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Spectrum Co-existence of IEEE 802.11b and 802.16a Networks Using Reactive and Proactive Etiquette Policies*

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Abstract This paper presents an investigation of spectrum co-existence between IEEE 802.11b and 802.16a networks in the same shared frequency band using cognitive radio techniques with different levels of complexity. Simple reactive interference avoidance algorithms as well as proactive spectrum coordination policies based on etiquette protocols are proposed and compared in terms of achievable spectrum efficiency in a shared Wi-Fi/Wi-Max scenario. In reactive interference avoidance methods, radio nodes coordinate spectrum usage without exchange of explicit control information—this is done by adaptively adjusting transmit PHY parameters such as frequency, power and time occupancy based on local observations of the radio band. Because local observations provide information only about transmitters, they may not be sufficient for resolving spectrum contention in scenarios with "hidden receivers". Proactive coordination techniques solve the hidden-receiver problem by utilizing a common spectrum coordination channel (CSCC) for exchange of transmitter and receiver parameters. Radio nodes can cooperatively select key PHY-layer variables such as frequency and power by broadcasting messages in the CSCC channel and then following specified spectrum etiquette policies. An ns2 simulation model is developed to evaluate both reactive and proactive etiquette policies in scenarios with co-existing IEEE 802.11b and 802.16a networks. The density of radio nodes in the coverage region, and their degree of spatial clustering are key parameters in the system evaluation. Detailed simulation studies were carried out for a variety of scenarios including both single and multiple 802.11b hotspots per 802.16a cell with and without spatial clustering. Our results show that simple reactive algorithms can improve system throughput when sufficient "free space" (in frequency, power or time) is available for PHY adaptation. In more congested scenarios with spatially clustered nodes and hidden receivers, the proposed CSCC etiquette can significantly improve overall system performance over reactive schemes.

Keywords Cognitive radio · Spectrum etiquette protocol · CSCC · Co-existence · Dynamic spectrum access

1. 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 both reactive interference avoidance methods and the CSCC (common spectrum coordination channel) etiquette protocol. 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

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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 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 4.

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 both reactive and proactive etiquette policies for co-existence between Wi-Fi and Wi-Max [1] networks sharing the 2.4 GHz ISM band. Both simple scenarios with one 802.16a cell and one 802.11b hotspot and more realistic scenarios with multiple hotspots are simulated using an ns2 [5] system model. Variations of node geographic distribution (clustered vs. uniform) are studied. The density of radio nodes in the coverage region and their degree of spatial clustering are key parameters in the system evaluation. Clustering regimes where CSCC can significantly improve the network throughput by solving the hidden-receiver problem are identified.

The rest of paper will be organized as follows: Section 2 presents cognitive radio background; then the proposed reactive and proactive etiquette policies will be introduced respectively in detail in Sections 3 and 4; the co-existing network framework is presented in Section 5; simulation parameters and results with discussions are demonstrated in Section 6; we conclude with future work in Section 7.

2. Cognitive radio background

A number of approaches have been proposed for improved spectrum sharing over the past decade. Notable methods being discussed in the technical and regulatory communities include property rights regimes [6, 7], spectrum clearinghouse [8], unlicensed bands with simple spectrum etiquette [9], open access [10–12] and cognitive radio [13–15] under consideration here. 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 [15] and the research community (such as DARPA XG Program [16]), span a fairly wide range of possible functionalities both at physical and network layers, as outlined in Fig. 1, which shows the protocol complexity and radio hardware complexity regimes for a number of possible coordinationschemes.

The "agile wideband radio" scheme [17, 18] shown at the lower right side of Fig. 1 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 although the agile radio has the least protocol complexity, it requires rapid waveform and modulation adaptation which may have a high level of hardware complexity. Without explicit coordination, it suffers from serious limitations due to near-far problems and hidden-receiver problem due to the fact that interference is a receiver property while spectrum scanning alone only provides information about transmitters. This can be overcome by a small amount of explicit protocol level coordination in

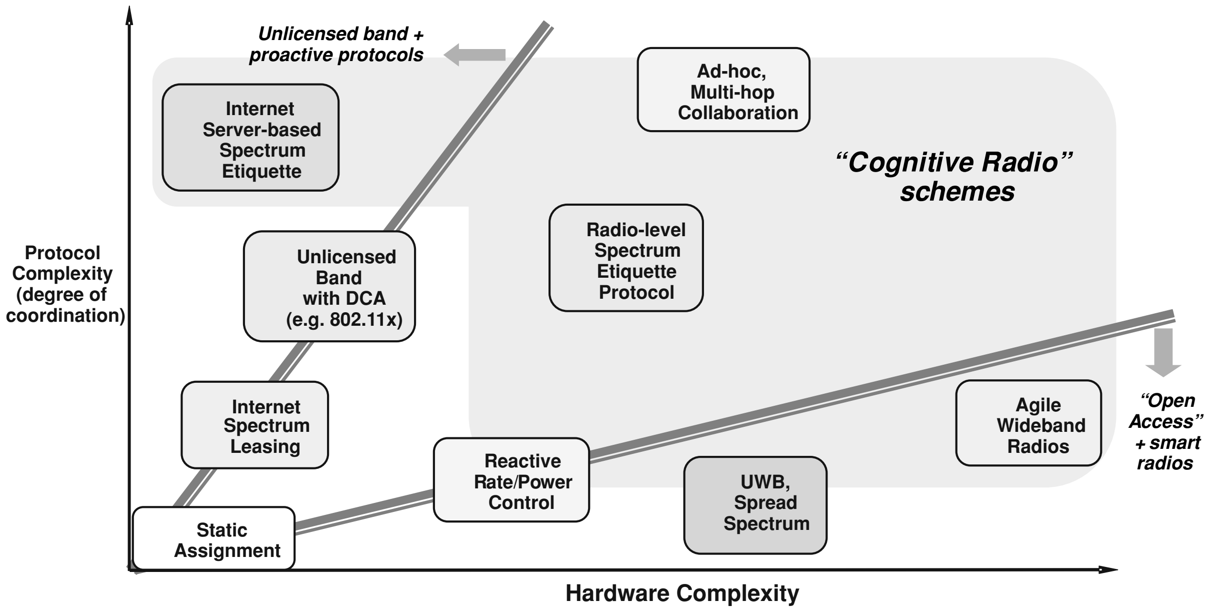


Fig. 1 Hardware and protocol complexity chart for potential cognitive radio approaches

which control information is exchanged between transmitters and receivers.

Another simple technique is "reactive control" of transmit frequency/rate/power/time, in which radio nodes do not have any explicit coordination with neighbors but seek equilibrium resource allocation using reactive algorithms to control frequency [19–21], bit-rate, power [22] and time occupancy, analogous to the way the TCP protocol reactively adjusts source bit-rate over the Internet when congestion occurs. Figure 2 shows a scenario where reactive schemes are deployed. Two transmit pairs AB and CD may use different wireless technologies, but they are flexible in controlling their operating frequencies (channels), their transmission rates, their transmit powers and their transmit time. Using simple reactive schemes, radio nodes can explore and fill the gaps in resource dimensions of frequency, space/power or time by scanning each channel and sensing the interference power.

