Spectrum Co-existence of IEEE 802.11b and 802.16a Networks using the CSCC Etiquette Protocol

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Abstract — **This paper considers the feasibility of operating both IEEE 802.11b (Wi-Fi) and 802.16a (Wi-Max) networks in the same shared frequency band. A specific method using the "CSCC" (Common Spectrum Coordination Channel) etiquette protocol is studied and compared with earlier results on reactive interference avoidance algorithms. The CSCC concept is outlined, and its application to this particular 802.11 & 16 spectrum sharing problem is described in detail. The CSCC protocol is used to exchange control information on transmitter and receiver parameters, and hence to cooperatively adapt key PHY-layer variables such as frequency or power. A NS2 simulation model is developed to evaluate performance for representative system scenarios. Both single and multiple 802.11b hotspots per 802.16a cell are considered with the degree of spatial clustering of radio nodes as a key parameter. Simulation results demonstrate that CSCC can improve 802.16a service quality at the expense of a modest decrease in 802.11b throughput in the one-hotspot hidden-receiver scenario considered. Overall system throughput can be significantly improved over reactive schemes depending on the degree of spatial clustering.**

Keywords* — *Cognitive Radio, Spectrum Etiquette protocol, CSCC, Co-existence, Dynamic Spectrum Access

I. Introduction

In this paper, we investigate the feasibility of spectrum co-existence between IEEE 802.11b (Wi-Fi) and 802.16a (Wi-Max) [1] networks using the CSCC (Common Spectrum Coordination Channel) etiquette protocol [2]. CSCC has been proposed as an explicit spectrum etiquette protocol which uses a common edge-of-band control channel for coordination between transceivers using different radio technologies. In an earlier paper [2], it was shown that a simple CSCC implementation can be used to significantly reduce interference between 802.11b and Bluetooth devices operating in close proximity. This motivated us to next consider the important emerging scenario in which both wide-area 802.16 and short-range 802.11 radio technologies could co-exist in the same unlicensed band with a small amount of coordination, either explicit or implicit. It is generally accepted that current unlicensed band etiquettes (such as listen-before-talk) are not applicable to the wide-area/short-range hybrid scenario under consideration due to hidden-receiver problems and the need to support stream services such as VoIP or video. As a result, we believe that it is appropriate to consider new "cognitive radio" [3] techniques which allow dynamic sharing of spectral resources between multiple radio devices in the same band.

Cognitive radio methods can be categorized in terms of their protocol and hardware complexity, covering a wide range of options from reactive interference avoidance to explicit protocol-based coordination, or even network-based collaboration [4]. Reactive cognitive radio techniques described in [5] are based on channel sensing and distributed adaptation of transmit parameters such as frequency, power, bit-rate and time occupancy. Reactive adjustment of PHY parameters is based only on local observations, which may sometimes be insufficient such as in scenarios where there are "hidden receivers". The hidden-receiver problem occurs when a receiver is located in between two potential transmitters which cannot sense each other's presence and hence may cause unintended interference at the receiver. This problem will be discussed further in section II.

The CSCC protocol coordinates radio nodes in a proactive way, where a common spectrum coordination channel at the edge of available spectrum bands is allocated for announcement of radio parameters such as frequency, power, modulation, duration, interference margin, service type, etc. Each node is equipped with a low bit-rate, narrow-band control radio (or software-defined radio) for listening to announcements and broadcasting its own parameters at the CSCC channel. Radio nodes receiving CSCC control information can then initiate appropriate spectrum sharing policies, such as FCFS (First-Come-First-Served), priority or dynamic pricing auction, to resolve conflicts in spectrum demand and share the resource more efficiently by adapting PHY parameters such as frequency or power. The hidden-receiver problem mentioned above can also be solved because the range of CSCC control can be designed to exceed that of regular service data, and receivers can also explicitly announce their presence to further optimize spectrum use.

The specific problem studied in this paper is that of evaluating the CSCC etiquette protocol for co-existence between Wi-Fi and Wi-Max [1] networks sharing the 2.4GHz ISM band and comparing the results to simpler reactive methods previously reported in [5]. Both simple scenarios with one 802.16a cell and one 802.11b hotspot and more realistic scenarios with multiple hotspots are simulated using a NS2 system model. We focus on regimes where 802.11b and 802.16a networks overlap in frequency and avoid interference by adjusting transmit power calculated from the interference margin indicated in the CSCC message. Variations of node geographic distribution (clustered vs. uniform) are studied and clustering regimes where CSCC can significantly improve the

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network throughput by solving the hidden-receiver problem are identified.

