A High Density (HD) Indoor Multi-Radio WLAN Testbed

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Abstract

The growing adoption of 802.11 networks in the enterprise segment has led to the emergence of High Density (HD) WLAN scenarios where large (100-1000) numbers of clients are serviced by 10-100s of APs in a multi-cell environment. This leads to an interference limited environment due to limited spectrum availability; hence network design for throughput scalability becomes the primary design challenge. Broadly speaking, we espouse ***adaptive tuning of 802.11 PHY/MAC parameters*** such as receiver sensitivity, clear channel assessment (CCA) threshold and link rates to improve network throughput for any network topology, traffic and interference conditions. This work seeks to corroborate, via measurements on an experimental multi-radio tested, an algorithm for CCA threshold adaptation based on our earlier work [2, 4].

***Index Terms*— System design, Network performance, Physical carrier sense, Clear channel assessment, Receiving Sensitivity, Spatial reuse**

I. Introduction

The rapid growth in mobile client handheld computing-cum-communication devices with embedded 802.11 radios has contributed to proliferation of 802.11 Wireless LAN (WLAN) networks in diverse environments beginning with the home, spreading to public hotspots and now, the enterprise. In the enterprise segment (and also possibly in public arenas with multiple WLAN providers with their own separate network domains that are un-coordinated), the inter-AP separations can be as small as a few meters [1], whereby co-channel interference is the dominant impairment. Traditionally, 802.11 networks for isolated single hot-spots (such as the individual home) have been designed based on RF site-survey for coverage, whereby a minimum received signal strength (RSSI), and hence a minimum link rate per end user is provisioned over the desired region. This approach is inappropriate for High Density (HD) WLAN networks where improving aggregate throughput is the primary concern.

Clearly, such high-density networks require some sort of cellular planning (or FDMA overlay) as a first-tier approach towards interference management; nevertheless, that alone is insufficient as any ***static*** frequency plan will be inadequate to account for the network dynamics resulting from the

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variation in traffic per user (load), number of users etc. Accordingly, it is evident that such networks must incorporate key elements of adaptivity and self-management which will potentially be embedded in architectural and protocol stack innovations. Our contribution in that direction is based on some earlier work that identified adaptive tuning of 802.11 PHY/MAC parameter - the CCA threshold – as key to enhancing network performance [2, 4]. Specifically, we wish to demonstrate the validity of these approaches via experimental verification on a multi-radio Intel StarEast™ based network testbed that has been set up to mimic HD WLAN scenarios on a small scale and also on a large scale deployment of SE HD WLAN testbed in EE building.

The 802.11 MAC protocol is based on CSMA/CA (Carrier Sensing Multiple Access with Collision Avoidance). All stations perform Clear Channel Assessment (CCA) or equivalently Physical Carrier Sensing (PCS) [2, 4] prior to initiating channel access. Typical CCA mechanisms include sampling the net RF energy on the channel and comparing it to a threshold; a transmit node initiates channel access if and only if the RF energy is lower than the pre-set CCA threshold. The value of this threshold has a significant impact on network performance. If set too high, a node may often transmit when it should not (i.e., it's transmission leads to unacceptable added interference with ongoing transmissions, degrading the aggregate throughput), the so-called hidden node problem. If set too low, a node may pass up opportunities to transmit when it could have without interfering with others, thereby again degrading network performance due to `exposed node' phenomena. Hence, adapting CCA threshold dynamically to local network conditions would appear to be a wise heuristic.

In that spirit, a CCA adaptation algorithm was proposed based on the dynamic Signal Interference Noise Ratio (SINR) observed by the nodes [2]; this was evaluated in simulation and also tested on an experimental testbed using Intel Centrino laptops with ***single*** 802.11 radios in [6]. Our work is aimed at similar prototyping but using StarEast (SE) ***multi-radio*** nodes equipped with Intel 2200/2915 chipsets. We catalog our preliminary results regarding the following:

1) Characterization of the RF propagation environment for our HD WLAN testbed;
2) Provide initial results demonstrating the utility of CCA, Rx sensitivity and rate adaptation for HD WLAN.

The rest of the paper is organized as follows. In Section II, we provide literature overview on the related work and various testbeds while Section III gives an overview of the StarEast™ multi-radio research platform. In Section IV, we describe the hardware and software configuration of the miniaturized testbed and Section V compiles some of the initial experimental results from the miniaturized testbed. Section VI describes the hardware and software configuration for the real deployment of SE HD WLAN testbed in EE and section VII describes some intitial results from the real deployment in EE building. Finally, we conclude the paper in Section VIII.

II TestBed Survey

Over the last few years, extensive research efforts have been employed to improve the performance of 802.11 by tuning various parameters such as transmit power [7][8], RTS/CTS handshaking [17], frame size [9], contention windows [13], and data rate [10][11]. Much less attention has been paid to mechanisms such as CCA adaptation to improve the performance of 802.11 MAC protocol. It was first shown in [4] by simulation that aggregate network throughput can be improved by tuning CCA threshold. In [5], authors proposed the analytical model to address the impact of MAC

overhead on the optimal CCA threshold, considering both bandwidth independent overhead coming from the PHY layer and bandwidth dependent overhead caused mainly by collisions. In [6], authors prototyped their proposed CCA adaptation algorithm in real HD WLAN environment inside Intel campus using Intel Centrino™ laptops.

