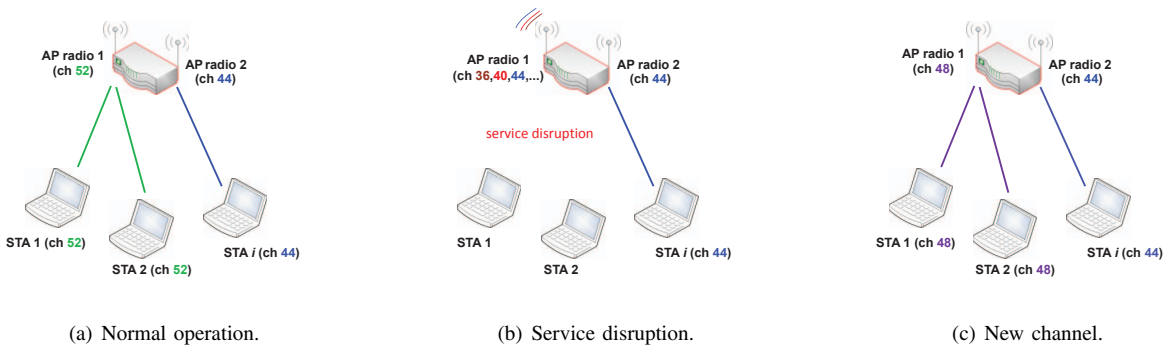


Fig. 1. Traditional multi-radio WLAN system.

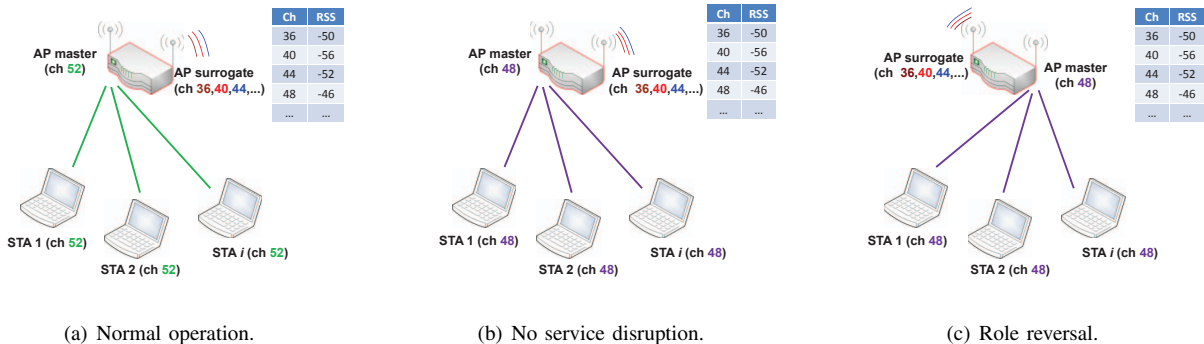


Fig. 2. Co-located surrogate system.

## II. MULTI-RADIO WIRELESS CHANNEL MONITORING SYSTEM

Our system uses multi-radio APs where the “master” radios communicate data and the co-located “surrogate” radio monitors the quality of channels. All wireless channel monitoring activities are handled by the surrogate while the master radio(s) serves the clients without disruption.

Let us compare our system with a typical multi-radio WLAN system using a two-radio AP example. Fig. 1 (a) shows the normal operation where both radios are involved in data communication, with each operating on different BSSs (Basic Service Set) and non-overlapping channels. Suppose the quality of the channel where radio 1 resides in degrades drastically or a radar signal is detected. In Fig. 1 (b), radio 1 stops data communication and scans the available channels. During this scanning time, the clients associated with this radio have their service disrupted. Radio 1 selects a new channel after scanning and resumes serving its clients in Fig. 1 (c).

Fig. 2 (a) depicts our system where only the master radio provides connectivity to the clients. The surrogate radio continuously scans the channels and updates the channel condition table that includes RSS (Received Signal Strength), channel busy time, and the list of APs and clients operating on the channels. When the master radio needs to select a new channel, it looks up the channel table and immediately switches to a new channel, thus reducing the disruption time, as shown in Fig. 2 (b).