The rest of the paper is organized in the following way: Sec II introduces cognitive radio background and the CSCC protocol; then the details of the spectrum coordination policies are discussed in Sec III; Sec IV presents the co-existence network scenarios and simulation results are shown in Sec V; we conclude with future work in Sec VI.

II. Background And CSCC Protocol

A. *Cognitive Radio Background*

Over the past decade, a number of approaches have been proposed for improved spectrum sharing. Notable methods being discussed in the technical and regulatory communities include property rights regimes [6], spectrum clearinghouse, unlicensed bands with simple spectrum etiquette [7], open access [8] and cognitive radio [3][9]. The distinctions between unlicensed spectrum regimes, open access and cognitive radio approaches are relatively subtle as they are all based on the concept of technology neutral bands to be used by a variety of services using radio transceivers that meet certain criteria. For example, cognitive radio may be viewed as a special case of open access or unlicensed regimes in which radio transceivers are required to meet a relatively high standard of interference avoidance via physical and/or network layer adaptation. The cognitive radio principles currently under consideration by the FCC [9] and the research community span a fairly wide range of possible functionalities both at physical and network layers, which are briefly discussed below.

The "agile wideband radio" scheme [10] is the most prevalent concept for cognitive radio in which transmitters scan the channel and autonomously choose their frequency band and modulation waveform to meet interference minimization criteria without any protocol-level coordination with neighboring radio nodes. We observe here that agile radios require rapid waveform and modulation adaptations which may have a high level of hardware complexity. Without coordination, it suffers from serious limitations due to near-far problems and the hidden-receiver problem due to fact that interference is a receiver property while spectrum scanning alone only provides information about transmitters. This problem can be overcome by a small amount of explicit protocol level coordination in which control information is exchanged between transmitters and receivers.

Another simple technique is reactive interference avoidance by control of transmit frequency, rate, power, and/or time occupancy [5], in which radio nodes do not have any explicit coordination with neighbors but seek equilibrium resource allocation using reactive algorithms to control their parameters or MAC behaviors, analogous to the way the TCP protocol reactively adjusts source bit-rate over the Internet when congestion occurs. The reactive techniques in [5] involve PHY and MAC level adaptations in filling available degrees of freedom in dimensions of frequency, space/power and time. But reactive methods still suffer from the hidden-receiver problem since the adaptations are only based on local observations which only provide information about transmitters rather than actual interference experienced by receivers.

With a slightly higher level of protocol complexity, proactive cognitive radio techniques can improve coordination between radio nodes by spectrum etiquette protocols, using either a common spectrum coordination channel (CSCC) at the edge of the shared frequency band or Internet-based spectrum services [4]. Note that the etiquette approach requires some protocol coordination ability including the use of a common control radio for coordination, but may not require full-fledged agile radio capabilities with programmable waveforms. The CSCC protocol considered here achieves the trade-off between the design complexity and the performance improvement, which can help to solve the hidden-receiver problem by explicit announcement of parameters in the CSCC channel.

B. *The CSCC Protocol*

The CSCC concept is to standardize a common control protocol between different radio systems for spectrum coordination purposes. A straightforward way to achieve this is to utilize a simple Common Control Radio (CCR) equipped with each device, which is a low bit-rate, narrow-band radio, such as a prototype IEEE 802.11b 1Mbps radio (covering a range of about 600 meters). A small amount of spectrum (called Common Spectrum Coordination Channel) at the edge of the available spectrum bands can be allocated for the CCR, as shown in Fig. 1 (Frequency vs. Time) where the whole shared spectrum is split into *Band1*, *Band2*, etc. for data communication and *CSCC* band at the lower edge for control purposes.

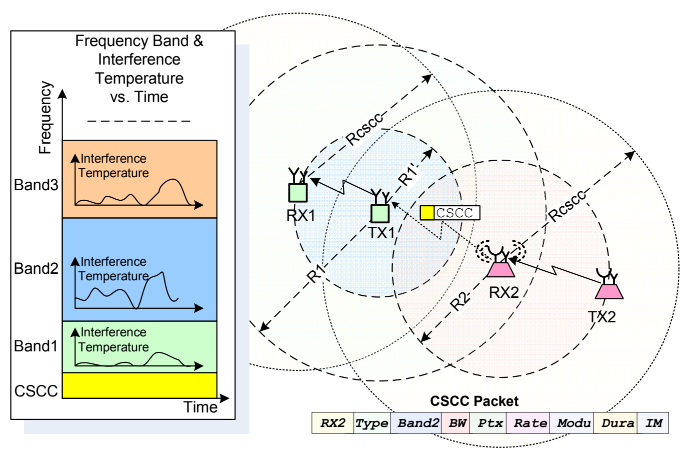


Figure 1: Illustration of the CSCC protocol and how it helps to solve the hidden-receiver problem.