The need for controlled environments where wireless propagation characteristics can be reproduced reliably towards building channel models based on real-world data has led to development of several research testbeds. These come in various flavors, notably the large scale deployments with many nodes to evaluate routing protocols such as at CMU [14] or Uppsala University [15], and MIT Roofnet intended as an experimental deployment to enable broadband access for users [16]. There are also ***shared*** platforms intended to facilitate outreach to a wider wireless research community such as Netbed [18] - a dense mesh of wireless nodes across the department building at Univ. of Utah. By selectively, turning the nodes on/off, it is possible to generate many different topologies. Similarly, ORBIT [19] at Rutgers University consists of an indoor radio grid of 400 nodes in a 20m x 20m space with planned extensions into an outdoor network consisting of both high speed cellular and 802.11 links.

The testbeds above match a real operational environment closely but are expensive to maintain due to significant management overhead incurred and also offer less flexibility in experimentation. However, the expenditure is justified keeping in mind the wide usage at which these testbeds are aimed. An alternative approach is aimed at developing more ***cost-effective, local area*** testbeds through scaling, e.g. by restricting and controlling radio ranges of PC cards via signal attenuators in the Sarnoff [21] and Emulated Wireless ad hoc Network Testbed (EWANT) [22] testbeds. The Physical Emulation Platform (CMU-emu) [23] uses digital emulation of signal propagation by field programmable gate array (FPGA) to make experiments repeatable while preserving the realism of MAC and physical layers. Another testbed which introduces miniaturization of wireless network is MINT [12] based on iRobot's Roomba as the mobility platform. MINT provides flexible integration with ns-2 by replacing MAC and PHY layers of ns-2 by real hardware and driver implementations, enabling the performance evaluation of network protocols already coded in ns-2 directly on WLAN hardware.

The major drawbacks of miniaturized testbeds is that they might not accurately emulate the PHY layer. For example, shrinking the radio radio range leads to placement of nodes in near-field zone of the sender. This is unlike the full scale testbed, where the nodes are typically placed far from each other, hence the receiver is usually in the far-field zone of the sender. This limitation of small scale testbeds has also been observed in MINT [12].

In the context of small-scale wireless testbeds available within the research community, none so far has been explicitly designed for the enterprise HD WLAN environment with the exception of [6] that was intended for a wide-area deployment. Our StarEast (SE) based HD WLAN testbed is designed to investigate the key problem of throughput scaling for HD Enterprise WLANs with a small-scale testbed for cost efficiencies. We also demonstrate some of our initial results in large scale deployments of SE based HD WLAN testbed in four research labs in EE building.

III. 802.11 Network Architectures

802.11 based WLANs have architecturally evolved through the following phases:

1. **1st Generation** - based on isolated BSSs in infrastructure mode (i.e. single AP with associated users) where each AP is directly wired (via Ethernet) to the backbone. All Layer 1 & 2 functionalities such as roaming, authentication, secure mobility, management resides at the AP, leading to what has been termed the "Fat AP" [24]. While this is adequate for single home network environments, it does not scale for large organizations which require 100s of APs.

2. **2nd Generation** – the above infrastructure model was amended by stripping some significant functionalities from the AP and moving it to a switch or controller. This resulted in the "Thin AP" architecture [24] where multiple APs communicate with a controller via Ethernet; the latter handles 802.1X user authentication, wireless encryption, secure mobility and WLAN management. The management controller configures and manages the APs, which cannot function as standalone units and has drawbacks such as single point of failure; further APs and controllers from different vendors do not typically inter-operate.

3. **3rd Generation** – The next-generation enterprise WLAN will be an intelligent network where only ***few APs (gateways) are wired to the Ethernet***; the majority inter-connect wirelessly among themselves via 802.11 links [20]. This requires multiple or multi-mode .11 radios to simultaneously support client traffic, ingress wireless backhaul traffic and egress wireless backhaul traffic; this is already present with the availability of integrated .11 a/b/g client-side wireless cards and integrated multi-mode APs. The use of multiple radios enables the best use of available 802.11 spectrum by dynamically mapping channels to radios as a function of the local environment. This architecture is expected to provide high performance and network robustness at modest cost, and is thus the most likely avenue of .11 network migration for scaling to support a large coverage area and number of users.

The StarEast™ platform enables a multi-radio multi-channel wireless network that fits well with the vision of 3rd generation high density (HD) Enterprise WLAN architecture as above.

StarEast: A Compact, Stackable, Multi-Radio, Multi-Channel Wireless Platform

StarEast is a stackable system with three kinds of modified PCI Mezzanine Cards. One is a baseboard, and the other two are adapter daughter cards to provide miniPCI and CardBus interfaces. The baseboard is based on an Intel® IXP425 network processor. It provides two fast Ethernet ports, one UART, and two mirror PMC PCI interfaces to connect the two daughter cards for miniPCI, CardBus or other customizing functions. To support large applications, the baseboard includes 133MHz, 256Mbytes of on-board SDRAM, and 32Mbytes of on-board Intel StrataFlash® memory. With two PMC2miniPCI daughter cards, StarEast supports four wireless Type IIIA miniPCI cards. Figure 1 shows the SE board.

Besides working in standalone mode, the StarEast baseboard can also act as a standard Processor PCI Mezzanine Card. When plugged into the 3U/6U CompactPCI blades, it provides low-power, high-performance general control functions. To facilitate the development, debug, and

troubleshooting of application software, StarEast is compatible with Intel® IXP400 software. In addition, StarEast™ provides a software development tool chain based on open source Linux.