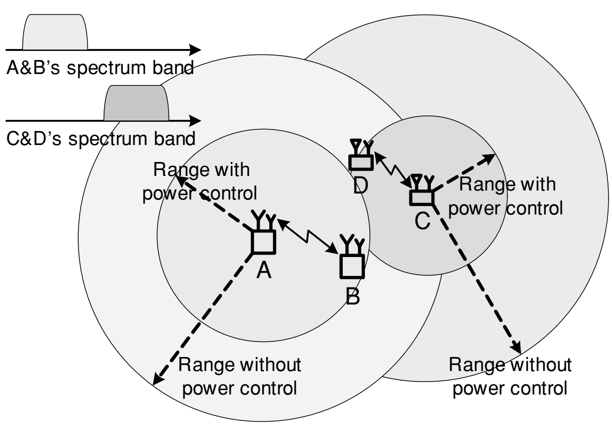


Fig. 2 Reactive schemes of frequency or power agility

For example, when C and D communicate, they will sense that the frequency band taken by A and B has a high interference power and other bands have a low interference power, so C and D will dynamically select a clearer frequency band to avoid interference between two systems. In cases when there is no available degree of freedom in frequency, radio nodes can explore the dimension of space by reactive transmit power control (RTPC) to increase spatial reuse. Both AB and CD can calculate the minimum transmit powers possible for their communications to reduce their interference areas to other systems. As illustrated in Fig. 2, both AB and CD can transmit in parallel in the same frequency band by reducing their transmit powers. Another simple technique is reactive control of transmit time by changing transmit probabilities based on interference conditions. When the interference power is high, transmit probability is reduced to avoid more congested situations in using the spectrum. Otherwise transmit probability can be increased when interference power is low and channel conditions are good. Since reactive adaptations are based on local observations, they may be expected to suffer from hidden-receiver problems.

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]. The CSCC concept is to standardize a common control protocol between different radio systems for spectrum coordination purposes. A simple way is to equip a Common Control Radio (CCR) with each node, which is a low bit-rate, narrow-band radio, such as a prototype IEEE

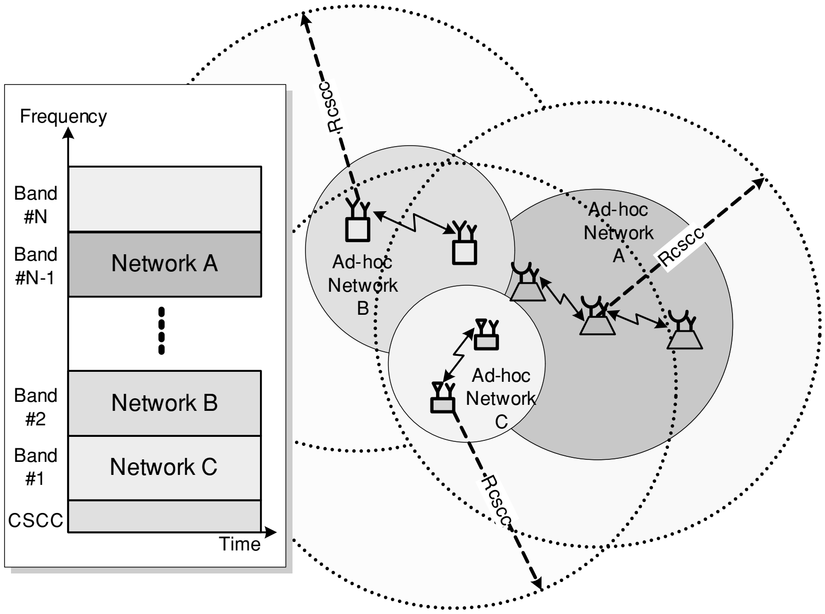


Fig. 3 CSCC etiquette protocol

802.11b 1 Mbps radio (covering a range of about 600 m). Note that this approach requires some protocol coordination ability including the use of a common physical layer for coordination, but may not require full-fledged agile radio capabilities with programmable waveforms. A small amount of spectrum (called the Common Spectrum Coordination Channel [2]) at the edge of the shared spectrum bands can be allocated for the CCR, as illustrated in Fig. 3 (Frequency vs. Time) where the shared spectrum is split into *Band#1*, *Band#2*, . . ., *Band#N* for data communication and the CSCC band at the lower edge for control purposes. Radio nodes can listen to announcements and broadcast their own parameters in the CSCC channel. Based on shared control information on the CSCC, appropriate spectrum sharing policies can be initiated, such as FCFS (First-Come-First-Served), priority or dynamic pricing auction [23], to resolve conflicts in spectrum demand and share the resource more efficiently by adapting PHY parameters such as frequency or power. For example, in Fig. 3, each ad hoc network A, B and C can set up appropriate operating channels or transmit powers to avoid interference. 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 radio receivers can also explicitly announce their presence to overcome the hidden receiver problem discussed earlier.

3. Reactive cognitive radio techniques

In this section, three reactive cognitive radio techniques are introduced: Dynamic Frequency Selection (DFS), Reactive Transmit Power Control (RTPC) and Time Agility (TA), which reactively adapt in dimensions of frequency, power and transmit time respectively.

3.1. Dynamic frequency selection (DFS)

In the DFS scheme, radio nodes periodically scan the spectrum band and measure interference power level in each available channel. When radio nodes have data to transfer,

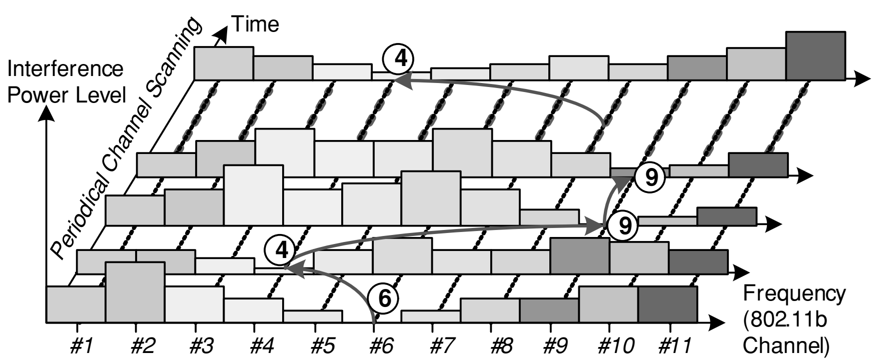


Fig. 4 An example of the dynamic frequency selection algorithm

they choose the channel with the least interference power. The concept is illustrated in Fig. 4, in which each node keeps a record of the interference power level of each channel and selects a sequence of channel *#6*, *#9*, *#9*, . . ., *#4*, etc. for communication. The updating interval can be determined by the statistics of the traffic, e.g., randomly chosen in the order of a short 802.11 data session (∼100 ms for about 50 packets with size of 512 Bytes at 2 Mbps bit-rate). Note that too frequent channel switching may cause packet loss due to link-level interruptions. On the other hand, infrequent switching may result in a slow response to channel condition changes. To prevent unnecessary channel switching, a new channel is used only if interference power of a clearer channel is at least 10% less than current interference level.

3.2. Reactive transmit power control (RTPC)

It is important for radio nodes to not only exploit available resources, but also at the same time emit the least interference to others. The RTPC algorithm achieves this by allowing transmitters to use the minimum transmit power possible for data transfer. Since interference is a receiver property, in the RTPC scheme, each receiver will estimate the minimum transmit power to maintain adequate link quality, based on its own QoS requirements and path loss estimates. This recommended transmit power level is fed back to transmitters by utilizing MAC packet headers (e.g., ACK header). As illustrated in Fig. 5, the receiver can sense interference power changes PI_e since the last measurement, and the received power of current received packet P_{rx}. By knowing the target received power P_{target}, determined by the QoS requirement of the receiver (e.g., a level of bit error rate less than 10^{-6}), it then can calculate the recommended next transmit power using Eq. (1). Transmit power is updated on a packet-by-packet basis and $P_{tx}(n)$ for the nth packet is calculated by

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

where γ_{target} is the expected target SINR (all terms measured in dB or dBm), and $P_{\text{target}} = \gamma_{\text{target}} + RSSI(n)$ is the target received power, $PI_e = RSSI(n) - RSSI(n-1)$ is the sensed interference power change between the nth and (n-1)th transmission. In Fig. 5, the “TX Power Adjustment” block is controlled by energy constraints, which is not considered in current study.

