Reactive Cognitive Radio Algorithms for Co-Existence between IEEE 802.11b and 802.16a Networks[*]

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Abstract — **This paper investigates the use of reactive cognitive radio algorithms to enable co-existence between IEEE 802.11b and 802.16a networks in the same unlicensed band. In particular, we develop a system model in which the two wireless systems share radio resources in frequency, space and time, and reactive coordination methods are used to reduce the mutual interference and improve link throughput. Reactive cognitive radio schemes utilize the available degrees of freedom in frequency, power and time, and react to observations in these dimensions to avoid interference. Dynamic Frequency Selection (DFS) enables radios to choose the band with the least interference. Power Control (PC) allows communications at the least possible transmit power. Time Agility (TA) enables radios to adapt to each other's traffic patterns and avoid increasing interference in poor channel conditions. Simulation results are given for the following scenarios: (i) single 802.16a cell with single 802.11b hotspot; (ii) multiple 802.16a cells with multiple 802.11b hotspots. The results demonstrate that reactive cognitive radio schemes can provide significant improvements in 802.11b and/or 802.16a throughputs in the typical operating scenarios considered.**

Keywords — **Cognitive Radio, Spectrum Management, Co-existence, Reactive Interference Avoidance**

I. INTRODUCTION

This paper investigates several simple reactive cognitive radio schemes that are intended to enable spectrum co-existence between short-range IEEE 802.11b (Wi-Fi) and long-range IEEE 802.16a (Wi-Max) radios. Co-existence of these wireless services in the same unlicensed band (or future cognitive radio bands) is motivated by the need for more efficient use of spectrum for high-speed data services. Measurements [1] have revealed spectrum usage inefficiency in the licensed spectrum regime, and the relative success of the experimental unlicensed ISM band prompted the FCC to seriously consider more unlicensed operations [2], especially by cognitive radios [3], to increase access efficiency.

Co-existence of short-range IEEE 802.11b WLAN and 802.16a WMAN is of interest, because in future wireless networks, IEEE 802.16a can provide wireless backhaul connectivity to homes and offices, while 802.11b offers complementary local area network capability within a home, office or campus. Since the IEEE 802.16a standard can operate in unlicensed spectrum bands, spectral resources may have to be shared with other wireless systems. For example, in the 2.4GHz ISM band, IEEE 802.11b/g and Bluetooth already exist, while for the 5GHz U-NII band, IEEE 802.11a and HIPERLAN II services exist, and they may be required to co-exist with UWB devices too. Currently there are limited spectrum sharing rules (based on listen-before-talk) in the unlicensed bands but they are considered inadequate for achieving co-existence between higher power services such as 802.16a and lower power ones such as 802.11b. Therefore a cognitive radio scenario with "smart" transceivers which scan the spectrum and try to avoid interference is of particular interest. Such techniques are under consideration by the US Federal Communications Commission as a possible mechanism for efficient spectrum sharing. Many characteristics of 802.11b and 802.16a allow easy adaptation for spectrum sharing, e.g., both systems consume limited bandwidth; their signals have simple spectral density shape (DSSS and OFDM); and multiple modulation levels with different bit rates are supported.

As the capability and complexity (hence cost) of a given cognitive radio technique are correlated, it is useful to classify cognitive radio techniques according to their complexities. Reactive schemes at the low end of complexity will have features allowing radios to adapt to spectrum resource changes without any explicit coordination with neighbors by seeking equilibrium resource allocation using reactive algorithms to control frequency [4], power [5], rate, and time of transmission. This is analogous to the way the TCP protocol adjusts its congestion window and thus reactively controls the source rate over the Internet when congestion occurs. Although strategies used by agile radios, a prevalent cognitive radio concept, can be considered as reactive, these involve considerable hardware complexity for frequency band and transmission-waveform adaptations. More complex cognitive radio techniques include proactive schemes based on explicit spectrum etiquette protocols [7], or an Internet-based spectrum service that provides information required for coordination between radio devices in a given region.

The overall goal of this work is to systematically evaluate the incremental benefit of each increase in cognitive radio complexity, aiming for results that will assist in making design trade-offs between performance and cost. The current study in this paper on reactive coordination schemes represents the first part of the effort. Here, we consider schemes that can control transmit frequency, power, and time of transmission. Two

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radios sharing the same spectrum should aim to create sufficient separation in these three radio resource dimensions, also defined as degrees of freedom (DF). When sufficient DF are available, simple avoidance or reactive type strategies are likely to provide good performance. When there are insufficient DF available, or when the DF usage patterns are not simple enough for incoming radios to exploit their gaps, more complicated coordination techniques such as an explicit etiquette protocol may be required.