IV. System design of miniaturized StarEast™ (SE) HD WLAN testbed.

A. Overall Architecture.

The overall architecture of SE HD WLAN testbed consists of SE boards remotely managed by the server for running experiments. Each SE node is equipped with Intel 2200/2915 wireless card and an external antenna with Snapgear Linux patched to run for Intel Xscale IXP425 platform. The server runs Redhat Enterprise Linux and uses perl to remotely login into the boards to run experiments. Figure 1 shows the typical deployment scenario for SE HD WLAN. We also use Iperf [3] as the bandwidth measurement tool developed by the **L**aboratory for **A**pplied **N**etwork **R**esearch (NLANR).

B. Testbed Setup

The testbed consists of eight SE boards of which four are APs and the rest four act as their respective clients. Figure 1 shows the four cell deployment scenario for HD Enterprise WLAN.

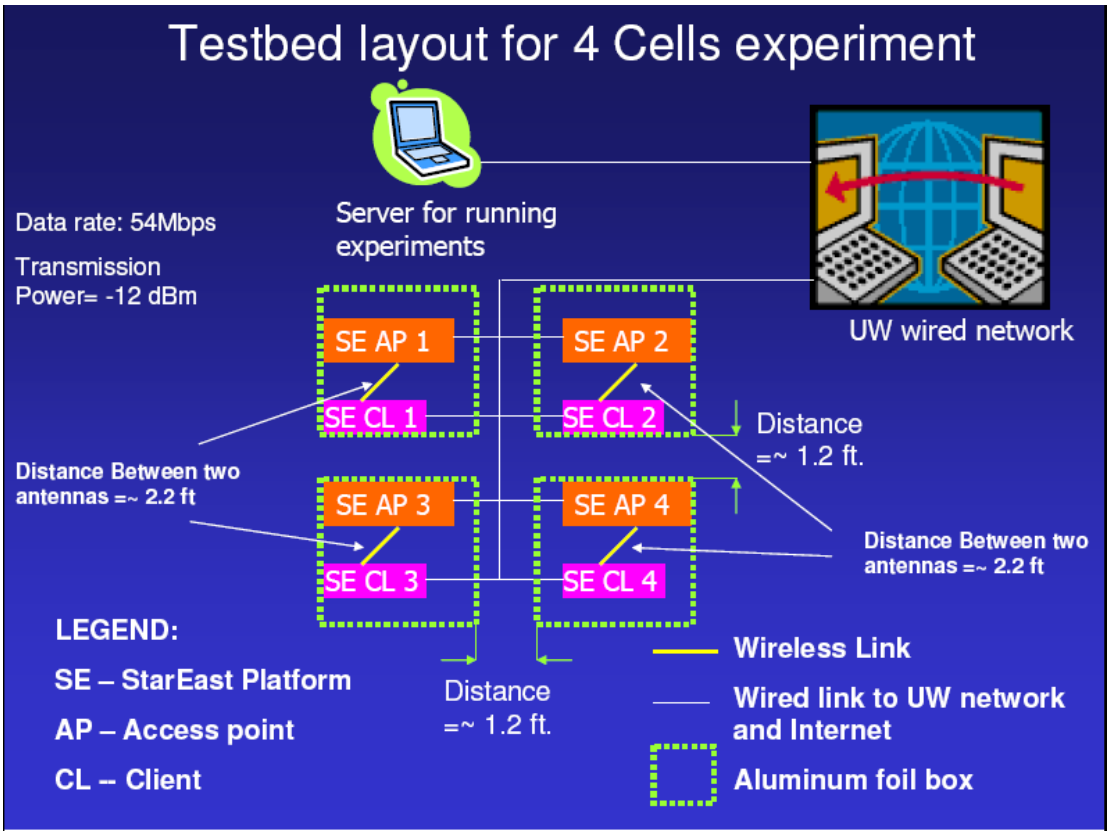

Figure 1: Miniaturized SE HD WLAN TestBed Layout

Fig 1 represents a small-scale laboratory version of the WLAN deployment [6] at Intel campus in Hillsboro, Oregon. All APs and clients were placed on the ground and their distances marked in Figure 1. Each cell consists of one CL-AP pair and is enclosed in a box of 24 x 24 x 24 inch^3

wrapped with one sheet of aluminum foil on all sides to ensure that RSSI (Received Signal Strength) between an intra-cell CL-AP pair significantly exceeds the RIS(Received Interference Strength) between an inter-cell CL-AP pair.

C. Signal Strength Measurements

We use per-frame RSSI value (in dBm) obtained from the (Intel PROWireless 2200BG) driver to measure received signal strength (RSS). Note, that all the APs and CLs use Intel 2200/2915 card in order to ensure the consistency of RSSI measurements from different APs and CLs.

V. Experimental Results for miniaturized SE HD WLAN testbed.

We first characterize the channel propagation by means of RIS and RSSI measurements and then publish some initial results showing the variation of throughput with CCA and Receiver Sensitivity (RS) threshold. Note that all the results presented here are only for single radio-single channel due to the lack of functionality in the driver. We plan to conduct multi-radio experiments in our future work.

A. Channel characterization

We investigate the distribution of RSSI for associated AP-client pairs. As shown in Figure 1, CL1-4 are deployed and they associate with each of the AP1-4 in round robin manner. Each time CL associates with an AP, it samples the RSSI from the AP every second for the total duration of 240 seconds. Figure 2 shows the RSSI distribution of each of the four cells. Note that the distribution spread does not exceed 15 dB.