When switching to a new channel, we can further decrease the switching latency by reversing the roles between the master

and the surrogate radios, as the two radios are co-located. Instead of the master radio performing the channel switch, it becomes the surrogate and starts monitoring the channels. The previous surrogate radio chooses the new channel and serves the clients on this new channel by becoming the master radio. This role reversal is illustrated in Fig. 2 (c). The handoff of clients from one radio to the other co-located radio can be implemented on top of existing fast layer-2 roaming schemes such as 802.11 pre-authentication [6].

One might argue that devoting a radio for channel monitoring is an expensive solution. However, when the network has a large number of channels to monitor and requires to perform DFS, we argue that efficient channel management is critical in achieving high performance. Moreover, there are APs with 16 radios already in the market [4], and dedicating one of many radios to monitoring is not costly in terms of throughput. In Section IV, we study how much capacity our system sacrifices as we vary the number of radios in the AP.

## III. MEASUREMENT-BASED EVALUATION

We evaluate the effectiveness of our system by performing channel quality and service disruption time measurements on our IEEE 802.11n network testbed. We use dual-band 802.11n mini-PCI card with Atheros AR9160 chipsets on Soekris net5501 boards equipped with three dual-band antennas.

### A. Link Quality of Co-located Radios

The success of the surrogate solution depends on the high-fidelity between the master and the surrogate radios; the interference estimated by the surrogate should be close to the one

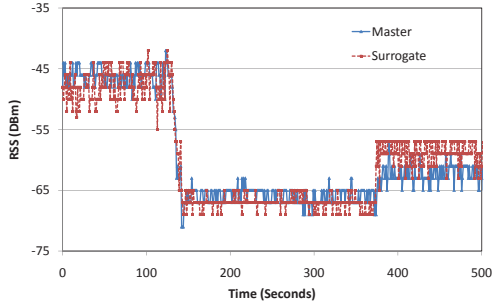


Fig. 3. Link qualities of the master and the surrogate over three different locations.

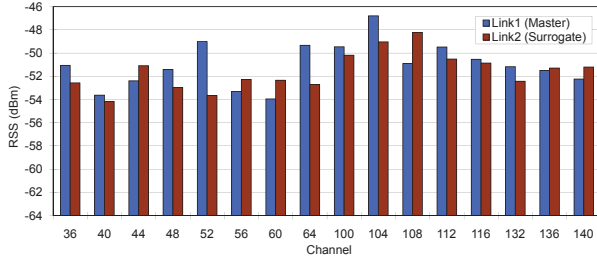


Fig. 4. Link qualities of the master and the surrogate over different channels.

experienced by the master. We conduct testbed experiments in which two co-located 802.11n MIMO (Multi-Input Multi-Output) radios measure the RSS of the same packet. The two radios are placed within a few inches of each other. The testbed is composed of one sender and two co-located receivers that each plays the role of the master and the surrogate radios of an AP. Two experiments are performed: (i) we move the location of the receiver pair while the sender location is fixed and (ii) we change the operating channel while all nodes are stationary. The measurement is performed at night when there is almost no people movement. We average the RSS of 600 received packets during one minute.

Fig. 3 shows the result with different locations and Fig. 4 with different channels. We observe that the RSSs from the co-located radios are very similar although RSSs change over different locations and channels. We see from Fig. 3 that the RSSs change drastically when the receivers move at time around 130 seconds and 370 seconds. However, the difference in RSS between the receivers remains small during the movements, with the average and the median difference of only 2.5 dB and 2 dB, respectively.

The results from Fig. 4 lead us to two conclusions. First, the link quality changes significantly over different channels. The RSSs of the surrogate link exhibit more than 7 dB difference between channels 60 and 104. Because a large portion of the wireless links have marginal RSS and frame reception ratio [7], that level of RSS difference ( $> 7$  dB) can alter the link connectivity and a link may lose its connectivity if the channel switching is not done carefully. Thus, when selecting a new channel, the quality of all considered channels for a given sender-receiver link must be known.