For implementation, the power value (in dBm) can be quantized to 256 levels stored in an 8-bit field in the MAC header, which is piggybacked between the transmitter and receiver. In case of piggyback packet loss, a power roll-back mechanism is used to avoid deadlock situations by increasing the (recommended) transmit power by a certain amount (e.g., 20% of current power level) each time a packet is lost until reaching the maximum value.

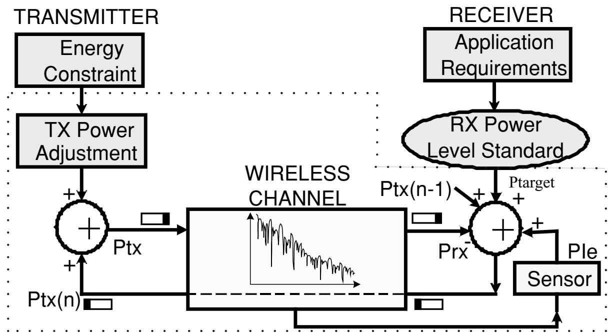


Fig. 5 Reactive transmit power control algorithm

3.3. Time Agility (TA)

Reactive interference avoidance can also be realized by controlling transmit probability or re-scheduling MAC packet transmissions in an interference-varying environment. The Time Agility algorithm explores gaps in the time dimension by avoiding transmissions (and thus potential retransmissions) when channel conditions are bad (i.e., interference level is high) and encouraging transmissions when channel condition is good. This is realized by changing transmitters' transmit probability $Prob_{tx}$ as a function of the interference power and SINR at the preferred receiver. This algorithm implicitly allows nodes to adapt to each other's traffic pattern by listening on the channel and controlling $Prob_{tx}$. An example of the algorithm is shown in Fig. 6 where $P_{\text{interference}}$ is the interference power. Note that the communication threshold is assumed to be at BER $\approx 10^{-6}$ or SINR ≈12 dB with QPSK modulation.

Similar to the RTPC scheme, the receiver listens on the channel and updates the recommended transmit probability $Prob_{tx}$ which is quantized to 8 bits and piggybacked in MAC headers. For the algorithm shown in Fig. 6, a SINR near to the threshold (12 dB) means that the channel condition is still good but there may be potential close interferers around. In order to avoid interfering more severely with the potential interferers, the transmit probability is proportional to the inverse of sensed interference power. When the SINR level is less than the threshold, the node 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

If *SINR>>12dB* ***then*** *$Prob_{tx}$ = 1*
If *SINR>≈12dB* ***then*** *$Prob_{tx} \sim 1/P_{interference}$*
If *SINR<12dB* ***then*** *$Prob_{tx} \sim SINR/max\{SINR\}$*

Fig. 6 Time agility algorithm

probability to be proportional to the current SINR value (in dB) to avoid re-transmissions and mutual interference.

Note that in terms of traffic engineering, when the traffic pattern is easy to learn (e.g. Pareto ON/OFF traffic model [24] with relatively long OFF periods), such a time agility algorithm can help radios to adapt to each other's traffic pattern and effectively utilize the available degree of "freedom" in time. $Prob_{tx}$ is increased when the interferer's traffic load is low (or off), and decreased 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 patterns on the channel. For example, it is easier to adapt to Pareto ON/OFF traffic than CBR traffic with the same load, due to the extended OFF period.

4. Proactive spectrum etiquette protocols

4.1. CSCC etiquette protocol

The basic CSCC concept was outlined earlier in Section 2 (see Fig. 3). In this approach to spectrum coordination, each radio node announces its parameters to neighboring nodes by broadcasting CSCC messages through a common CSCC channel at the edge of the band. 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., is 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. 7 which shows that a separate CSCC control stack consisting of CSCC PHY and MAC operates 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. Since interference needs to be considered at receivers rather than transmitters, CSCC announcements may be made by receivers involved in active data sessions by 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 that there is a data session going on between neighboring

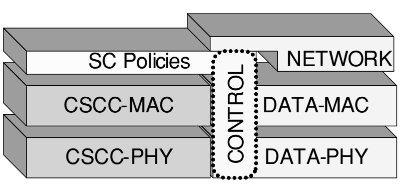


Fig. 7 CSCC protocol stack

nodes at a specified frequency slot for some duration. Then, a coordination procedure is initiated either by switching to other bands with lower interference or by limiting transmit power to avoid interference with existing radio links following specified coordination policies.

The CSCC protocol can help to solve the hidden-receiver problem, as illustrated in Fig. 8. R_{cscc} is the coverage range of CCR 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 broadcasts a CSCC message in the CSCC channel to claim the current spectrum, i.e., *Band#2*, for a duration of T_2. When TX1 receives the CSCC message from RX2, it will know the spectrum *Band#2* is taken by RX2 and TX1 will either switch to other available bands or coordinate with RX2 at *Band#2* by reducing its transmit power, i.e., coverage range from $R1$ to $R1'$.

Without explicit coordination from the CSCC protocol (or some other similar mechanism), node RX2 would become "hidden" to the interference from TX1. Similar to the well-known hidden terminal problem in IEEE 802.11 networks [25], 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 with 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 channel as in the CSCC method proposed here. 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.

4.2. Spectrum coordination policies

Spectrum coordination policies refer to specific algorithmic procedures used for adaptation of frequency or power based on the in-band interference power. Alternative coordination policies will also be discussed.

4.2.1. Coordination by adaptation in frequency

Radio nodes can change operating frequencies to avoid interference by the CSCC protocol. Following the example of Fig. 8, when TX1 and RX1 have on-going data communication, RX1 broadcasts a CSCC message in the CSCC channel stating it will take *Band#2* for some duration, as shown in Fig. 9. After a while, TX2 notifies RX2 that it has data to send, and then RX2 broadcasts a CSCC message stating it wishes to use *Band#2* for data transfer. In the event that RX2

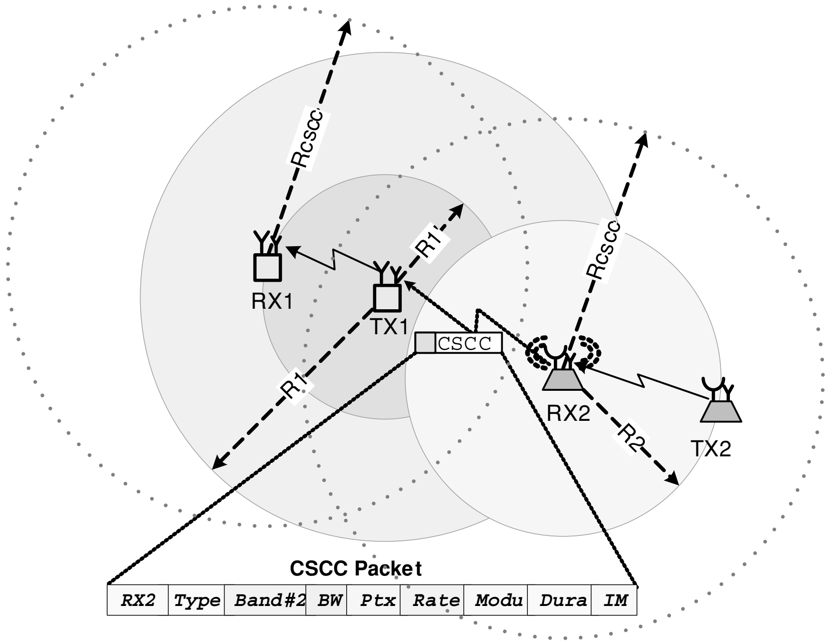


Fig. 8 Illustration of the CSCC protocol and how it helps to solve the hidden-receiver problem