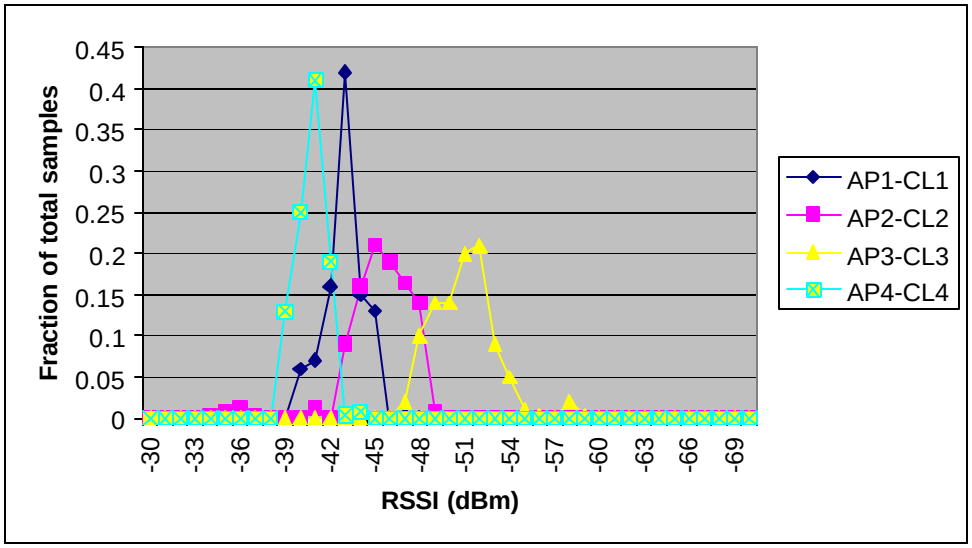

Figure 2: RSSI distribution for all the four cells

Similarly, Figure 3 shows the Received Interference Strength (RIS) distribution for CL2, CL4 when they associate with AP1. CL3 was not able to associate with AP1 as the signal from AP1 was too

weak for it to receive. Figure 3 also shows the RSSI distribution of signal strength received by CL1 from AP1. For the sake of simplicity, the results shown here are only for cell 1; however similar behavior was observed for the rest of the three cells.

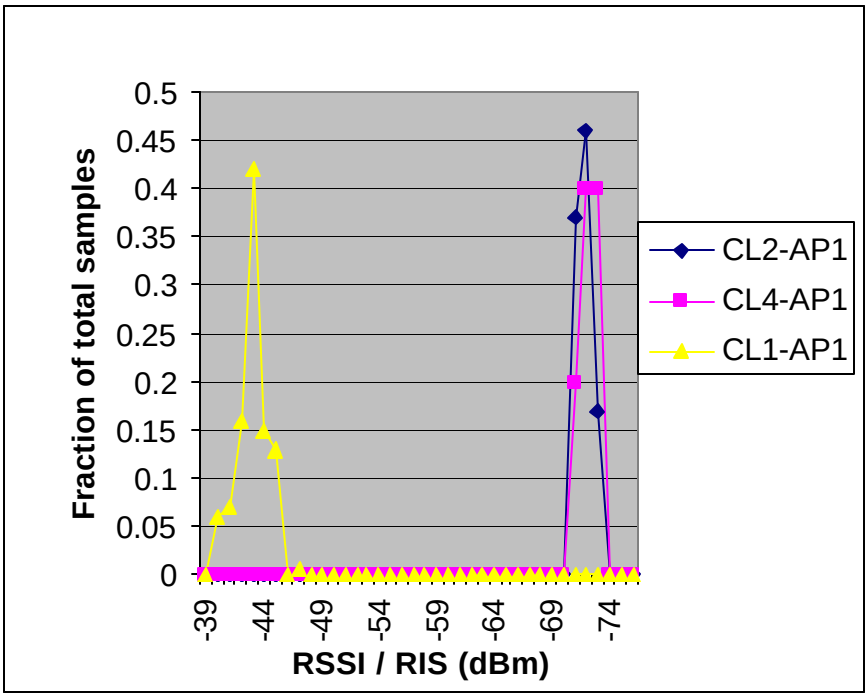

Figure 3: RSSI /RIS distribution for AP1

To summarize, the results included in Table 4 which shows the average signal strengths from each of the AP1,2,3,4 with CL1,2,3,4.

	CL1	**CL2**	**CL3**	**CL4**
AP1	-43	-72		-72
AP2	-70	-44	-68	
AP3			-50	-68
AP4			-73	-42

Table 4: The average Received Signal Strengths (dBm) measured from each AP-CL pair.

Another important observation is that RSSI measured by the client from its own cell is about 20 dB higher than the RIS measured from the neighboring cell in all cases. This is very important as it forms the basis of the testbed representing the real HD WLAN scenario in [6].

B. Variation of throughput Vs Receiver Sensitivity for fixed CCA

The receiver sensitivity threshold for Intel Centrino™ 220/2915 wireless cards is based on Energy detect (ED) mechanism; packet reception is not attempted if the energy detected in the wireless

medium is below this threshold. Receiver Sensitivity (RS) threshold has a major impact in the performance of HD WLANs. Due to the proximity of APs and CLs, an 802.11 receiver can be triggered by an interference signal from the neighboring APs/CLs in co-channel cells if the RS threshold is set too low. When the devices are associating with an AP that has the strongest signal amongst all APs, the RS threshold can be adjusted to each client such that only strong signals trigger packet reception, reducing the likelihood of decoding weaker interfering signals. In fact, the default threshold in Intel 2200/2915 cards is around -95 dBm which is too low for the HD deployments and results in very poor performance in terms of aggregate throughput. Our experiments suggest that this threshold should be tuned for a particular HD deployment and in our case, the optimal value has been found to be around -60 dBm.