In this paper, we consider co-existence scenarios between Wi-Fi and Wi-Max in which Wi-Fi hotspots are inside a Wi-Max cell and share the 2.4GHz ISM frequency band. Three basic reactive schemes are evaluated: Dynamic Frequency Selection (DFS), Power Control (PC) and Time Agility (TA). Each scheme is first analyzed in detail for a simple scenario with one 802.16a cell and one 802.11b hotspot. More realistic network scenarios with multiple 802.16a cells and multiple 802.11b hotspots are also simulated and system performance improvements are demonstrated. Note that only best effort traffic is covered for each scheme.

This paper is organized as follows: first the system architecture is introduced in Section II; next various reactive cognitive radio schemes will be discussed in Section III; and Section IV provides the simulation results with discussions. We conclude with future work in Section V.

II. SYSTEM ARCHITECTURE

A. *IEEE 802.16a and 802.11b*

IEEE 802.16 (Wi-Max) represents a global standard for wireless broadband access, akin to cable and DSL services. It is designed for outdoor, long-range and carrier-class applications, with high throughput in non-line-of-sight propagation environments. The 802.16 standard supports both licensed and license-exempt spectrum, where 802.16a considered in this paper specifies the operation in the 2-10GHz band, supporting raw bit rates up to 75Mbps with variable channel bandwidth of 1.5MHz to 20MHz. The link from 802.16a base station (BS) to subscriber station (SS) is called the downlink (DL) and the link from SS to BS is called the uplink (UL). In this paper, we model the 802.16a MAC as a simple TDMA MAC with 1 microsecond slot duration, where each DL time slot is followed by one UL time slot, and the BS polls each SS in a round-robin manner.

The IEEE 802.11b (Wi-Fi) standard is widely deployed in campus, office and home settings. 802.11b hotspots can cover areas of up to 500 meters, with basic bit rates of 1 Mbps, 2 Mbps (considered in this study), and extended rates of 5.5Mbps and 11Mbps. Wi-Fi radios operate in the 2.4 GHz unlicensed band and consume 22 MHz bandwidth. A standard 802.11 MAC, i.e. CSMA/CA with RTS/CTS extension, is taken as the baseline in this study. When implementing reactive coordination schemes, the 802.16a DL/UL frame headers and the 802.11b RTS/CTS messages are utilized to piggyback control information from terminals to access point/BS.

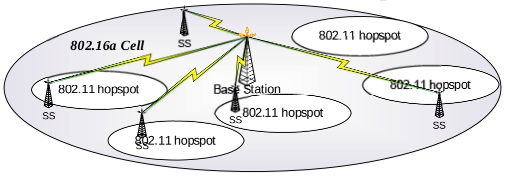


Figure 1: A co-existing IEEE 802.16a and 802.11b network

B. *System framework*

In the system to be studied, IEEE 802.16a and 802.11b cells coexist in overlapping channels using reactive algorithms to be specified later. An example of such a network is shown in Figure 1, which consists of one 802.16a cell, with one BS and multiple subscriber stations. 802.11b hotspots are deployed inside the 802.16a cell with one AP (Access Point) and multiple clients. Both the two systems are assumed to cover a circular area with different radii. The 802.16a BS/SS positions are independent from the 802.11b AP/client locations.

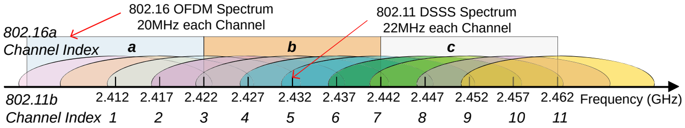


Figure 2: 802.16a and 802.11b channel allocation in ISM band

Fixed bandwidth allocation is considered for the two systems. The 802.16a radios use OFDM with 20MHz bandwidth. Three non-overlapping channels are considered, as shown in Figure 2 (indexed ***a***, ***b***, ***c***). 802.11b radios use direct sequence spread spectrum (DSSS) with a bandwidth of 22MHz per channel. A total of 11 overlapping channels are allocated for 802.11b in the ISM band. In this study we assume alignment of the center frequencies of 802.16a channel index ***a*** with 802.11b channel index 1 at 2412MHz.

