

# A Coexistence-Aware Spectrum Sharing Protocol for 802.22 WRANs

Kaigui Bian and Jung-Min “Jerry” Park  
Department of Electrical and Computer Engineering  
Virginia Tech, Blacksburg, VA 24061  
Email: {kgbian, jungmin}@vt.edu

**Abstract**—IEEE 802.22 is the first wireless standard based on cognitive radio (CR) technology. It defines the air interface for a wireless regional area network (WRAN) that uses fallow segments of the TV broadcast bands. CR technology enables unlicensed users in WRANs to utilize licensed (incumbent) spectrum bands on a non-interference basis to incumbent users. The coexistence between incumbent users and unlicensed users is referred to as incumbent coexistence. On the other hand, the coexistence between unlicensed users in different WRAN cells is referred to as self-coexistence. 802.22 defines several inter-base station (BS) dynamic resource sharing mechanisms to enable overlapping cells to share spectrum. However, those mechanisms do not adequately address some of the key issues concerning incumbent and self coexistence. In this paper, we propose an inter-BS Coexistence-Aware Spectrum Sharing (CASS) protocol for overlapping 802.22 cells that takes into account coexistence requirements. We show that the proposed protocol outperforms 802.22’s self-coexistence solutions using simulation results. To the best of our knowledge, the work presented here is the first systematic study of the self-coexistence problem in the context of 802.22 WRANs.

## I. INTRODUCTION

IEEE 802.22 specifies the air interface for a Wireless Regional Area Network (WRAN) that operates in fallow TV broadcast bands [6]. An 802.22 *cell* is a single-hop, point-to-multipoint wireless network composed of a Base Station (BS) and several Consumer Premise Equipments (CPEs). Incumbent services refer to TV broadcasting services or services for Part 74 devices<sup>1</sup> (wireless microphones) operating in TV bands, and secondary users refer to IEEE 802.22 entities (BS and CPEs). In 802.22, secondary users access licensed (incumbent) spectrum bands opportunistically on a non-interference basis to incumbent users. The coexistence between incumbent users and secondary users is referred to as *incumbent coexistence*, and the coexistence between WRAN cells is referred to as *Self-coexistence*. There are two main objectives in self-coexistence: minimizing the self interference between co-channel overlapping cells and satisfying the QoS of the cells’ admitted service workloads in a dynamic spectrum access environment.

802.22 prescribes two types of inter-BS dynamic resource sharing mechanisms so that cells can satisfy the QoS of their admitted workloads. A BS in need of spectrum (*renter* BS) is allowed to selectively rent *candidate* channels of neighboring cells (surplus channels that can be given up) via the Resource Renting mechanism. Note that a candidate channel of one cell may be an *active* channel (a channel in use) of another cell. Thus, Resource Renting is a *non-exclusive spectrum*

*sharing* scheme that enables neighboring BSs to share one or more channels. 802.22 also defines an *exclusive spectrum sharing* scheme called inter-BS *On-Demand Spectrum Contention (ODSC)*. In ODSC, a BS in need of spectrum (*contention source*) selectively contends for candidate channels of neighboring BSs (*contention destinations*). If the contention source wins the contention, it occupies the contended channels exclusively, while the contention destinations vacate those channels via channel switching.

Unfortunately, 802.22’s inter-BS resource sharing mechanisms do not consider incumbent coexistence issues when a renter BS selects channels to rent. If the appearance of incumbent signals in the rented channels is frequent, it is likely to have two negative impacts: the QoS degradation due to frequent channel switches in the renter cell when incumbent signals are detected by the renter and interference experienced by incumbent users. Another shortcoming of the resource sharing mechanisms is their failure to adequately address self-coexistence issues. The non-exclusive spectrum sharing scheme does little to prevent self-interference among co-channel overlapping cells, which can render 802.22 networks to be useless [1]. Although the exclusive spectrum sharing scheme can avoid self-interference altogether, it incurs heavy control overhead due to its channel contention procedure. Thus, an appropriate tradeoff has to be made between self-interference and control overhead. An ideal spectrum sharing mechanism needs to have the ability to dynamically “switch” between non-exclusive and exclusive spectrum sharing when the situation requires it.