We now investigate the relationship of aggregate throughput vs Receiver Sensitivity for a given CCA. We setup the four cell scenario as shown in Fig 1. The transmit power of all the nodes was set to -12 dBm and the data rate of all clients was fixed at 48 Mbps. We then used iperf [3] as a bandwidth measurement tool in uplink scenario where all the CL nodes were sending data to their respective APs. We ran this scenario for four minutes and measured the individual and aggregate throughput (of four cells), which are presented in Figure 5.

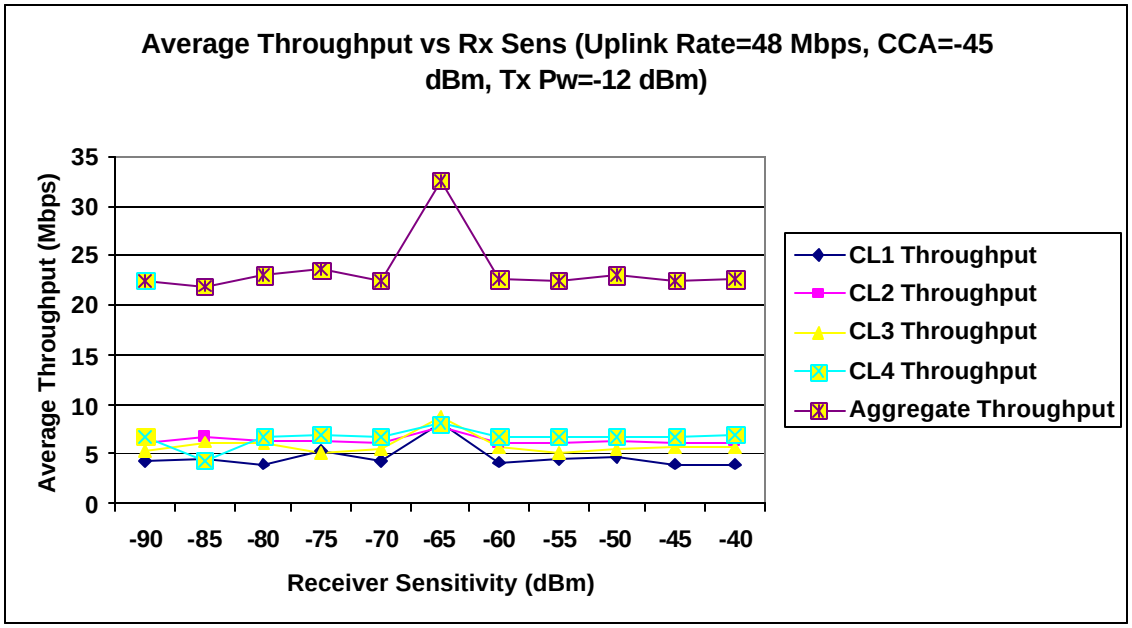

Figure 5: Aggregate throughput Vs Receiver Sensitivity

It is clear from Fig. 5 that the higher receiver sensitivity (RS) initially increases the aggregate throughput in HD WLANs as it rejects the weaker co-channel signals from neighboring APs. However setting the Receiver Sensitivity too high degrades the throughput performance as in that case AP is not even able to receive signals from clients its own cell. We discovered from our experiments that the optimal setting for receiver sensitivity is about 15 dB lower than the average RSSI received by the CL from its own cell. Note that RSSI for any intra-cell AP-CL pair is not constant in real environment, so a safety margin is needed to account for fluctuations of RSSI in real environment.

B. Variation of throughput with CCA for fixed Rx sensitivity and different rates

Next, we investigate the relationship of throughput Vs CCA threshold for a given receiver sensitivity. This experiment was also conducted with the similar settings as above. Figure 6 shows the relationship of aggregate throughput with CCA threshold for fixed uplink rate of 48 Mbps. Note that, the optimal CCA threshold for this case is around -60 dBm. The optimal CCA threshold and Rx sensitivity settings will be a function of the data rates and more experiments will be conducted in our future work.