III. REACTIVE COORDINATION METHODS

In this section, three basic reactive coordination methods will be studied: Dynamic Frequency Selection (DFS), which utilizes agility in operating frequency; Power Control (PC), which adjusts transmit power based on observed interference; and Time Agility (TA), which schedules transmissions to avoid interference based on traffic patterns in time.

A. *Dynamic Frequency Selection (DFS)*

802.11b devices can dynamically switch channels based on interference levels in available sub-bands. In DFS, radios scan all the channels in the service band and select the channel with the lowest received signal strength indicator (RSSI) for data transmission. In 802.11b networks, channel selection is done by the AP, which periodically scans the spectrum band for channels with lower interference levels.

Ideal channel switching is assumed for 802.11b WLAN, i.e., the AP in the hotspot selects new channels and all clients in the hotspot will be notified by a broadcast message and immediately switch to the same new channel that AP selected. The only penalty of switching channels is the loss of the current packet if any. The typical frequency scanning interval is assumed to be uniformly distributed between 100ms and

200ms. This is the same order of magnitude as the transmission time for a short data session (~50 packets with size of 512 bytes at 2Mbps). The RSSI value is measured and channel switching is actually carried out after a rescan when the interference power level of clearer channel is at least 10% less than that of the current channel. The reason for the extra 10% is to avoid unnecessary oscillations in channel switching.

B. *Power Control (PC)*

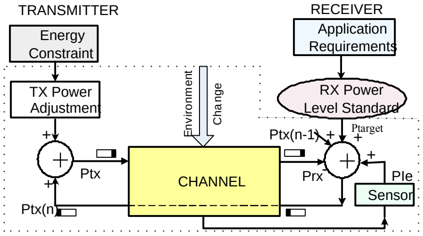


Figure 3: Reactive Power Control scheme

Interference mitigation can also be realized by transmit power control, applied to both the 802.16a UL, DL and also to 802.11b links. The radios are allowed to dynamically choose transmit powers from 256 predefined discrete power levels. The reactive power control scheme is receiver-based, which means that only the receiver will perform scanning for a target interference level, and make the recommendation of the minimum transmit power level necessary to maintain adequate link quality, which is fed back to the transmitter by utilizing MAC packet headers, as shown in Figure 3. Note that what matters is the interference level at the intended receiver and hence spectrum sensing should be done at the receivers if possible. The “environment change” label in Figure 3 refers to channel condition changes caused by fading or mobility. The “TX Power Adjustment” block is the transmit power adjustment controlled by transmitter power constraints, which is not considered currently. Also note that only a fixed modulation scheme is used here. The transmit power is updated on a packet-by-packet basis in the MAC layer. The transmit power for the *n*th packet is calculated by

$$P_{tx}(n) = P_{tx}(n-1) + (\gamma_{\textbf{target}} + RSSI(n) - P_{rx}(n-1)) \\ + (RSSI(n) - RSSI(n-1)) \qquad (1)$$

where $\gamma_{\textbf{target}}$ is the expected target signal to interference and noise ratio, i.e., SINR (all terms measured in dB or dBm), and $P_{\text{target}} = \gamma_{\text{target}} + RSSI(n)$ is the target receive power, $PI_e = RSSI(n) - RSSI(n-1)$ is the interference power change between *n*th and *(n-1)*th transmission.

The transmitter and receiver will agree on the minimum required power level to satisfy the BER target. When the *(n-1)*th MAC packet is initiated in the sender, the current transmit power level (an 8-bit integer number between 0 and 255) is placed into 802.11b RTS or 802.16a frame header. The receiver obtains the received packet power $P_{rx}(n-1)$ from its radio transceiver (PHY) and $P_{tx}(n-1)$ from the received packet header. The RSSI difference between the *n*th and *(n-1)*th measurements is PI_e. $\gamma_{\textbf{target}}$ can be obtained from receiver applications or users (pre-set or by I/O function calls), but in this paper, we will use a constant target SINR of 12dB, which approximately corresponds to a BER of 10^{-6} when using QPSK modulation, which is the minimum required for acceptable TCP performance for wireless links. $P_{tx}(n)$ can be calculated from equation (1) by the receiver, quantized and piggybacked to the transmitter. Maximum transmit power is used for 802.11 RTS/CTS due to their short length. For 802.16, BS can either use maximum transmit power constantly or apply the PC algorithm depending on different PC schemes (UL PC only or PC for both DL and UL), as in certain scenarios only UL power control is applicable. In case of piggybacking information loss, power roll-back strategy is used, where the transmitter increases its power by 20% until maximum is reached, and the receiver will also indicate a power level of 20% more than the latest value. The power roll-back strategy avoids deadlock situations in which the transmitter or receiver is using a lower power than needed and never closes the link.