In this paper, we propose an inter-BS *Coexistence-Aware Spectrum Sharing (CASS)* protocol. CASS has the following noteworthy features: (1) it supports both non-exclusive and exclusive spectrum sharing and can dynamically switch between the two to minimize self-interference while keeping control overhead (induced by channel contentions) under control; (2) it uses a new channel selection algorithm that utilizes spectrum sensing results in order to minimize the likelihood of interference to incumbent transmissions; and (3) it uses an inter-BS channel contention procedure that enables a BS in need of more channels to borrow channels from its neighboring cells more readily (compared to 802.22’s ODSC).

The rest of the paper is organized as follows. In Section II, we provide the technical background. In Section III, we propose the CASS protocol, and we evaluate the performance of CASS in Section IV. We discuss related work in Section V and conclude the paper in Section VI.

<sup>1</sup>Part 74 devices are low-power wireless devices, such as wireless microphones, which are licensed to operate in the TV broadcast bands.

## II. TECHNICAL BACKGROUND

### A. PHY-layer Support and MAC-layer Control Messages

802.22 employs a Distributed Spectrum Sensing (DSS) framework to identify fallow licensed bands free of incumbent signals. In a cell, every CPE is required to report its local spectrum sensing results to its BS via intra-cell measurement (control) messages. The BS has multiple radio interfaces for monitoring a number of channels simultaneously, and it determines the existence of incumbent signals on those channels using the local spectrum sensing reports from CPEs.

802.22 also defines inter-cell control messages as *beacons* to support the inter-BS communication. In every 802.22 time frame, there is a self-coexistence window for a BS to exchange beacons with neighboring BSs on multiple channels. If a beacon from a neighboring BS is received on a channel, that neighboring BS is deemed as a *co-channel BS* by the receiver BS. When direct inter-BS communication is infeasible, a BS instructs its associated CPEs (a.k.a. *bridge CPEs*) to listen for beacons from overlapping cells and report the information back. This feature enables a BS to obtain accurate information about other cells.

### B. Non-Exclusive Spectrum Sharing: Resource Renting

In an inter-BS dynamic resource sharing process, 802.22 defines *offerers* to be the BSs that have available resources and the *renter* to be the BS in need of spectrum. A renter BS initiates a Resource Renting process by broadcasting a *resource request* using inter-cell beacons. Upon reception of the resource request, neighboring BSs respond by broadcasting beacons that indicate their active channel sets and candidate channel sets. The *union* of candidate channel sets from neighboring BSs forms the renter BS's *grand candidate channel set* from which it selects channels to rent. The renter BS sends beacons to the offerers indicating the selected channel number and the duration of renting time. The Resource Renting process is concluded when the offerers transmit an acknowledgement back to the renter. 802.22 prescribes the following rule that the renter needs to comply with when selecting a channel:

**Rule 1.** *The renter should select a channel that interferes with the minimum number of channels being used by its neighbors.*

After selecting a channel, the renter BS has to determine whether non-exclusive sharing of the selected channel is feasible using the following rule:

**Rule 2.** *Non-exclusive spectrum sharing is feasible as long as the maximum achievable signal-to-interference ratio (SIR) on the selected channel is higher than the required SIR threshold of the network's supported services.*

If non-exclusive sharing is feasible, the BS schedules data transmissions on the selected channel with appropriate transmission power control settings.

1) *Self-interference caused by Resource Renting:* The above Resource Renting mechanism may cause severe self-interference among overlapping cells. We use  $r(x)$  to denote the minimum number of channels required by a BS  $x$  to satisfy the QoS of its workload. Let  $G(x)$  denote the grand candidate channel set for the renter BS  $x$ . In Fig. 1, we

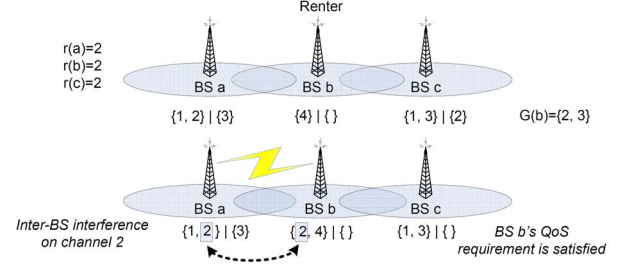


Fig. 1. Inter-cell Resource Renting in 802.22.

illustrate a scenario with three overlapping cells  $a$ ,  $b$ , and  $c$ . In this example, we have four channels in total, and  $r(a) = r(b) = r(c) = 2$ . BS  $a$ 's active channel set is  $\{1, 2\}$  and its candidate channel set is  $\{3\}$ . BS  $c$ 's active channel set is  $\{1, 3\}$  and its candidate channel set is  $\{2\}$ . Since BS  $b$  only has one active channel 4, it needs more channels to satisfy the QoS of its workload. Its neighboring BSs,  $a$  and  $c$ , have candidate channels to share with BS  $b$ . According to Rule 1, BS  $b$  can select channel 2 in  $G(b)$  to rent from BS  $c$ . Unfortunately, BS  $b$ 's renting of channel 2 will cause interference to BS  $a$ 's communications since BS  $a$  also uses channel 2. In this case, self-interference between BS  $a$  and BS  $b$  may severely degrade the network performance of both cells.