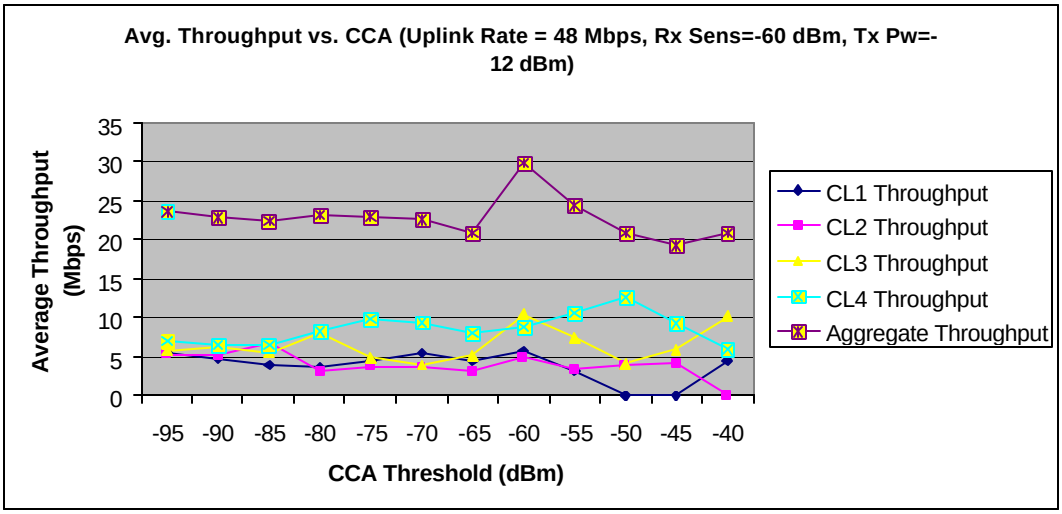

Figure 6: Aggregate Throughput Vs CCA for fixed Receiver Sensitivity

VI. System Design of Enterprise HD WLAN testbed at UW.

The overall architecture of Enterprise SE HD WLAN testbed consists of 20 SE boards remotely managed by the server for running experiments. Each SE node is equipped with Intel 2200/2915 wireless card and an external antenna with Snapgear Linux patched to run for Intel Xscale IXP425 platform. The server runs Redhat Enterprise Linux and uses perl to remotely login into the boards to run experiments. Figure 7 shows the typical deployment scenario for Enterprise SE HD WLAN. We also use Iperf [3] as the bandwidth measurement tool developed by the **L**aboratory for **A**pplied **N**etwork **R**esearch (NLANR).

VII Experiment Results for Enterprise HD WLAN testbed at UW.

A. Signal Strength measurements.

In this section we describe the signal strength measurements of just one AP-CL pair to characterize the indoor RF environment. This measurement was conducted using just one cell using AP7 and CL1. Each experiment was conducted for 4 minutes and the RSSI values were measured per second. The RSSI values were then averaged and plotted corresponding to particular distance. The results are plotted in figure 8.

B. Variation of throughput with CCA for fixed Receiver Sensitivity.

Next, we investigate the variation of throughput with respect to CCA for fixed Receiver sensitivity. In this scenario, all the CLs were connected to their respective APs and were running uplink traffic

with respect to their APs. Figure 9 shows a plot of throughput of individual cells and also aggregate throughput Vs CCA for fixed Rx sensitivity of -55 dBm. It is clearly evident from this figure that there is sharp jump in aggregate throughput at CCA = -55 dBm. We can clearly see that the default value of CCA in hardware for commercial radios which is around -95 dBm gives poor performance for HD WLAN. Also note that increasing CCA beyond -55 dBm reduces the aggregate throughput as there is too much loss of packets due to the aggressiveness of transmitters sending the data in the network.

C. Variation of throughput with Receiver Sensitivity for fixed CCA.

Next, we investigate the variation of throughput with respect to Receiver Sensitivity for fixed CCA. In this scenario, all the CLs were connected to their respective APs and were running uplink traffic with respect to their APs. Figure 10 shows a plot of throughput of individual cells and also aggregate throughput Vs Receiver Sensitivity for fixed CCA of -50 dBm. It is clearly evident from this figure that there is sharp jump in aggregate throughput at Receiver Sensitivity = -50 dBm. We can clearly see that the default value of Receiver Sensitivity in hardware for commercial radios which is around -95 dBm gives poor performance for HD WLAN. Also note, that increasing Receiver beyond -50 dBm reduces the aggregate throughput as in that case the receiver is not able to receive any signals from its own transmitters.