C. *Time Agility (TA)*

MAC packet re-scheduling in time can also be used to avoid interference. The basic idea is to allow 802.16a and 802.11b devices to adapt to each other’s traffic pattern and the time-varying channel conditions. To avoid transmissions (and thus potential re-transmissions) during poor channel conditions, the transmit probability is decreased when interference power increases, thus avoiding severe interference scenarios. The algorithm is described in Table 1. Note that the SINR threshold of 12dB is used.

TABLE 1: TIME AGILITY ALGORITHM

If *SINR>>12dB* ***then*** *transmit at probability 1*
If *SINR>≈12dB* ***then*** *transmit probability is proportional to the inverse of interference power*
If *SINR<12dB* ***then*** *transmit probability is proportional to SINR in dB.* $Prob_{tx} = \max\{0, SINR/\max\{SINR\}\}$

In the TA algorithm, a SINR close to the threshold may indicate potential close interferers around, and to avoid interference with the potential interferers, the transmit probability is made inversely proportional to the sensed interference power. When the SINR is less than the threshold, the radio can infer that either the signal strength is too weak, or that the interference power is too strong, or both. Thus it is preferable to control the transmit probability to be proportional to current SINR value to avoid mutual interference.

In the sense of traffic engineering, when the traffic pattern is easy to learn (e.g. Pareto ON/OFF traffic model [8] with relatively long OFF periods), this algorithm can help radios to adapt to each other’s traffic pattern and effectively utilize the available degree of freedom in time. It is accomplished by transmitting when the interferer’s traffic load is low (or off), and avoids transmitting when the interferer’s traffic load is high. This algorithm is traffic-type-independent, and the difference is in the degree of difficulty in adapting to the specific traffic pattern. For example, Pareto ON/OFF is easier to adapt to than CBR traffic with the same load, due to the extended OFF period. When implementing this algorithm, piggybacking scheme is also used to embed the transmit probability in packet header, which is calculated by the receiver and sent to the transmitter.

IV. SIMULATIONS

A. Simulation Parameters

Co-existing IEEE 802.16a and 802.11b networks and the reactive schemes were implemented and simulated with Network Simulator 2 (NS2). The interference model is based on the calculation of SINR,

$$SINR_i = \frac{\text{Rx Power of device } i}{\text{Noise} + \sum_{\substack{\text{Overlap} \\ \text{Proportion}}} \text{Interference Power}} \qquad (2)$$

where the interference power (in watts) is summed over overlapped regions (in frequency and time) of transmitted signals (OFDM and DSSS). Bit Error Rate (BER) can be obtained by looking up the modulation performance curve [6] with knowledge of SINR.

The simulation parameters are listed in Table 2.

TABLE 2: SIMULATION PARAMETERS

	IEEE 802.16a	IEEE 802.11b
MAC protocol	TDMA	IEEE 802.11b BSS mode
Channel Model	AWGN, two ray ground propagation model	
Bandwidth/ channels	20 MHz / 3 non-overlapping channels	22MHz / 11 overlapping channels
Raw Bit Rate	14Mbps	2Mbps
Radio parameters	OFDM (256-FFT, QPSK)	DSSS (QPSK)
Background Noise Density	-174 dBm/Hz	
Receiver Noise Figure	9 dB	9 dB
Receiver Sensitivity	-80dBm (@BER 10^{-6}, 14Mbps)	-82dBm (@BER 10^{-5}, 2Mbps)*
Antenna Height	BS 15m, SS 1.5m	All 1.5m
Receiver Antenna Gain	BS 10dB, SS 0dB	0dB
Maximum Coverage	~3Km (@BS 33dBm)	~550m (@20dBm)
Transmitter Power Range	BS 0-33dBm, SS 0-23dBm	0-20dBm

**From CNWLC-811 Wireless 802.11b PC Card specification.*

B. Simulation Results

1) Single 802.16a Cell and single 802.11b hotspot case:

Individual coordination schemes are first evaluated in a simple network scenario with one 802.16a cell (one BS and one SS) and one 802.11b hotspot (1 AP in the center and 1-4 clients A, B, C and D), as shown in Figure 4. The distance D between 802.16a BS and 802.11b AP is a varying parameter and the hotspot radius is fixed at 100 meters in this simulation.