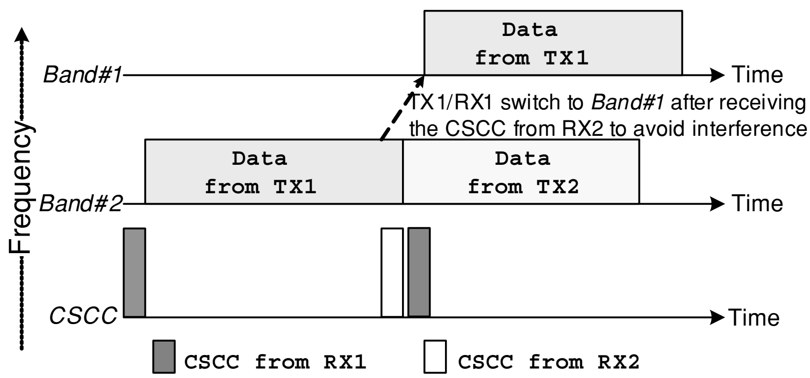


Fig. 9 Coordination by adaptation in frequency

has a higher priority, it will take over *Band#2* and starts communication, while TX1 is forced to change its data channel to a clear channel, e.g., *Band#1* and notifies RX1 by either broadcasting a CSCC message or piggybacking in the data packet. Then RX1 will broadcast a CSCC message to claim *Band#1*.

4.2.2. Coordination by adaptation in power

When the spectral band is heavily loaded and frequency selection alone cannot be used to avoid interference between simultaneous users, adaptation of transmit power is an efficient way to reduce interference. By listening to CSCC messages, radio nodes can determine appropriate transmit power levels required to reduce interference in a specific frequency band. In this case the CSCC message carries a field called the receiver's interference margin (IM). 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.

The power adaptation algorithm is illustrated in Fig. 10. Assume at the data channel #*n*, the received power at node *i* from node *j* is $\mathrm{Pr}_{ij}^{(n)}$ and its current signal to interference and noise radio (SINR) is $SINR_{ij}^{(n)}$, the interference margin can

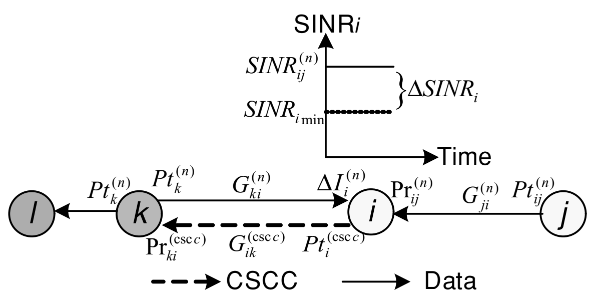


Fig. 10 Coordination by adaptation in power

be calculated by

$$\Delta I_i^{(n)} = \left(\frac{1}{SINR_{i\min}} - \frac{1}{SINR_{ij}^{(n)}}\right) Pr_{ij}^{(n)} \quad (2)$$

where $SINR_{i\min}$ is the minimum SINR required to maintain the on-going communication at node i, e.g., maintain a minimum bit error rate of 10^{-6} for TCP traffic [26]. Node i will broadcast a CSCC message with power $Pt_i^{(\mathrm{csc}\,c)}$ at the CSCC channel. The IM $\Delta I_i^{(n)}$ and $Pt_i^{(\mathrm{csc}\,c)}$ 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 $G_{ik}^{(\mathrm{csc}\,c)}$. Then we have $Pt_i^{(\mathrm{csc}\,c)} G_{ik}^{(\mathrm{csc}\,c)} = \mathrm{Pr}_{ki}^{(\mathrm{csc}\,c)}$, and $\mathrm{Pr}_{ki}^{(\mathrm{csc}\,c)}$ can be reported by the PHY of node k. Assume the CSCC channel is symmetric, so $G_{ki}^{(\mathrm{csc}\,c)} = G_{ik}^{(\mathrm{csc}\,c)} = \mathrm{Pr}_{ki}^{(\mathrm{csc}\,c)} / Pt_i^{(\mathrm{csc}\,c)}$. Since the control channel is usually close to the data channel in frequency, the path loss gain at the CSCC channel is a good estimation of that at the data channels, i.e., $G_{ki}^{(n)} = G_{ik}^{(n)} \approx G_{ik}^{(\mathrm{csc}\,c)}$. 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:

$$Pt_k^{(n)} G_{ki}^{(n)} \leq \Delta I_i^{(n)} \quad (3)$$

i.e.,
$$Pt_k^{(n)} \leq \frac{\Delta I_i^{(n)}}{G_{ki}^{(n)}} \approx \frac{\Delta I_i^{(n)} Pt_i^{(\mathrm{csc}\,c)}}{\mathrm{Pr}_{ki}^{(\mathrm{csc}\,c)}} \quad (4)$$

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 (i.e., more IM available), or just keep silent by backing off its transmissions following a defined back-off policy. In the example of Fig. 8, TX1 can calculate its maximum transmit power at *Band#2* by (4) and reduce its transmission range from *R1* to *R1′*, keeping the interference power experienced at RX2 less than its IM.

4.2.3. 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 approach 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 [23, 27] 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.

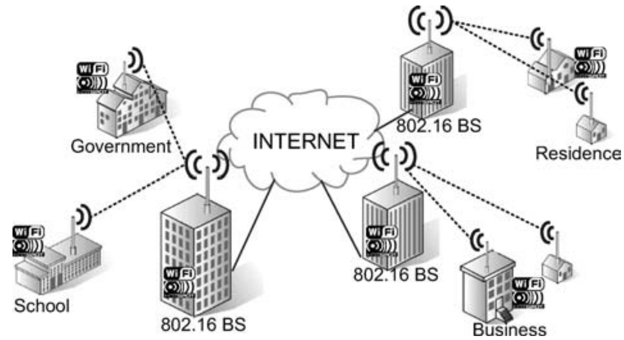


Fig. 11 A co-existing IEEE 802.11b and 802.16a network

5. Co-existence of IEEE 802.11b and 802.16a

A co-existing system with IEEE 802.11b hotspots and 802.16a cells in the same shared spectrum is considered to evaluate the effectiveness of proposed reactive and proactive spectrum coordination policies.

5.1. System framework

An example of the co-existing network is shown in Fig. 11, which 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 m as wireless local area networks and Wi-Max cells cover a longer range of ∼3 km 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 that 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 12 shows a sketch of the channel allocation for the two systems. Wi-Fi radio uses DSSS with 22 MHz bandwidth, and there are 11 overlapping channels with center frequencies from 2412 to 2462 MHz. OFDM is used in Wi-Max radios with 20 MHz bandwidth, and in this study we assume there are three non-overlapping channels centered at 2412, 2432 and 2452 MHz. To simplify the simulation, bandwidth and rate are fixed for both systems, and QPSK

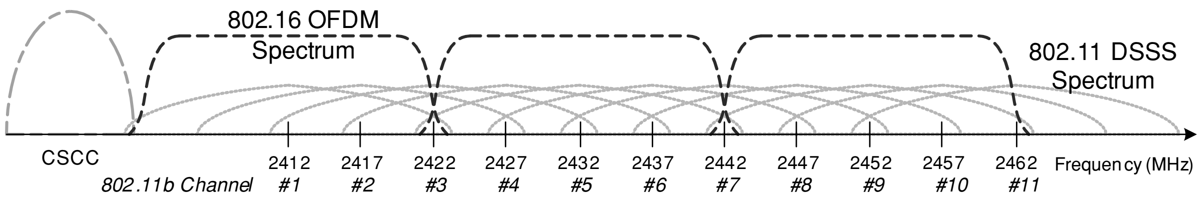


Fig. 12 Channel allocation for IEEE 802.11b and 802.16a

modulation is used with 2 Mbps data rate for 802.11b and 14 Mbps 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.