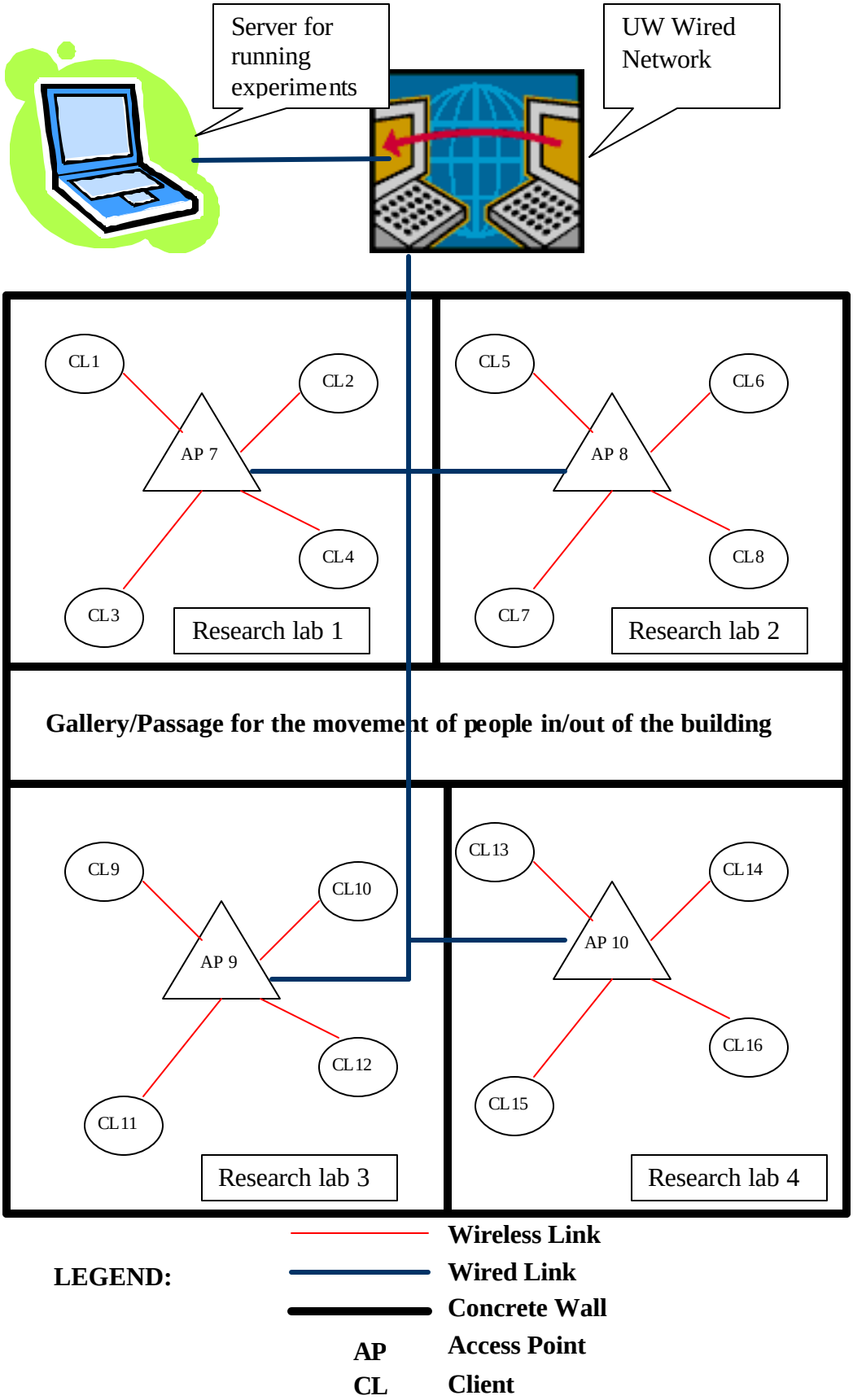

Figure 7: Experiment setup of Enterprise HD WLAN deployment at UW

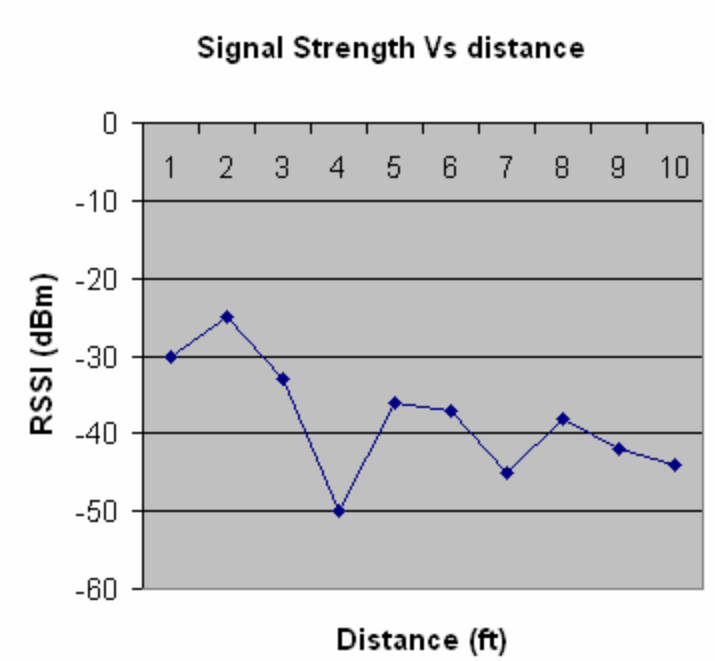

Figure 8: Signal Strength Vs distance for experiments conducted in real indoor environment.