### C. Exclusive Spectrum Sharing: ODSC

To completely avoid self-interference, 802.22 also prescribes exclusive spectrum sharing of the selected channel (target channel) via ODSC [2]. The renter BS becomes the contention source when initiating the ODSC. The contention source randomly selects a *channel contention number* (CCN) that is uniformly distributed in the range  $[0, W]$ , where  $W$  is a constant representing the contention window size. The contention source includes its CCN and the target channel number in a spectrum contention request that it broadcasts to contention destination BSs. After receiving a spectrum contention request, a contention destination selects a CCN in the same manner as the contention source. Then the contention destination determines the outcome of the pair-wise contention using this contention resolution rule: the BS with a greater CCN value wins the pair-wise contention. This rule implies that the contention source's probability of winning a pair-wise contention is  $1/2$ . Note that the contention source wins the contended channel only if it wins *all* of the pair-wise contentions. If the contention source wins the contended channel, all contention destinations perform channel switching to vacate the channel.

## III. THE CASS PROTOCOL

### A. Basic Assumptions

We assume that the presence or absence of incumbent users' signals on a channel, say channel  $i$ , can be modeled as a continuous-time "ON/OFF" Poisson process [3], where inter-arrival times of consecutive incumbent signals are exponentially-distributed with a rate parameter. Let the random variable  $V_i$  denote the length of an incumbent's idle interval (*incumbent idle time period*) on channel  $i$ . Similarly, let the

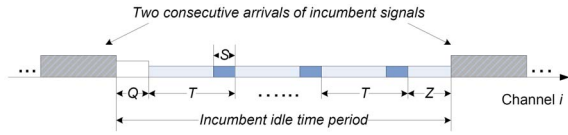


Fig. 2. Incumbent idle time period and channel contention periods.

random variable  $U_i$  denote the length of an incumbent's busy interval (*incumbent busy time period*) on channel  $i$ . Suppose that  $E[V_i] = v_i$  and  $E[U_i] = u_i$ . As shown in [8], the value of  $v_i$  and  $u_i$  can be estimated using spectrum sensing results. The probability that channel  $i$  is free of incumbent users' signals is

$$\alpha_i = \frac{v_i}{v_i + u_i}.$$

### B. Dynamic Switching between the Two Spectrum Sharing Modes

CASS supports two spectrum sharing modes: non-exclusive spectrum sharing and exclusive spectrum sharing. It can switch from one mode to the other depending on the channel conditions. CASS performs channel evaluation to determine when to switch from one mode to the other. In this channel evaluation process, CASS needs to calculate the channel capacity in each of the two spectrum sharing modes.

1) *Channel capacity in non-exclusive spectrum sharing mode:* If the renter BS shares channel  $i$  with its neighbors, self-interference may cause packet collisions. Let  $\gamma(i)$  denote the maximum achievable SIR perceived by the renter on the selected channel  $i$ . Let  $e(i)$  denote the packet error rate on the selected channel at a receiver (a CPE) in the renter's cell. The capacity of channel  $i$  in non-exclusive spectrum sharing can be expressed as

$$C_N(i) = \alpha_i \cdot (1 - e(i)).$$

In [12], Shellhammer describes a way of estimating  $e(i)$  based on  $\gamma(i)$ : given the modulation method, the symbol error rate (SER) can be estimated based on  $\gamma(i)$ ; then,  $e(i)$  can be calculated based on the SER.

2) *Channel capacity in exclusive spectrum sharing mode:* If exclusive spectrum sharing of the selected channel is necessary, a contention phase is periodically scheduled so that the channel contention procedure can be invoked. Let  $T$  denote the duration of a channel contention period. At the end of every contention period, a contention phase of length  $S$  is scheduled, as shown in Fig. 2.  $S$  must be long enough to perform channel contention-related operations, such as determining the target channel(s), performing channel contentions (via the exchange of inter-BS beacons), and preparing to resume transmissions on the new channels (if new channels have been acquired or if channel switches have occurred).