Each radio node announces its parameters to neighboring nodes by broadcasting CSCC messages through the CSCC channel. The information in the CSCC message, such as node ID, center frequency, bandwidth, transmit power, data rate, modulation type, data burst duration, interference margin (IM), service type, etc., can be used by neighboring nodes to coordinate and share the spectrum in an efficient way. Note that the CSCC protocol mechanism is independent of the spectrum coordination policy itself, which can be implemented to reflect regional or application-specific requirements. This is explained further in Fig. 2 which shows that a separate CSCC control stack consisting of CSCC PHY and MAC operate in parallel with the data service. The spectrum coordination (SC) policy runs on top of the CSCC protocol stack and can be specified in a completely general way as long as necessary parameters are carried by the CSCC packet.

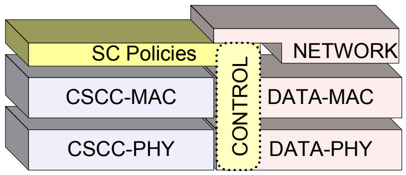


Figure 2: CSCC protocol stack.

Since interference needs to be considered at receivers rather than transmitters, CSCC announcements may also be made by receivers involved in active data sessions. CSCC works in a distributed fashion, and the control messages can simply rely on one-hop broadcast and contention can be resolved by periodic repetition with some randomization of transmit time to avoid multiple collisions.

When a node receives a CSCC message, it will know there is a data session going on between neighboring nodes at a specified frequency slot for some duration. It will then coordinate its operations by either switching to other bands with lower interference temperature [11] or limiting its own transmit power to avoid interference with the on-going communications following coordination policies. The interference temperatures varying in time indicate interference power levels in each band, shown as example curves in Fig. 1. Distributed coordination via the CSCC etiquette protocol can help to reduce or even eliminate interference.

The CSCC protocol can help to solve the hidden-receiver problem, which is illustrated in Fig. 1. Each node is equipped with a common control radio of range R_{cscc}, which is generally ~1-2x the minimum service data radio range. When TX2 initiates a data session to RX2, it first notifies RX2 of the transmit power and the estimated data burst duration T_2 by data packet piggybacking. Then RX2 will broadcast a CSCC message in the CSCC channel to claim the current spectrum, e.g., *Band2*, for T_2 time. When TX1 receives the CSCC message from RX2, it will know the spectrum *Band2* is taken by RX2 and TX1 can either switch to other available spectrum bands (*Band1* or *Band3*) or coordinate with RX2 in *Band2* by reducing its transmit power, i.e., coverage range from *R1* to *R1'*.

Without explicit coordination by the CSCC protocol (or other similar mechanism), node RX2 will become "hidden" to the interference from TX1. Similar to the well-known hidden terminal problem in IEEE 802.11 networks [12], the hidden-receiver problem exists in networks with heterogeneous radios. Initially TX1 covers a range of *R1*, and RX2 covers a range of *R2*. There is no way for TX1 to notice the existence of RX2 only by reactive scanning or sensing, especially when $R2<R1$, and therefore the transmission of TX1 will interfere RX2 if they share the spectrum. Note TX1/RX1 and TX2/RX2 use different radio technologies for data communication and thus they require a common spectrum coordination protocol such as CSCC proposed here to avoid this problem. TX1 then receives CSCC messages from RX2 which is no longer "hidden" to TX1, and TX1 can switch to a different frequency or reduce its power to avoid interference.

III. Spectrum Coordination Policies

In this section, further details about the CSCC-based spectrum coordination policies are given. Spectrum coordination policies refer to specific algorithmic procedures used for adaptation of frequency or power based on the in-band interference temperature. Alternative coordination policies are also discussed.

A. Coordination by Adaptation in Frequency

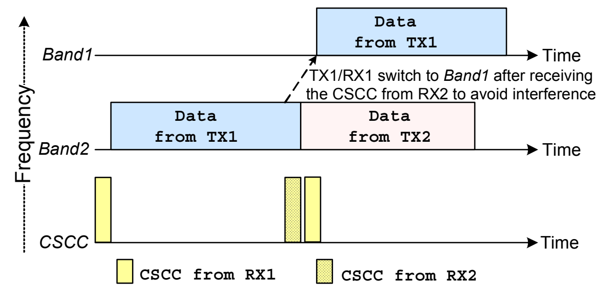


Figure 3: Coordination by adaptation in frequency.