In order to capture the interference effects between the two systems, a physical-layer interference model is constructed to calculate the 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 [28] 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:

$$\mathrm{SINR}_j^{(n)} = \frac{Pt_{ij}^{(n)} G_{ij}^{(n)}}{N_j^{(n)} + \sum_{l \neq i} \alpha_{lj}^{(n)} Pt_l G_{lj}^{(n)}} \tag{5}$$

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.

5.2. Implementation in ns2

Both reactive (DFS, RTPC and TA) and proactive (CSCC) spectrum etiquette policies are implemented in Network Simulator version 2.27 (ns2) [5]. For DFS, ideal channel switching is assumed for 802.11b hotpots, 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 which AP selected. The 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 100 and 200 ms, which is the same order of magnitude as the transmission time for a short data session (∼ 50 packets with size of 512 bytes at 2 Mbps).

For RTPC, when a MAC packet is initiated at the sender, the current transmit power level (quantized to an 8-bit integer number between 0 and 255) is placed into 802.11b

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

Fig. 13 CSCC packet format

RTS or 802.16a frame header. The receiver then can obtain the received power of this packet and the sender's transmit power from the header. In this paper, we will use a constant target SINR of 12 dB, which approximately corresponds to a BER of 10^{-6} when using QPSK modulation. Then the receiver can compute the recommended transmit power from equation (1) and piggyback in the MAC header to the sender. Maximum transmit power is used for 802.11 RTS/CTS due to their short length and RTPC is applied to both 802.16a BS and SS (both downlink and uplink). The TA algorithm is implemented similar to RTPC. Receivers calculate the recommended transmission probabilities by Fig. 6, which are then piggybacked in MAC headers to the transmitters. In cases of packet loss, transmitters will transmit with probability 1 if there is data to send.

The CSCC etiquette protocol is implemented with a dual radio structure in each node. The spectrum coordination agent is between network and MAC layers, which monitors both data radio (IEEE 802.11b or 802.16a) and control radio (1 Mbps 802.11-type). The control radio is fixed at the CSCC channel. The packet format for CSCC messages is shown in Fig. 13.

A Pareto ON/OFF traffic model [24] is used to simulate Internet traffic, 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 in the CSCC message. A FCFS-based policy is used when there are contentions, 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.

6. Simulations

Scenarios with single or multiple 802.11b hotspots are simulated and various 802.16a SS node geographic distribu-

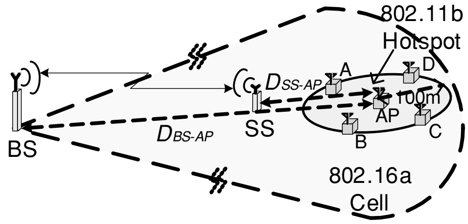


Fig. 14 Network scenario for single cell case

tions are also studied. DFS, RTPC, TA and the CSCC protocol are evaluated and compared in the scenarios considered.

6.1. Simulation parameters

The parameters used in the simulations are summarized in Table 1.

6.2. Simulation results

6.2.1. Single 802.16a cell and single 802.11b hotspot case

Each coordination algorithm is 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 placed 100 m away from the AP), as shown in Fig. 14. D_{BS-AP} is the distance between 802.16a BS and 802.11b AP and D_{SS-AP} is the distance between 802.16a SS and 802.11b AP.

6.2.1.1. Effect of DFS for spectrum overlapping In this simulation, we assume the center frequency of 802.16a cell is fixed at 2412 MHz, which overlaps the most with 802.11b channel #*1*, partially overlaps with 802.11b channel #*2*, #*3*, or #*4*, and does not overlap beyond channel #*5*. DFS enables 802.11b devices to avoid interference by switching their operating channels dynamically. Figure 15 shows the benefit of switching to different channels. We define the interference radius (IR) as the distance between two systems when their throughputs begin to degrade due to interference. When both 802.16a DL and 802.11 links are overloaded with CBR traffic (the most severely interfering case), IR will be 1.7 km if 802.11b is at channel #*1*, but IR can be reduced to 1.6, 1.4 and 1.2 km by switching 802.11b channel to #*2*, #*3* or #*4* respectively. By operating at channel #*5* or beyond, there will be no interference between the two systems (IR is zero). Similar results are observed with two 802.11b traffic flows in Fig. 15(b).

6.2.1.2. Effect of RTPC The same scenario shown in Fig. 14 is used and D_{BS-AP} is fixed at 3 km. RTPC is applied to both 802.11b links and 802.16a uplink and D_{SS-AP} is varied (the closer the 802.16a SS to 802.11b hotspot, the stronger the interference). Note that since the interference from 802.16a BS is fixed, RTPC is not applied to the 802.16a downlink here. Figure 16 shows the benefit by applying RTPC: the 802.16a SS throughput can increase up to 4 times at the expense of slight degradation in 802.11b throughput. When the SS node is close to the hotspot (strong interference), 802.11b node tends to more back-offs which will benefit 802.16a SS (throughput increase when D_{SS-AP} is small) by less inter-

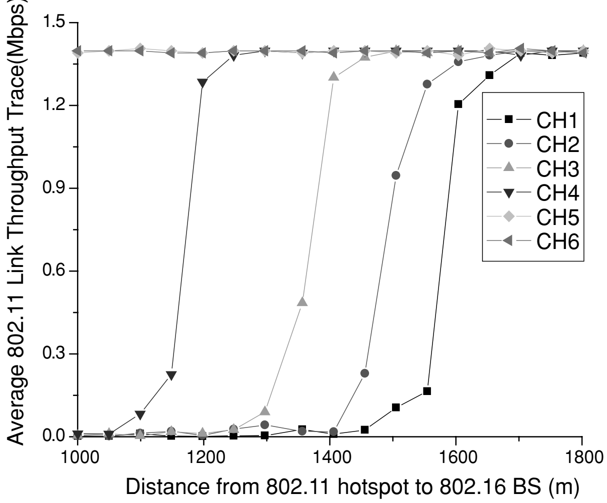
Table 1 Simulation parameters

	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	22 MHz / 11 overlapping channels
Raw Bit Rate	14 Mbps	2 Mbps
Radio parameters	OFDM (256-FFT, QPSK)	DSSS (QPSK)
Background noise density	– 174 dBm/Hz	
Receiver noise figure	9 dB	9 dB
Receiver sensitivity	– 80 dBm (@BER 10^{-6}, 14 Mbps)	– 82 dBm (@BER 10^{-5}, 2 Mbps) ∗
Antenna height	BS 15 m, SS 1.5 m	All 1.5 m
CSCC coverage	600 meters	
Maximum coverage	∼ 3 Km (@BS 33 dBm)	∼ 500 m (@20 dBm)
Transmitter power range	BS 0–33 dBm, SS 0–23 dBm	0–20 dBm

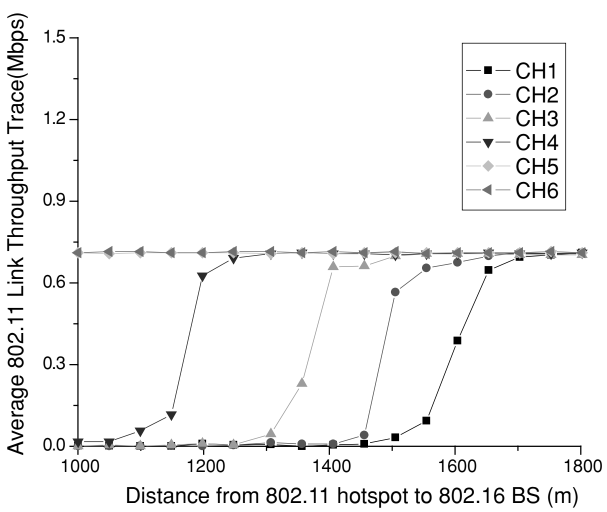
∗From CNWLC-811 Wireless 802.11b PC Card specification.

ference. In this case, DFS will have more benefit when there is no more degree of "freedom" to explore in the dimension of power.