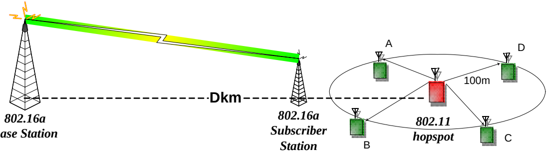
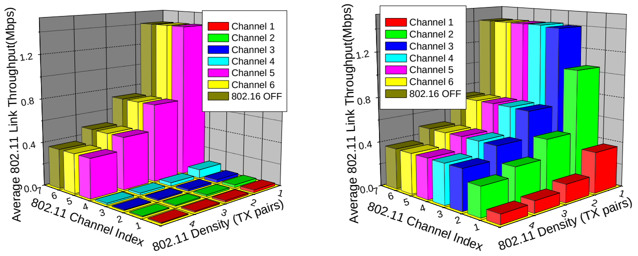


Figure 4: Network scenario for single cell case

a) Effect of DFS for spectrum overlapping: The 802.16a cell will always operate on 802.16a channel index ***a*** (centered at 2412MHz), which will totally overlap with 802.11b hotspot if it operates on channel 1. But if 802.11b devices change to channel 2, 3, or 4, the two systems only have partial overlapping bands. Beyond channel 5, there is no overlap between them, as shown in Figure 2. By DFS, 802.11b devices are capable of avoiding interference with 802.16a by switching their operating channels dynamically.



(a) D=1Km (b) D=1.5Km

Figure 5: Average 802.11b link throughput when switching to different channels, when both systems have overloaded CBR traffic

In Figure 5, the X-axis is the 802.11b channel number index 1 to 6 (X=7 corresponds to the case without 802.16a traffic, i.e. no interference), and the Y-axis is the number of transmission pairs in one hotspot, ranging from 1 to 4 pairs. When the hotspot is near the 802.16a BS, both systems degrade since interference is strong (Figure 5-a). While at D=1.5Km, there is still interference because of complete overlap at channel index 1 and ***a***. However, for channel indices greater than 3, the link throughput is almost unaffected by interferers. For partial overlap at channel 2, the throughput is still degraded. The benefit of avoiding interference by switching 802.11b channels to other available bands is observed in this case.

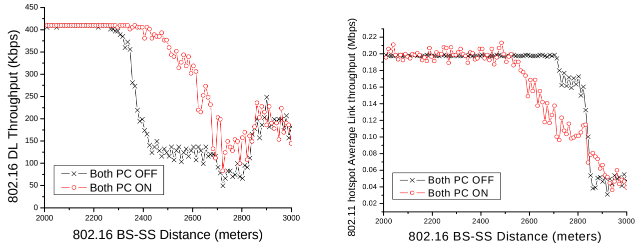


Figure 6: Average link throughput trace, 4 links for hotspot, each has Poisson arrival rate with inter-arrival mean time 3ms when D=3Km

b) Effect of PC for 802.16a UL: To observe the effect of UL power control, the 802.16a SS is positioned between the BS and the hotspot, moving slowly toward the 802.11b hotspot, and thus their interference will increase. By applying power control on both 802.16a SS and 802.11b devices, the 802.16a SS throughput can increase up to 4 times (shown in Figure 6), at the expense of slight degradation in 802.11b throughput, which is because under strong interference, 802.11b node tends to more back-offs when experiencing a busy media, which will benefit 802.16a SS (throughput increase at trace end) by less interference. When 802.16a SS is close to the hotspot, both systems degrade even with power control, which is the worst case scenario, and DFS would likely have more benefit here.

c) Effect of Time Agility: By avoiding each other's transmission interval in the time domain, different radios can adapt to fill available gaps and avoid busy periods. Pareto ON/OFF traffic [8] is used for 802.16a links and the duty cycle (ON to OFF ratio) is kept constant at 1:1. 802.11b nodes (using CBR traffic) will try to adapt to the 802.16a traffic pattern by decreasing transmit probability when 802.16a traffic is ON and increase this probability when 802.16a traffic is OFF, by observing the current interference level. From Figure 7, the time agility algorithm can help to improve the hotspot link throughput by up to 30% when the interferer traffic ON time is of the order of one second. Although the simple time agility only performs well under limited circumstances, this experiment serves as an example of the spectral DF usage pattern dependence of coordination algorithms.