The CSCC protocol itself has been introduced in the previous section. When a transmitter initiates data communication with a receiver, the receiver will broadcast its operating parameters in the CSCC channel using the common control radio. Following the example of section II, when TX1 and RX1 have on-going data communication, RX1 broadcasts a CSCC message in the CSCC channel stating it will take *Band2* for some duration, as shown in Fig. 3. After a while, TX2 notifies RX2 that it has data to send, and then RX2 broadcasts a CSCC message stating it wishes to use *Band2* for data transfer. In the event that RX2 has a higher priority, it will take over *Band2* and starts communication, while TX1 is forced to change its data channel to a clear channel *Band1* and notifies RX1 by either broadcasting a CSCC message or piggybacking in the data packet. Then RX1 will broadcast a CSCC message to claim *Band1*.

B. Coordination by Adaptation in Power

We consider the case when the spectral band is heavily loaded and frequency selection alone cannot be used to avoid interference between simultaneous users. In such a scenario, adaptation of transmit power is an efficient way to reduce interference. By listening to CSCC messages containing appropriate control information, radio nodes can determine appropriate transmit power levels required to reduce interference in a specific frequency band. The CSCC protocol in this case carries a field called the receiver's interference margin (IM) in the CSCC message. The IM is defined as the maximum interference power a receiver (the one broadcasting the CSCC message) can tolerate without disturbing its on-going data communication. When the IM value is changed, it will be updated to neighboring nodes by CSCC messages.

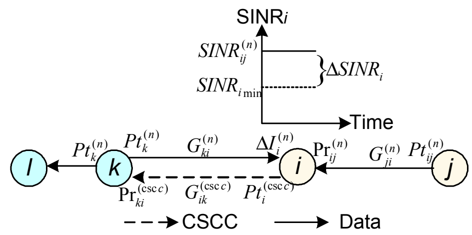


Figure 4: Coordination by adaptation in power.

The power adaptation algorithm is illustrated in Fig. 4. Assume at the data channel #*n*, the received power at node *i* from node *j* is $\Pr_{ij}^{(n)}$ and its current signal to interference and noise radio is $SINR_{ij}^{(n)}$, the interference margin can be calculated by

$$\Delta I_i^{(n)} = (\frac{1}{SINR_{i\min}} - \frac{1}{SINR_{ij}^{(n)}})\Pr_{ij}^{(n)} \qquad (1)$$

where $SINR_{i\min}$ is the minimum signal to interference and noise ratio required to maintain the on-going communication at node *i*, e.g., maintain a minimum bit error rate of 10^{-6} for TCP traffic. Node *i* will broadcast a CSCC message with power $Pt_i^{(cscc)}$ at the CSCC channel. The interference margin $\Delta I_i^{(n)}$ and $Pt_i^{(cscc)}$ are both contained in the CSCC message. Assume that node *k* receives the CSCC message at the control channel, and the path loss gain of the control channel from node *i* to node *k* is $G_{ik}^{(cscc)}$. Then we have $Pt_i^{(cscc)} G_{ik}^{(cscc)} = \Pr_{ki}^{(cscc)}$, and $\Pr_{ki}^{(cscc)}$ can be reported by the PHY of node *k*. Assume the CSCC channel is symmetric, so $G_{ki}^{(cscc)} = G_{ik}^{(cscc)} = \Pr_{ki}^{(cscc)} / Pt_i^{(cscc)}$. Since the control channel is usually not far from the data channel in frequency, the path loss gain at the CSCC channel is a good estimate of that in the data channels, i.e., $G_{ki}^{(n)} = G_{ik}^{(n)} \approx G_{ik}^{(cscc)}$. The maximum transmit power of node *k* at data channel #*n* then is bounded by the constraint in order not to disturb the signals received at node *i*:

$$Pt_k^{(n)} G_{ki}^{(n)} \le \Delta I_i^{(n)} \qquad (2)$$

$$\text{i.e., } Pt_k^{(n)} \le \frac{\Delta I_i^{(n)}}{G_{ki}^{(n)}} \approx \frac{\Delta I_i^{(n)} Pt_i^{(cscc)}}{\Pr_{ki}^{(cscc)}} \qquad (3)$$

If $Pt_k^{(n)}$ is too small for node *k* to reach its receiver, say node *l*, it should either switch channels seeking a band with less interference temperature (i.e., more interference margin available), or just keep silent by backing off its transmissions following a defined back-off policy. In the example shown in Fig. 1, TX1 can calculate its maximum transmit power at *Band2* by (3) and reduce its transmission range from *R1* to *R1'*, keeping the interference power received at RX2 less than its interference margin.