6.2.1.3. Effect of time agility The TA algorithm is implemented for both systems to fill available gaps and avoid busy period in time domain by setting transmit probabilities to transmitters. Pareto ON/OFF traffic [24] 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 increasing it when 802.16a traffic is OFF by measuring SINR levels. Figure 17 shows that the TA 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

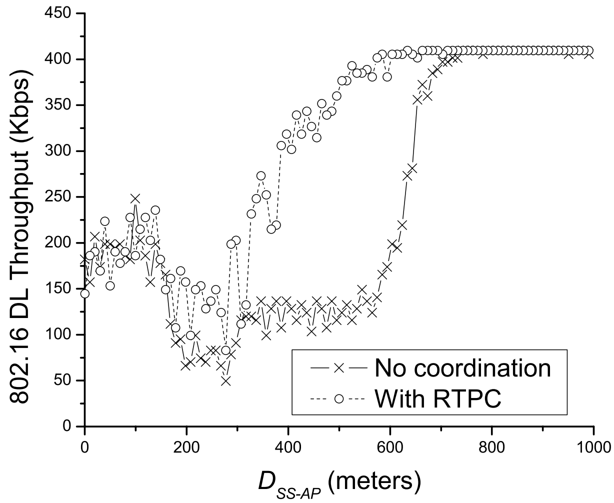


(a) With one 802.11b traffic flow

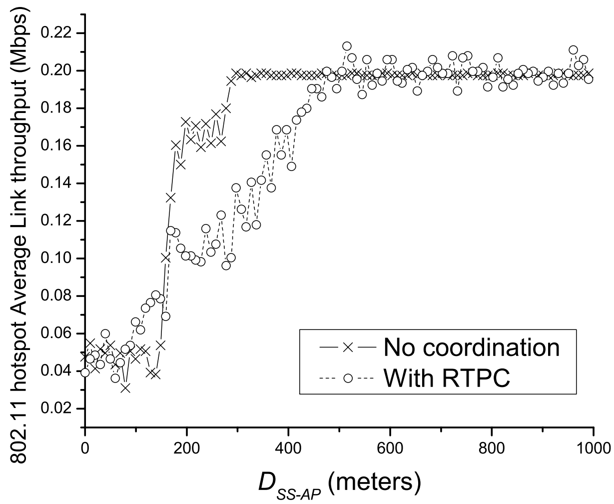


(b) With two 802.11b traffic flows

Fig. 15 Average 802.11b throughput vs. DBS-AP at different channels, when both systems have overloaded CBR traffic



(a) 802.16a DL throughput



(b) 802.11b hotspot throughput

Fig. 16 Average link throughput trace, 4 links for hotspot, each has Poisson arrival rate with inter-arrival mean time 3 ms

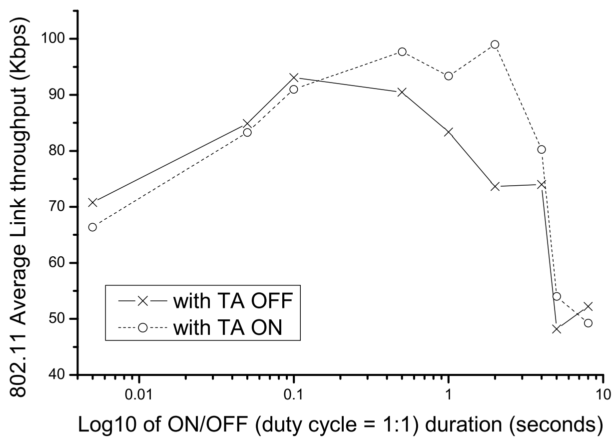
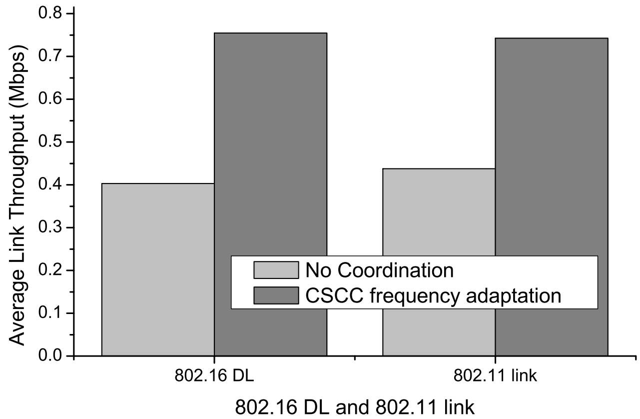
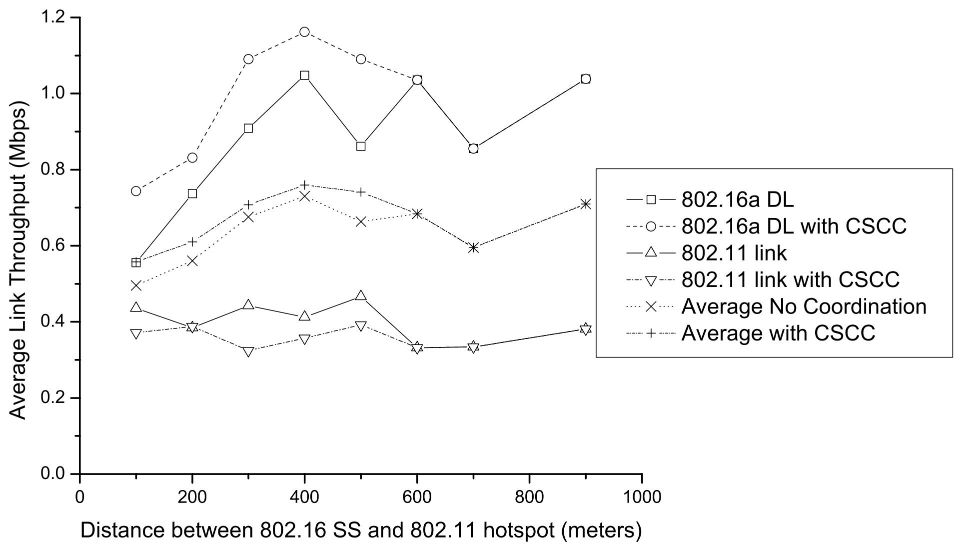


Fig. 17 Time agility by varying 802.16a Pareto traffic ON time, 802.11b nodes use CBR traffic with load 200 Kbps, and 802.16a node load is 1.3 Mbps

Fig. 18 Network throughput by using CSCC frequency or power adaptation when both systems have Pareto traffic with ON/OFF time = 500 ms/500 ms and traffic load 2 Mbps



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



(b) CSCC power adaptiation

agility only performs well under limited circumstances, this experiment serves as an example of the spectral "freedom" usage pattern dependence of coordination algorithms.