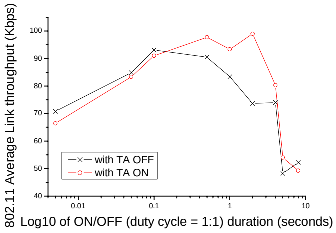


Figure 7: Time agility by varying 802.16a Pareto traffic ON time, 802.11b nodes use CBR traffic with load 200Kbps, and 802.16a node load is 1.3Mbps

2) Multiple 802.16a Cells/multiple 802.11b hotspots case:

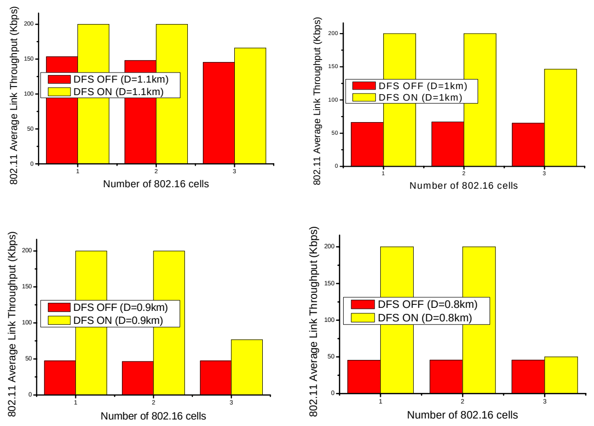


Figure 8: DFS for 802.11b hotspot in 1-3 802.16a cells with different D, and both systems use Pareto ON/OFF traffic with 200Kbps load

a) DFS effect for multiple 802.16a cells: One 802.11b hotspot is placed with equal distance to each of the 802.16a BS (thus equal interference from each cell). In this simulation, 802.11b link is affected by the 802.16a DL traffic, and 802.16a UL traffic is not considered here. From Figure 8, using DFS, the hotspot can adapt to the spectrum band with the least interference power, and the hotspot throughput can improve up to 2.2 times when there are three 802.16a cells. More improvements can be expected for hotspots near the edges of 802.16a cells in a realistic network.

b) DFS and UL-PC effects in an artificially over-crowded scenario: DFS and PC (802.16a UL PC only) are applied to a network of 6km by 6km, with three 802.16a cells at different bands randomly placed inside the network (no mobility). There are 4 SS and 8 802.11b hotspots (4 clients each hotspot with 400m range) randomly placed each cell. Pareto traffic model is applied to all links for a wireless backhaul network with aggregated Internet traffic. As shown in Figure 9, all links can benefit by applying power control schemes to 802.16a UL and 802.11b links, while DFS is also helpful to 802.16a DL and 802.11b links, but not to 802.16a UL. This is probably because in such a dense network, 802.16a uplinks can be adversely affected when 802.11b hotspots switch to the same channels. By applying both DFS and PC schemes, 802.16a DL improves throughput by up to 50%, approaching the performance without interference between the two systems.

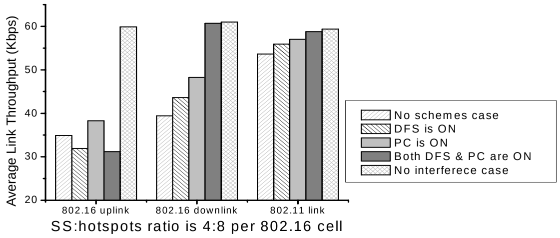


Figure 9: Multiple 802.16a cells with multiple 802.11b hotspots, with Pareto traffic ON/OFF time = 500ms/1000ms

V. Conclusion And Future Work

In this paper, we have proposed and analyzed reactive control methods for spectrum coordination. The goal is to reduce interference and use spectrum more efficiently by efficiently sharing limited radio resources such as frequency, power (space) and time. Three reactive coordination methods are implemented using NS2: Dynamic Frequency Selection (DFS), Power Control (PC) and Time Agility (TA), and they are evaluated in various network scenarios. Simulation results show that such reactive cognitive-radio techniques can significantly improve spectrum efficiency, reduce mutual interference and improve throughput in scenarios with a reasonable amount of "available space" in the selected degrees of freedom (frequency, power and/or time).

Future work includes evaluations of more complex collaborative schemes [7] such as link-layer or network-level etiquette protocols. System performance based on additional metrics including spectrum efficiency, cost and complexity will also be addressed.

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