C. *Alternative Policies*

A wide variety of spectrum coordination policies can be applied within the CSCC protocol framework. The policies define rules that radio nodes must follow when they are competing for spectrum resources. A simple access rule is First-Come-First-Served (FCFS), which means the first one coming into a channel will claim the spectrum for some duration by CSCC protocol. Another way to share the spectrum is priority-based, where nodes have different pre-assigned priorities based on their carried traffic type, and high priority nodes will take precedence over low priority ones when there is contention for the same piece of spectrum. A dynamic pricing auction policy [13] in which users bid on available spectrum is another choice. Radio nodes can offer their prices for using the spectrum and the allocation can be done in a distributed way by CSCC protocol to maximize the system revenue.

IV. CO-EXISTENCE OF IEEE 802.11B AND 802.16A

To evaluate the effectiveness of the proposed CSCC etiquette protocol, a co-existing system with IEEE 802.11b hotspots and 802.16a cells in the same shared spectrum is considered.

A. *System Framework*

As shown in Fig. 5, the network consists of IEEE 802.11b hotspots, with one Access Point (AP) and multiple clients in each hotspot, and 802.16a cells, with one Base Station (BS) and multiple Subscriber Stations (SS) per cell. Wi-Fi hotspots can cover a range of ~500 meters as wireless local area networks and Wi-Max cells cover a longer range of ~3km as wireless metropolitan area networks. Both systems are deployed in one geographic area and 802.11b hotspots are inside 802.16a cells. This is a typical cognitive radio scenario where 802.16a SS may be clustered with 802.11b hotspots and they overlap in space. We assume both systems will share a current or future unlicensed or "cognitive radio" band and will need to co-exist by coordinating with each other.

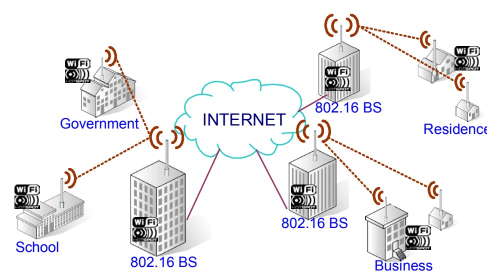


Figure 5: A co-existing IEEE 802.11b and 802.16a network.

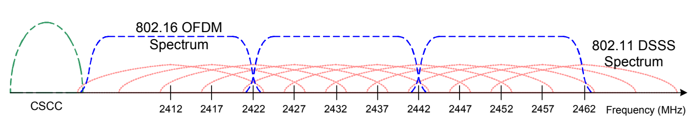


Figure 6: Channel allocation for IEEE 802.11b and 802.16a.

IEEE 802.11b radio uses DSSS with 22MHz bandwidth, and there are 11 overlapping channels centered from 2412MHz to 2462MHz. OFDM is used in IEEE 802.16a radios with 20MHz bandwidth, and in this study we assume there are three non-overlapping channels centered at 2412, 2432 and 2452MHz. To simplify the simulation, bandwidth and rate are fixed for both systems, and QPSK modulation is used with

2Mbps data rate for 802.11b and 14Mbps for 802.16a radios. We also assume that the CSCC channel is allocated at the left edge of the whole spectrum and is orthogonal to other data channels. Fig. 6 shows a sketch of the channel allocation.

To capture the interference effects between the two systems, a physical-layer interference model is constructed to calculate the signal to interference and noise ratio (SINR) at a receiver. Packet reception is based on simulated packet error rate (PER), which is calculated from bit error rate (BER) knowing the packet length in bits. The BER is obtained from the modulation performance curve [14] by knowledge of SINR. Assume at data channel #*n*, node *i* transmits to node *j* with transmit power $Pt_{ij}^{(n)}$, the path loss gain between them is $G_{ij}^{(n)}$, and the in-band background noise observed at node *j* is $N_j^{(n)}$, then the SINR at the receiver *j* can be expressed as:

$$SINR_j^{(n)} = \frac{Pt_{ij}^{(n)} G_{ij}^{(n)}}{N_j^{(n)} + \sum_{l \neq i} \alpha_{lj}^{(n)} Pt_l G_{lj}^{(n)}} \qquad (4)$$

where $0 \leq \alpha_{lj}^{(n)} \leq 1$ is the spectrum overlapping ratio of node *l* and *j* at channel #*n*. The interference powers (in watts) from all transmitted signals (DSSS and/or OFDM) are summed over overlapped regions (in frequency). Here we assume the transmissions of nodes other than node *i* are additive interference.