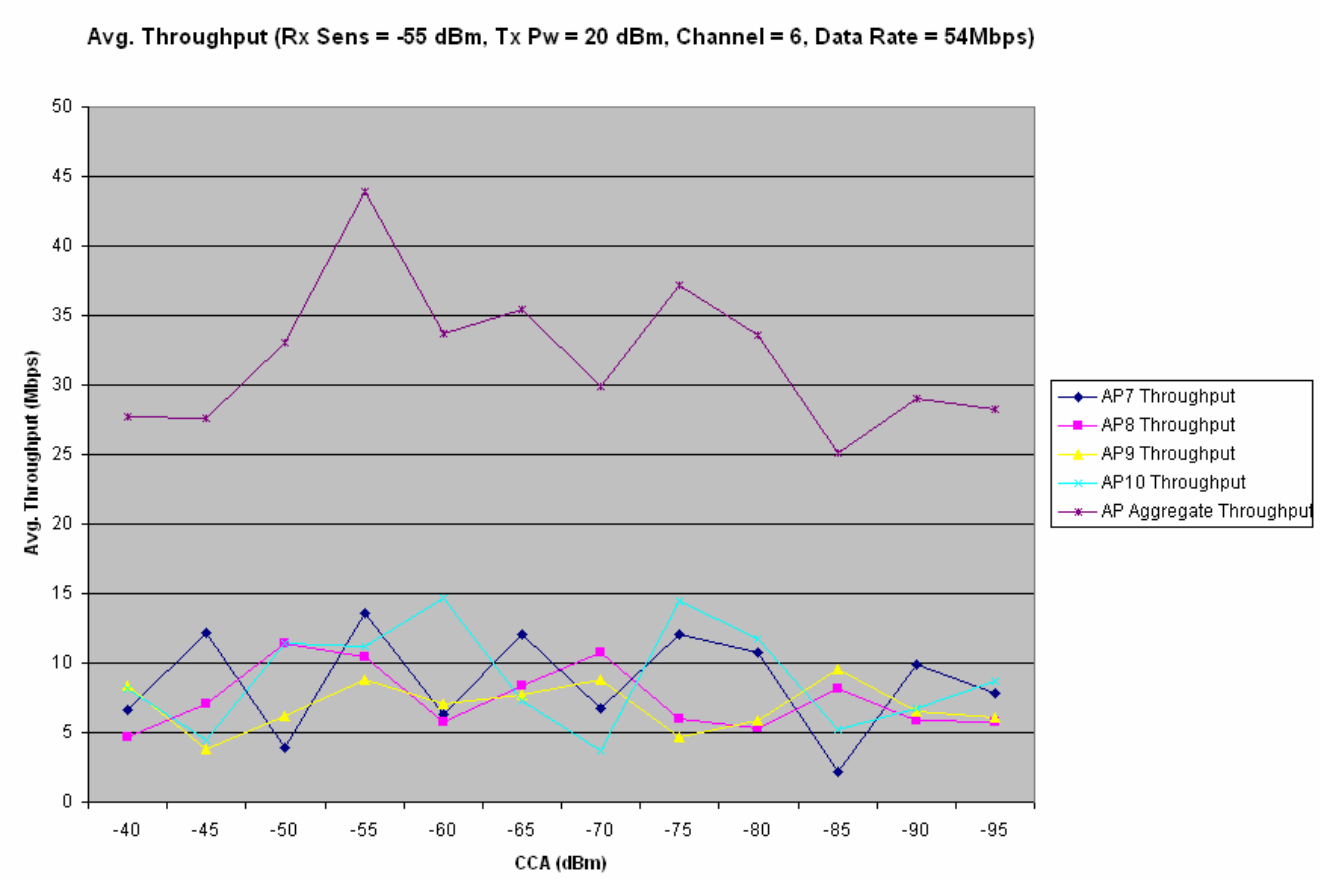

Figure 9: Throughput Vs CCA for fixed Rx sensitivity

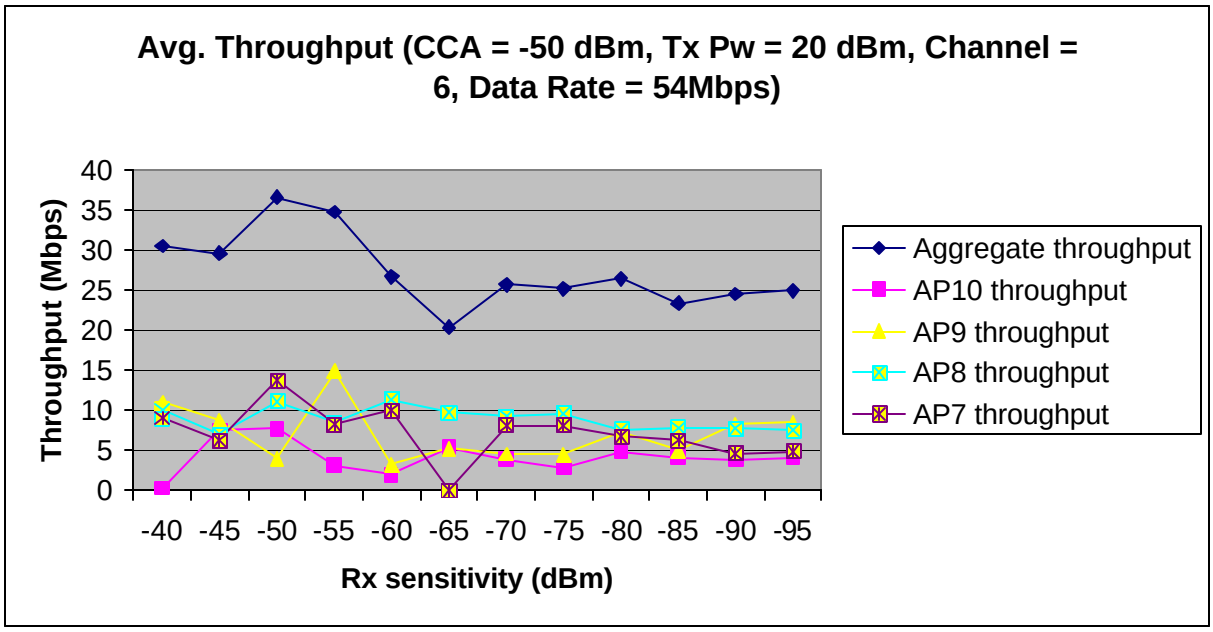

Figure 10: Throughput Vs Receiver Sensitivity for fixed CCA

VIII. Results and Conclusions

This paper introduced a small scale SE based wireless testbed modeling the HD Enterprise WLAN environment. We also introduce some results characterizing the channel for this indoor testbed. We also demonstrated some initial results from our work indicating the relationship of receiver sensitivity and CCA threshold with throughput. Our next step will be to develop algorithms that combine CCA and Receiver Sensitivity threshold with other 802.11 MAC parameters such as Transmit Power, Rate and Contention Window. We also discussed the usefulness of tuning CCA/Rx sensitivity parameters for real deployment of HD WLAN testbed in four research labs in UW. In the future, we would like to extend the IPw2200 driver and extend the capability of our testbed for multi-radio functionality. In summary, this work paves a way for the development of architectural solutions for improving the performance of HD WLAN.

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