6.2.1.4. Evaluation of CSCC The network is the same as Figure 14, which is a typical hidden-receiver scenario. In the hotspot, traffic goes from AP to node A, and for 802.16a, only downlink (DL) traffic is considered so that the 802.16a SS becomes "hidden" to 802.11b interferers. All nodes are static and $D_{\mathrm{BS-AP}}$ is 1 km.

The throughputs for both systems are plotted in Fig. 18. By applying CSCC frequency adaptation (see Fig. 18(a)), both 802.16a DL and 802.11b throughput can almost be doubled since in this scenario there is enough vacant spectrum to use with CSCC coordination. To evaluate CSCC-based power adaptation algorithm in the highest interference case, we consider both systems' center frequencies fixed at 2412 MHz (they overlap mostly in frequency as shown in Fig. 12). Figure 18(b) shows 802.l6a DL throughput is improved by $\sim$35% which varies by $D_{\mathrm{SS-AP}}$. Since the 802.16a BS is

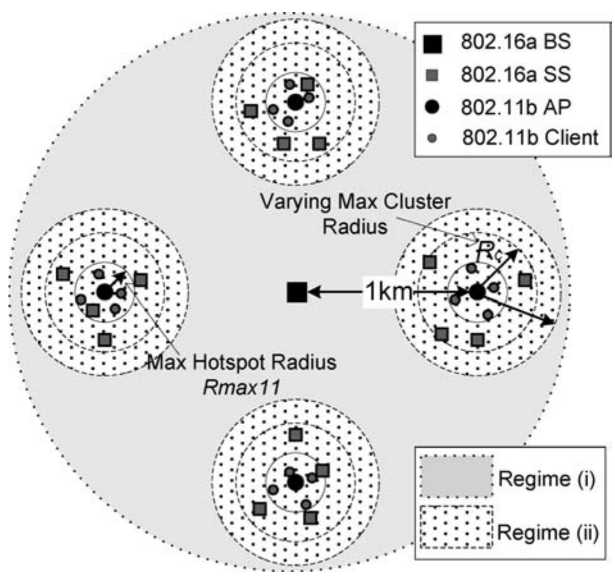


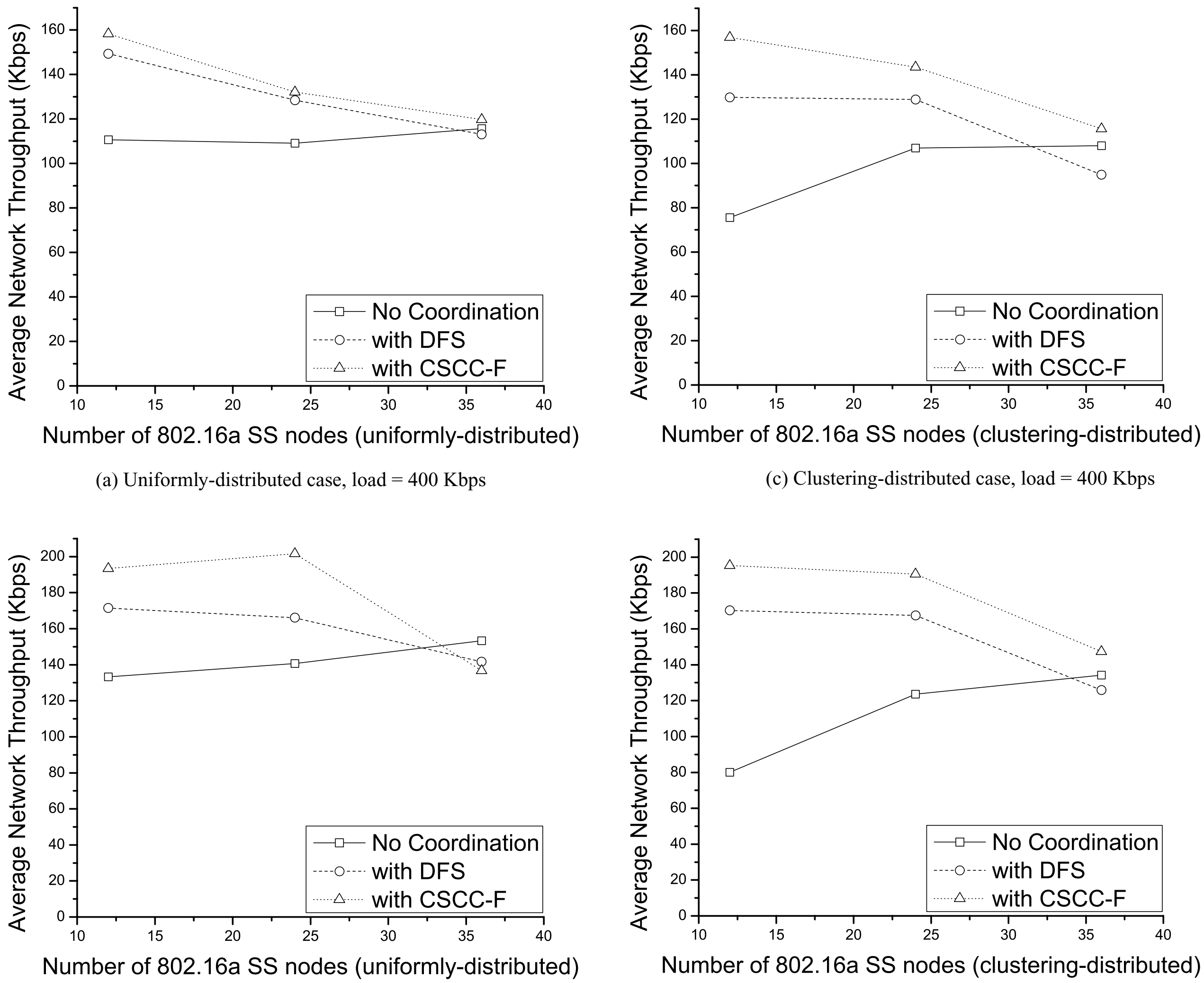
Fig. 19 Clustered hotspots and 802.16a SS (overlap in space)

1 km away (out of CSCC range), 802.11b hotspot 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.

6.2.2. Multiple 802.11b hotspots with varying 802.16a SS distribution case

In addition to the network scenario in Fig. 14, four 802.11b hotspots (with 4 clients and 1 AP per hotspot) are placed in one 802.16a cell with 1 km away from the BS, which is illustrated in Fig. 19. 802.11b nodes are randomly placed inside the hotspot with the distance to AP less than R_{max11} meters. The following geographic distributions of 802.16a SS were studied: (i) randomly (uniformly) distributed inside the 802.16a cell with a radius of 1.5 km; (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 the previous simulation.