B. CSCC Implementation

The CSCC protocol is implemented in Network Simulator version 2.27 (NS2) with a dual radio structure in each node. The protocol is implemented between network and MAC layers as an agent, which monitors both data radio (IEEE 802.11b or 802.16a) and control radio (1Mbps 802.11-type). The control radio is fixed at the CSCC channel. The packet format for CSCC messages is shown in Fig. 7.

Bit 1	8	16	24 32
Source ID			
Destination ID			
Data Burst Session Duration			
NodeType	Priority	BandWidth	Modulation
Center Frequency			
CSCC Message Transmit Power			
Interference Margin at Data Band			

Figure 7: CSCC packet format.

To simulate aggregated Internet traffic, a Pareto ON/OFF traffic model [15] is used and a CSCC message is broadcast per data burst session (Pareto ON session). Only best-effort traffic with UDP packets is considered here. The estimated burst duration in milliseconds is included together with the node ID, node type, bandwidth, modulation type, center frequency, CSCC message transmit power, interference margin at the data band. A FCFS-based spectrum coordination policy is used, i.e., the first node claiming the spectrum will take it and subsequent transmissions from other nodes must coordinate with the first one by switching channels or bounding their transmit powers satisfying the interference margin of the first node.

V. SIMULATIONS

Scenarios with single or multiple 802.11b hotspots are simulated and the 802.16a SS node geographic distribution is varied to evaluate spectrum coordination methods under consideration.

A. Simulation Parameters

Table 1 lists the detailed simulation parameters.

TABLE 1: 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
CSCC Coverage	600 meters	
Maximum Coverage	~3Km (@BS 33dBm)	~500m (@20dBm)
Transmitter Power Range	BS 0-33dBm, SS 0-23dBm	0-20dBm

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

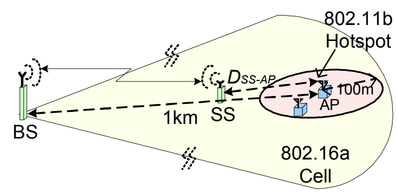


Figure 8: One 802.11b hotspot with one 802.16a cell.

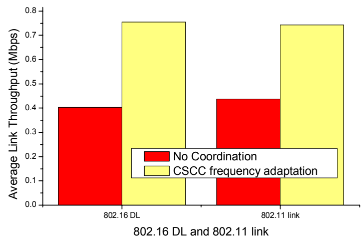
B. Simulation Results

1) One 802.11b hotspot in one 802.16a cell

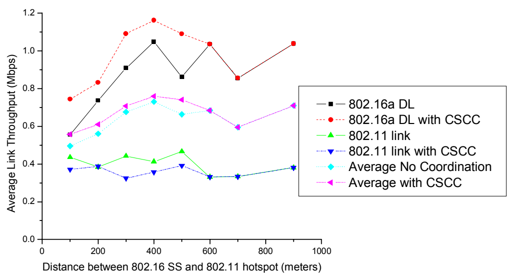
First a simple network with a typical hidden-receiver scenario is considered in Fig. 8. In the hotspot, traffic goes from AP to the client, and for 802.16a, only downlink (DL) traffic from BS to SS is considered so that the 802.16a SS becomes "hidden" to 802.11b interferers. D_{SS-AP} is the distance from 802.16a SS to the hotspot AP, varying from 100 to 900m, and the hotspot is static and 1km away from BS.

The throughputs for both the 802.16a BS-SS link and the hotspot are plotted in Fig. 9. By applying CSCC frequency adaptation (Fig. 9-a), both 802.16a DL and 802.11b throughput can almost be doubled since in this scenario there is enough vacant spectrum to use by CSCC coordination. To evaluate CSCC based power adaptation algorithm in the highest interference case, we consider both systems' center frequencies are fixed at 2412MHz (they overlap mostly in frequency as shown in Fig. 6). Fig. 9-b shows 802.l6a DL throughput is improved by ~35% which varies by D_{SS-AP} when using CSCC power adaptation. Since 802.16a BS is 1km away (out of

CSCC range), 802.11b throughput is slightly degraded, but the average network throughput for both systems is still improved by about 5% to 15%. When the 802.16a SS is out of the hotspot CSCC range, the link throughput is the same for the case with or without CSCC, as might be expected. Since the BS is always out of the hotspot CSCC range, we would expect greater improvement for 802.11b throughput in cases with shorter links.