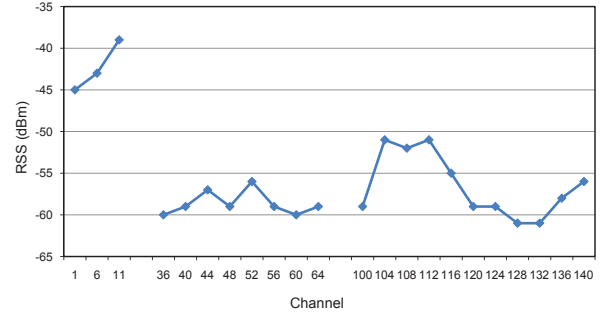


Fig. 5. RSS over different channels.

Second, the co-located radios experience similar quality on the same channel. Except for one channel (Channel 52), that has near 5 dB difference between the two radios, the average and the median gap between the master and surrogate RSSs is 1.6 dB and 1.3 dB. Hence, we believe the channel quality estimated by the surrogate is a good indicator of the channel quality for the master. When the role switching between the master and the surrogate is performed, the estimated channel quality becomes more accurate, as the radio that conducted the monitoring is now used for data communication.

The above observation is contrary to the previous reports [8] that showed the link quality varies when a radio on one end of the link pairs up with different radios on the other end of the link. We believe the difference stems from MIMO antenna diversity of our 802.11n testbed. The Atheros chipset we use provides the RSS of a received packet as the average RSS from the three receive antennas.

### B. Link Quality Variance over Channels

We observed from Fig. 4 that the wireless link quality varies over different channels. In order to quantify this observation, we measure the RSS of a link over multiple channels in 2.4 GHz and 5 GHz bands. During the measurement over multiple channels, both the sender and the receiver of the link are stationary and the measured RSSs in one channel are relatively stable with about 2 dB fluctuation. The sender transmits at its highest default transmission power setting. Fig. 5 shows the average RSS of 300 packets received for 30 seconds. The largest difference is about 10 dB between channels 112 and 128, and the difference is larger in the 5 GHz than the 2.4 GHz channels.

We need to consider the channel propagation model when analyzing the link quality variance over different channels. The RSS is a function of multiple factors.

$$RSS = P_t + G_t + G_r - PL \quad (1)$$

where  $P_t$  is the transmission power,  $G_t$  and  $G_r$  are the transmit and the receive antenna gains, and  $PL$  is the path loss. All four factors are affected by the channel frequency. Different frequency bands have different maximum transmission power limitations. For example, if a radio transmits at the maximum power limit of each channel, the transmission power driven to its antenna in channel 36 will be 13 dB less than in channel 149.

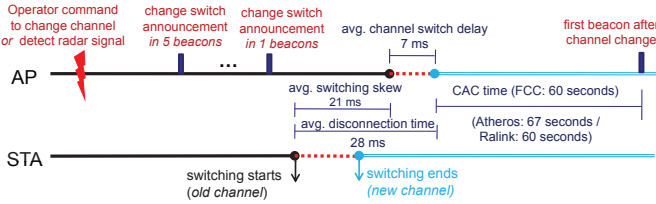


Fig. 6. Channel switching delay and CAC time with Atheros wireless cards.

One can expect a gradual decrease of RSS as the channel number (frequency) increases within the same band but such a pattern is not observed. Instead, we see random fluctuations over channels. We believe that the TX/RX gains also play an important role. Every antenna is designed to be the most effective at some frequency bands. Even dual-band antennas can not resonate well at all of the claimed frequency range. For example, the specification of the antenna we used claims 5 dBi and 3 dBi gains for 2.4 GHz and 5 GHz, respectively [9] and we believe its gain varies over multiple channels even in the 5GHz band. In addition, amplifier and other analog components in the radio interface are affected by the frequency change.

The path loss  $PL$  is frequency-dependent by its nature. Not only the propagation loss over the air but also the penetration loss through hard materials increases as the frequency increases. The center frequency difference between the lowest and the highest channels in the 5 GHz band is 625 MHz which is large enough to create notable changes in path loss. We reason that the higher transmission power limit and the smaller path loss in the 2.4 GHz band are the major contributors that result in higher RSSs than in the 5 GHz band.