First the results for CSCC adaptation in frequency (denoted as CSCC-F in Fig. 20) are compared with reactive dynamic frequency selection (DFS). Both 802.16a DL and UL traffics are considered. In Fig. 20(a) and (b) are the cases with uniformly-distributed 802.16a SS (regime (i) in Fig. 19); (c) and (d) are the cases with clustering-distributed SS



(a) Uniformly-distributed case, load = 400 Kbps

(c) Clustering-distributed case, load = 400 Kbps

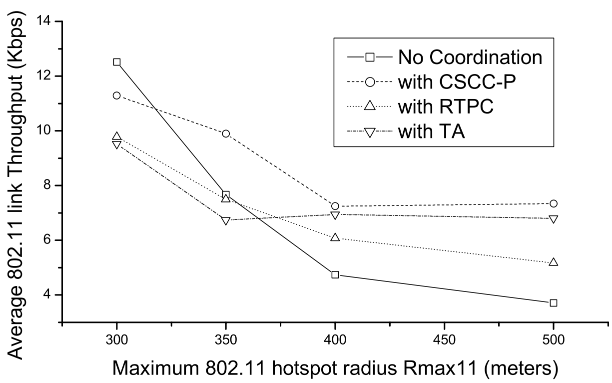
(b) Uniformly-distributed case, load = 600 Kbps

(d) Clustering-distributed case, load = 600 Kbps

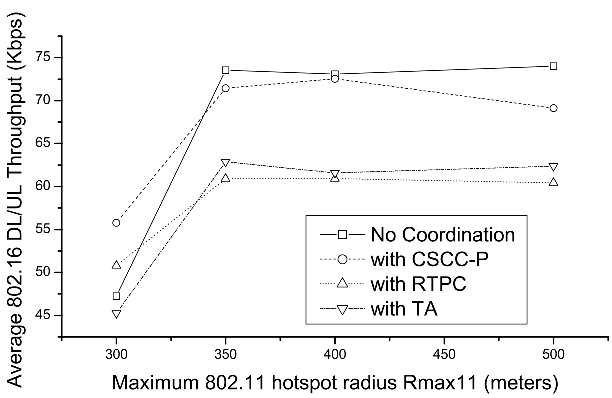
Fig. 20 Throughput for uniformly (a, b) and clustering (c, d) distributed 802.16a SS nodes (with 12 nodes in each 802.16a channel), when R_{max11} = 100 m, Rc = 200 m and Pareto traffic with ON/OFF time = 500 ms/500 ms nodes (regime (ii) in Fig. 19). The results show CSCC-F can significantly improve the average network throughput (up to ∼50% in uniformly distributed case and ∼140% in the clustering case). It also performs better than reactive DFS when the 802.16a SS node density is not very high, which means there is vacant spectrum for the two systems to operate in different channels. Comparing Fig. 20(a) with (b), the improvement amount is higher with more traffic load. When 802.16a SS nodes take all available spectrum bands (i.e., 36 nodes taking all 3 available 802.16a channels), the coordination in frequency may be insufficient due to lack of available spectrum, while adaptation in power will be explored.

To evaluate coordination via power adaptation, we assume the highest interference case with fixed center frequency at 2412 MHz for both systems (no adaptation in frequency). The CSCC-based power adaptation algorithm (denoted as CSCC-P in the Figures) is compared with reactive ones, i.e., RTPC (Reactive Transmit Power Control) and TA (Time Agility). The results for uniform distribution of 802.16a SS nodes in regime (i) are shown in Fig. 21 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". Figure 21-(a) shows that when the hotspot size is larger, its throughput is severely affected by the interference from 802.16a DL/UL, but the CSCC protocol can help improve hotspot throughput by ∼70–100% when R_{max11} is greater than 350 m accompanied 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 tend to degrade 802.16a throughput more severely.

The results for clustering-distributed 802.16a SS in regime (ii) are shown in Fig. 22. 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 50 m and C_i is varied by changing R_c. By applying CSCC-P, average network throughput can be improved up to ∼20% when the clustering index is greater than about 0.2 and the amount of

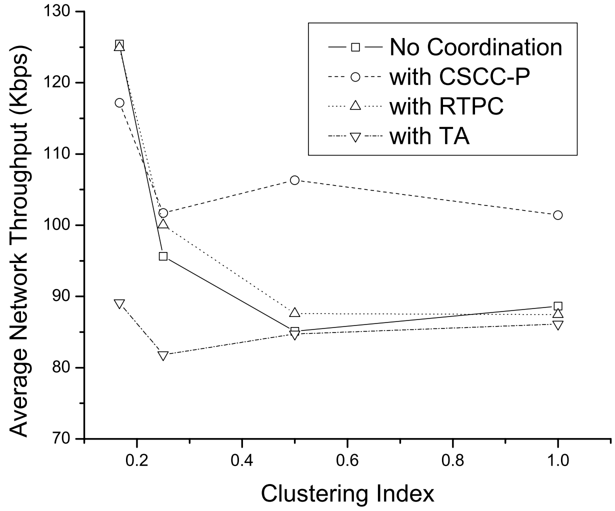


(a) Average hotspot throughput

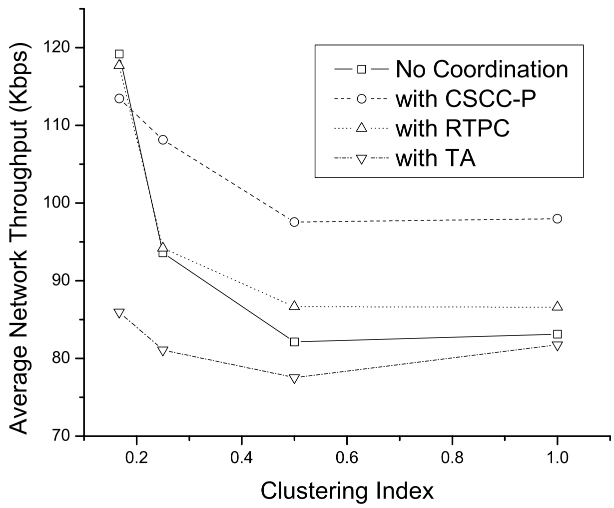


(b) Average 802.16a DL/UL throughput

Fig. 21 Throughput for 802.16a SS random distribution in regime (i) with varying hotspot radius Rmax11, and the number of 802.16a SS nodes : 802.11b nodes = 2:1, load 600 Kbps



(a) Offered load = 600 Kbps



(b) Offered load = 1 Mbps

Fig. 22 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 = 500 ms/500 ms improvement increases with C_i, which means higher interference between the two systems. The amount of throughput improvement increases with the offered traffic load (600 Kbps vs. 1 Mbps). The CSCC protocol also performs better than reactive methods in cases with significant spatial clustering, mainly due to the fact that it can deal with the hidden-receiver problem discussed earlier.

In summary, when the network scenario is simple and there is sufficient "free space" in frequency, power and time, simple reactive algorithms may be adequate for reducing interference and improving system throughput. Coordination schemes utilizing frequency adaptation (CSCC-F and DFS) can significantly improve the network throughput when there is vacant spectrum and the improvement will depend on the availability of vacant spectrum. When available spectrum is somewhat more congested the CSCC-based power adaptation algorithm can benefit hotspot throughput when the hotspot size is large with uniformly distributed 802.16a SS. In spatially clustered scenarios, the CSCC protocol can significantly improve average network throughput over reactive schemes when the clustering index is large.

7. Conclusions and future work

Spectrum co-existence of IEEE 802.11b and 802.16a networks has been studied using both reactive and proactive spectrum coordination policies to coordinate and reduce interference. Specifically, reactive algorithms such as DFS, RTPC and TA and proactive CSCC etiquette protocols are studied. The hidden-receiver scenario in which reactive algorithms may not work well was identified, and it was shown that the CSCC approach can help to solve this problem. Proposed reactive and proactive coordination policies were simulated in representative WiFi-WiMax co-existence scenarios, and system performance based on average throughput was evaluated and compared. Various 802.16a SS node density and geographic distributions were studied leading to an identification of spatial clustering regimes where CSCC coordination can significantly improve system throughput by solving the hidden-receiver problem. Our results demonstrate that CSCC power adaptation can help maintain 802.16 service quality at the expense of a modest decrease in 802.11 throughput in the hidden-receiver scenario considered. Overall system throughput can be significantly improved over reactive schemes depending on the degree of spatial clustering.

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 802.11b/802.16a co-existence. A prototype implementation for experimental verification is also planned.

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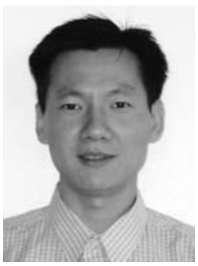

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