(a) Throughput by using CSCC frequency adaptation when $D_{SS\text{-}AP}$=200m.



(b) Throughputs vs. $D_{SS\text{-}AP}$ by using power adaptation

Figure 9: Network throughput by using CSCC frequency or power adaptation when both systems have Pareto traffic with ON/OFF time = 500ms/500ms and traffic load 2Mbps.

2) Multiple 802.11b hotspots with varying 802.16a SS geographic distributions in one 802.16a cell

In addition to the network scenario in Fig. 8, four 802.11b hotspots (with 4 clients and 1 AP per hotspot) are placed in one 802.16a cell with coordinates (1km, 0), (0, 1km), (-1km, 0) and (0, -1km) relative to the BS at (0, 0), illustrated in Fig. 10. 802.11b nodes are randomly placed inside the hotspot with the distance to AP less than R_{max11} meters. To simulate a realistic network similar to Fig. 5, the following geographic distributions of 802.16a SS were studied: (i), randomly (uniformly) distributed inside the 802.16a cell with radius 1.5km; (ii), clustered around each hotspot with the distance to each AP less than R_c. The "clustering index" C_i is defined as the ratio of R_{max11} and R_c, which is between 0 and 1, and obviously the larger the clustering index, the more closely the cluster couples spatially with hotspots (and thus the higher the interference between the two systems). The total number of 802.16a SS is kept the same as the total number of 802.11b clients in the network and the traffic type is the same as previous simulations.

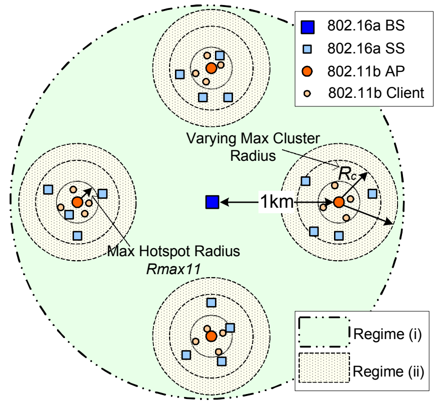


Figure 10: Uniform and Clustering-distributed 802.16a SS.

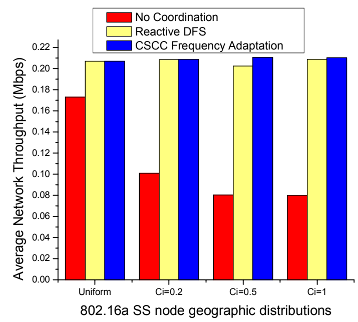
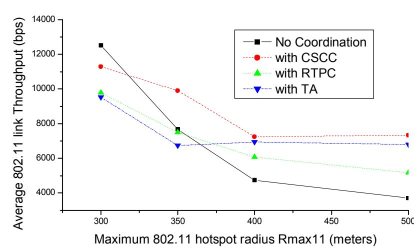
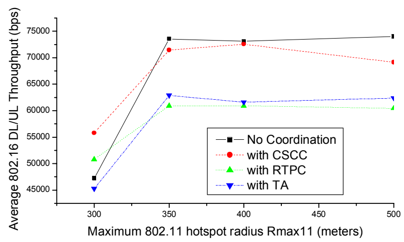


Figure 11: Throughput comparison for (i) uniformly and (ii) clustering distributed 802.16a SS nodes with adaptation in frequency, when R_{max11}=50m and Pareto traffic with ON/OFF time = 500ms/500ms and traffic load 1Mbps.

First the results for adaptation in frequency are compared with reactive dynamic frequency selection (DFS) [5] and the no coordination case, shown in Fig. 11. Both 802.16a DL/UL traffics are considered. Since in this network there is sufficient vacant spectrum for the two systems to operate in different channels, and by CSCC coordination or reactive DFS, radio nodes can switch to channels with less interference and improve the system throughput by about 15% in the uniform-distributed case (with less interference between nodes) and up to 160% in the clustering case varying by the clustering index. In a more crowded network with multiple 802.16a cells taking more spectrum bands, this improvement may be less due to high interference in each available channel.