### C. Dynamic Frequency Selection

Another important issue for all wireless devices operating on the 5 GHz UNII-2 band is the DFS. When an AP selects a new channel in the UNII-2 band, it can transmit on the channel only when no radar signal above a threshold power is detected for 60 seconds. This period is the Channel Availability Check (CAC) time.

If a radar signal is detected during the operation on the channel, the entire cell must migrate to a different channel within 10 seconds. This is the channel move time. The data traffic can be transmitted for a maximum of 200 ms (European standard requirement is 260 ms) after the radar detection, and the rest of the channel move time is used for management frame transmissions. The channel where a radar signal resides in is removed from the available channel list for at least 30 minutes. This duration is the non-occupancy time.

The CAC time contributes to the service disruption time more than the other DFS overheads; the channel move time and the non-occupancy period come into play only when a radar signal is detected. On the other hand, APs and clients can not exchange data traffic during the CAC time whenever the system newly selects a channel in the UNII-2 band triggered either by a DFS operation or a channel management decision.

As shown in Fig. 6, the Atheros card used in our testbed waits for 67 seconds for CAC, which is compliant to the

standard of at least 60 seconds. We also measured the CAC time of another 802.11n card from Ralink [10] (RT2870 chipset) and it was shown to be 60 seconds.

Our surrogate monitoring system reduces or eliminates CAC time. When the master detects a radar signal, it switches to a new channel. If the surrogate has monitored the new channel for more than the CAC time, the master uses the new channel instantly without stopping the data communication.

### D. Channel Switching Delay

As shown in Fig. 6, the atomic channel switching operation itself can cause disruption. We measure the switching delay time between the last frame in the old channel and the first frame in the new channel. From 20 measurements, the switching delay is about 7 ms on average. The station always switches to the new channel before the AP and the average gap is 21 ms. Thus, the total disconnection time is about 28 ms which would cause TCP to suffer from packet drops and perform slow start especially in a short RTT connection.

In our system, the channel switching delay is reduced by reversing the roles between the master and the surrogate radios. The surrogate waits in the new channel for the clients migrating from the old channel and serves the clients instantly. In the example of Fig. 6, the total channel switching delay experienced by the clients is reduced from 28 ms to 7 ms.

## IV. CASE STUDIES

We now present case studies that analyze the amount of disruption time our system reduces in building a network interference map and assess the amount of capacity our system sacrifices.

### A. Interference Map Generation

When assigning a channel to a cell in WLANs with multiple APs, we must know which APs and clients interfere with the cell. This is because even when two APs do not interfere with each other, clients associated with one AP might interfere with the other AP or its clients. The previous “client-aware” channel assignment algorithms [11], [12] assume the knowledge of the interference map that indicates the interference relation of any two nodes in the network. They use active probing to build the interference map or assume it is given by the client reporting feature of IEEE 802.11k [13]. In both approaches, APs and clients must stop data communications to scan the channels. This service disruption time increases drastically as the number of nodes and channels increases. In our system, as the surrogate radio performs the channel monitoring and collects the information needed to build the interference map, the communication need not stop.

We compare the service disruption time of various interference map generation schemes. The disruption time comparison is presented in Table I, where the total channel scan time consumed by all  $N$  APs and  $M$  clients is calculated when

TABLE I  
DISRUPTION TIME COMPARISON.

Scheme	Disruption time	AP ↔ AP	AP ↔ Client	Client ↔ Client
SMARTA	2409 sec ≈ 40 min	$(N(N-1)/2)T_p = 19$ sec	$NMT_p = 400$ sec	$(M(M-1)/2)T_p = 1990$ sec
RSS-based method + 11k clients	1050 sec = 17.5 min	$(C-1)T_a = 10.5$ sec	$(C-1)T_c = 1050$ sec, $(C-1)T_a = 10.5$ sec	$(C-1)T_c = 1050$ sec
AP Surrogate Radio	0	0	0	N/A
AP Surrogate + 11k clients	1050 sec = 17.5 min	0	0	$(C-1)T_c = 1050$ sec

TABLE II  
PARAMETERS.

Notation	Description	Value
N	Number of APs	20
M	Number of clients	200
C	Number of 5 GHz channels	22
$T_a$	AP scanning time in a given channel	500 ms
$T_c$	Client scanning time in a given channel	50 sec
$T_p$	SMARTA link probing time	100 ms

there are  $C$  channels.<sup>3</sup> We consider a typical enterprise WLAN scenario with 20 APs and 200 clients. The parameters and the values used in this comparison study are listed in Table II.

1) *SMARTA*: SMARTA [11] sends a set of active probes to detect interference relations of the nodes. The total service disruption time is 40 minutes. Note that SMARTA tests must be conducted in an interference-free environment where all nodes stop data transmissions during the tests.

2) *RSS-based Method*: Another way to create an interference map is to have every node passively scan a channel for a specified period to detect a list of APs and clients and measure RSSs from them. We assume 802.11k client reporting feature is utilized to enable APs to request their clients to scan the given channel. We define two parameters –  $T_a$  and  $T_c$  – to denote the required monitoring time to find APs and clients in a channel, respectively. Here, we set  $T_a$  as 500 ms and  $T_c$  as 50 seconds based on our measurements.

In order to detect interference between APs, every AP scans each  $C$  channels for  $T_a$ . Because an AP can monitor the channel it operates on without disruption, the total disruption time each AP suffers from is  $(C-1)T_a$ . Similarly, to measure interference from APs to clients, each client leaves its channel and scans  $C-1$  channels for  $(C-1)T_a$ . To measure interference from clients to APs, each AP scans for  $(C-1)T_c$ . To measure the client-to-client interference, which is possible via 802.11k, each client scans for  $(C-1)T_c$ . Note that an AP and a client simultaneously can monitor a channel and detect the APs and clients in the channel. Thus, the disruption time of each AP and client is bounded by  $(C-1)T_c$  as  $T_c$  is larger than  $T_a$ . With the parameters we set in Table II, each AP and client has the same disruption time of 17.5 minutes. Note that unlike SMARTA, this disruption time is applied to each node independently without requiring the entire network to stop and participate in the measurement. If we assume bidirectional link connectivity (or interference) between APs and clients, the disruption time for each AP is drastically reduced to  $(C-1)T_a$  of 10.5 seconds.

During the AP's scan time, no clients associated with the AP

<sup>3</sup>For simplicity, we assume the link quality measured on one channel is used for generating the global interference map. If we consider the link quality variance over different channels as discussed in Section III-B, the disruption time of all schemes will increase approximately by a factor of  $C$ .

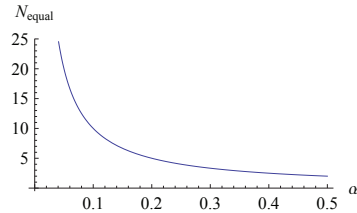


Fig. 7.  $N_{\text{equal}}$  with varying value of  $\alpha$ .

can communicate data. On the other hand, during the client's scan time, the client's AP can communicate with other clients. Thus, the disruption of AP has a larger impact than the clients on the system performance. Regardless, the AP disruption time of 17.5 minutes during the data service will result in serious performance degradation.

3) *Surrogate Radio*: To detect interference between the APs, the surrogate radio of each AP performs the scanning of  $C-1$  channels while the master radio serves its clients. Hence, the service disruption time is zero. The surrogate radio also measures interference from the clients during the channel scanning, and no service disruption occurs when measuring the interference from the clients to the APs. To measure the interference from the APs to the clients, the surrogate radio generates the 'Measurement Pilot' frames in the  $C-1$  channels so that the clients operating in those channels measure the RSSs from the surrogate radio and report them back. The Measurement Pilot frame is defined in 802.11k and it provides a subset of the information provided in the Beacon frame. If 802.11k is not supported by the clients, we can assume bi-directional interference relations and use the client-to-AP interference measurements to infer the AP-to-client interference. Regardless, the clients need not leave their channel and hence zero disruption time.

Because we assume the use of surrogate radios only for APs and not clients, the client-to-client interference measurement overhead is not applicable to the surrogate solution. When 802.11k is supported, its client-to-client overhead is the same as the RSS-based method.