(a) Average hotspot throughput



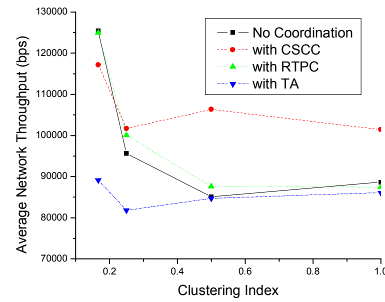
(b) Average 802.16a DL/UL throughput

Figure 12: Throughput for 802.16a SS random distribution in regime (i) with varying hotspot radius R_{max11}, and numbers of 802.16a SS nodes : 802.11b nodes = 2:1, load 600kbps.

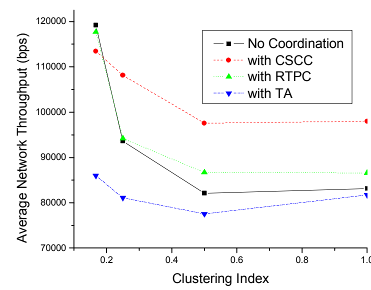
To evaluate the coordination by power adaptation, we assume the highest interference case with fixed center frequency at 2412MHz for both systems (no adaptation in frequency). The CSCC based power adaptation algorithm is compared with reactive ones, i.e., RTPC (Reactive Transmit Power Control) and TA (Time Agility) [5] and the baseline case without any coordination. The results for uniform distribution of 802.16a SS nodes in regime (i) are shown in Fig. 12 with average hotspot and 802.16a DL/UL throughputs plotted separately. In this case the SS nodes are sparsely distributed in the cell and there is a lower probability of "hidden receivers". Fig. 12-a shows that when the hotspot size is larger, its throughput is severely affected by the interference from 802.16a DL/UL, but CSCC protocol can help improve the hotspot throughput by ~70-100% when R_{max11} is greater than 350 meters, by a slight degradation of 802.16a average throughput. The CSCC protocol performs better than the reactive RTPC and TA because the reactive schemes can also improve the hotspot throughput but degrade 802.16a throughput more.

The network throughputs for clustering of 802.16a SS nodes in regime (ii) are shown in Fig. 13. X-axis is the clustering index $C_i = R_{max11}/R_c$, and Y-axis is the average network throughput of both systems. The R_{max11} is fixed at 50m and C_i is varied by changing R_c. By applying CSCC, average network throughput can be improved up to ~20% when the clustering index is greater than about 0.2 and the amount of improvement increases with C_i, which means higher interference between the two systems. The more intense the traffic load (600kbps vs. 1Mbps), the larger the improvement. The CSCC protocol also performs better than reactive methods in cases with significant clustering, mainly due to the fact that it can deal with the hidden-receiver problem discussed earlier.

In summary, when there is vacant spectrum to use frequency adaptation, CSCC protocol can significantly improve the network throughput by ~1-2x especially in the clustering case when in-band interference is high. For the fixed channel allocation case, the CSCC-based power adaptation algorithm can also benefit the hotspot throughput when the hotspot size is large with uniformly distributed 802.16a SS. In the clustering case, CSCC protocol can significantly improve average network throughput over reactive schemes when the clustering index is large, which indicates a high spatial coupling between the 802.16a SS clusters and hotspots.



(a) 600kbps load



(b) 1Mbps load

Figure 13: Throughputs for power adaptation with clustering-distributed 802.16a SS in regime (ii), with numbers of 802.16a SS : 802.11b nodes = 1:1, and Pareto traffic with ON/OFF time = 500ms/500ms.

VI. Conclusion And Future Work

Spectrum co-existence of IEEE 802.11b and 802.16a networks has been studied using the CSCC spectrum etiquette protocol to explicitly coordinate the two wireless systems and reduce interference. The hidden-receiver problem was analyzed where simple reactive methods are unable to detect its existence, and it is shown that the CSCC approach can help to solve this problem. The etiquette protocol is simulated in various Wi-Fi/Wi-Max co-existence scenarios, and system performance based on average throughput is evaluated and compared with reactive techniques. Various 802.16a SS node geographic distributions are studied and spatial clustering regimes are identified where CSCC coordination can significantly improve system throughput by solving the hidden-receiver problem.

In future work, alternative spectrum coordination algorithms and additional system performance metrics (such as delay and control overhead) will also be studied in context of 802.11/802.16 co-existence. A prototype implementation for experimental verification is also planned.

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