## B. Throughput with Multi-Radio APs

Using multiple radios has been a popular technique in increasing the network throughput. One instantiation of a multi-radio system is to distribute the clients associated with the APs over different radios working over orthogonal channels. We compare the throughput achieved by such traditional multi-radio networks with that of our surrogate approach. Let us assume a network with backlogged stations where the nodes always have data to transmit and the maximum achievable throughput with one AP radio is given by  $B_{\text{SingleRadio}}$ . The  $B_{\text{SingleRadio}}$  can only be achieved if there is no interference or channel quality degradation. In case of channel quality



degradation, assume that the degradation event happens every  $T_{\text{BadEvent}}$  and it takes  $T_{\text{DisruptionTime}}$  to scan and switch to a better channel. The average throughput achieved by such a system is  $(1 - \alpha)B_{\text{SingleRadio}}$ , where  $\alpha$  is the ratio of  $T_{\text{DisruptionTime}}/T_{\text{BadEvent}}$  and should be less than 1. Similarly a system with  $N$  radios can achieve throughput of  $N(1 - \alpha)B_{\text{SingleRadio}}$ . In our approach, one radio is used as a monitoring surrogate and does not transmit data. Our system reduces the disruption time, including the CAC, from in the order of minutes down to milliseconds. Hence we set the disruption time for our system to *zero* for the simplicity of analysis. Thus the throughput achieved by an  $N$  radio system using our approach is  $(N - 1)B_{\text{SingleRadio}}$ . As the value of  $\alpha$  grows, the throughput of the traditional system decreases while the throughput of the surrogate system does not change.

The channel scanning time increases with the number of available channels. Similarly the frequency of channel switching can change with the degree of interference and channel quality variance. Hence different systems will have different values of  $\alpha$ . For a given  $\alpha$ , the number of radios at which the throughput of the two systems are the same,  $N_{\text{equal}}$  can be derived as  $N_{\text{equal}} = \frac{1}{\alpha}$ , which is shown in Fig. 7. When  $N$  is larger than  $N_{\text{equal}}$ , the system with our surrogate monitoring approach outperforms the traditional multi-radio system. For example, when  $\alpha$  is 0.2, a system with five or more radios per AP will benefit from increased system throughput when assigning one surrogate monitor radio.

## V. RELATED WORK

Research in multi-radio networks has focused on channel assignment, scheduling, and routing [14]–[16]. In these schemes, multiple radios are operating on orthogonal channels and each radio is responsible for data communication and monitoring. Our scheme differs from these work as we devote a radio for channel monitoring.

Signal power leakage was demonstrated using 802.11a/b/g experimental testbed [17]. It was shown that nearby radios operating on orthogonal channels can interfere with each other, and the degree of interference depends on the hardware vendor. Our 802.11n experiments showed that signal power leakage was small and does not significantly affect our findings.

Jigsaw [5] uses a dedicated monitoring infrastructure that is deployed separately from the service infrastructure. This solution is different from ours as its monitoring sensors are not co-located with the master APs, and can be implemented on top of our surrogate monitors.

A recent study [8] measured interference in 802.11a/g multi-radio networks. It showed that the same link yields varying quality over different channels, which we also observed in our study. It also showed that the link quality varies when the same interface pairs up with different interfaces. Our 802.11n testbed showed contrary results and we believe the difference stems from the MIMO antenna diversity of 802.11n instead of the SISO (Single-Input Single-Output) link of legacy 802.11a/g radios.

## VI. CONCLUSIONS

We presented a co-located surrogate channel monitoring system for WLANs. By having a surrogate radio continuously monitor the channels, the master radio serves its clients without disruption even when it switches to a new channel. Using our 802.11n testbed measurements, we demonstrated the importance of channel monitoring and showed our proposed system can be effective and reduces the service disruption time. The channel quality difference between the master and the surrogate radios is typically below 2 dB, and the disruption time is reduced from minutes to milliseconds.

Some multi-radio APs in the market are equipped with directional antenna arrays [4]. Our evaluation is based on omnidirectional antennas, and extending our proposed surrogate radio solution to the directional antenna systems is our future work.

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