The capacity of channel  $i$  in exclusive spectrum sharing can be calculated as

$$C_E(i) = \alpha_i \cdot \frac{T_X(i)}{v_i},$$

where  $T_X(i)$  is the expected maximum transmission time for 802.22 entities on channel  $i$  during an incumbent idle time period.

802.22 entities cannot immediately start to access a channel once spectrum sensing determines that the channel is fallow. A quiet period of length  $Q$  is needed for performing spectrum sensing and channel setup before an 802.22 entity can access the channel, as shown in Fig. 2. Let the random variable  $\tau$  and random variable  $L_i$  denote the length of the incumbent idle time period and the length of an 802.22 entity's maximum transmission time on channel  $i$  (during an incumbent idle time period), respectively. One of two possible scenarios can occur:

- if  $\tau \leq Q$ ,  $L_i = 0$ ;
- If  $\tau > Q$ , the incumbent idle time period is composed of a quiet period,  $\lfloor \frac{\tau - Q}{T} \rfloor$  contention periods and a residual time interval  $Z$  as shown in Fig. 2, where  $0 \leq Z < T$ .

Let  $p_{FN}$  denote the false negative<sup>2</sup> probability of spectrum sensing in the contention source's cell. Now we can calculate the expected maximum transmission time on channel  $i$  as

$$T_X(i) = E[L_i] = 0 + (1 - p_{FN}) \cdot \int_Q^\infty \left( \lfloor \frac{\tau - Q}{T} \rfloor \cdot (T - S) + \min(Z, T - S) \right) \cdot p_\tau(i) d\tau,$$

where  $p_\tau(i)$  is the probability that there is no incumbent signal arrival in channel  $i$  during the time duration  $\tau$ . This value can be calculated using the following equation:

$$p_\tau(i) = \int_\tau^\infty \frac{1}{v_i} \cdot e^{-\frac{u}{v_i}} du = e^{-\frac{\tau}{v_i}}.$$

3) *An approach of switching between two modes:* In 802.22, the non-exclusive spectrum sharing of the selected channel is attempted first. As stated in Rule 2, if the maximum achievable SIR on the selected channel is not sufficiently high, 802.22 prescribes exclusive spectrum sharing. However, 802.22 fails to give specific guidelines on when to use exclusive sharing. We propose one possible approach for determining when to use exclusive spectrum sharing. CASS determines which spectrum sharing mode to operate in, for a given channel  $i$ , by comparing  $\gamma(i)$  with the required SIR threshold parameter  $\gamma^*(i)$ . To obtain the value of  $\gamma^*(i)$ , we need to first solve for  $e(i)$  in the equation  $C_N(i) = C_E(i)$ ; and then find the SIR value corresponding to the solved  $e(i)$ , which is used as the value of  $\gamma^*(i)$ . CASS determines the spectrum sharing mode as follows:

- 1) If  $\gamma(i) \geq \gamma^*(i)$ , CASS operates in the non-exclusive spectrum sharing mode. The benefits of non-exclusive sharing (e.g., low control overhead) outweigh the benefits of exclusive sharing (e.g., no self-interference).
- 2) If  $\gamma(i) < \gamma^*(i)$ , CASS operates in the exclusive spectrum sharing mode. The benefits of exclusive sharing outweigh the benefits of non-exclusive sharing.

### C. The Channel Selection Mechanism

The channel selection criterion in 802.22's mechanisms (Rule 1) implies that the renter BS does not consider any incumbent coexistence issues. It may not be suitable in environments where the appearance of incumbent signals are frequent and unpredictable—such a scenario would likely occur

<sup>2</sup>This type of error occurs when the spectrum sensing results erroneously indicate that a channel is free of incumbent signals when in fact the opposite is true.

in areas where Part 74 devices operate. After the incumbent signals on active channels have been detected in a cell, the BS and CPEs need to vacate those channels as soon as possible and find suitable replacement channels. The incumbent users in the cell's vicinity are also likely to experience some level of interference. Instances of such undesirable situations can be reduced by considering the incumbent coexistence requirement during the channel selection process. We propose to use an incumbent protection criteria—probability of interfering with incumbent signals on an 802.22 channel. CASS prescribes that the renter BS should select an 802.22 channel that has the lowest probability of interfering with incumbent signals.

For a BS  $x$  in need of spectrum, let  $N(x)$  denote the set of neighboring BSs of  $x$ . Let  $C(y)$  denote BS  $y$ 's set of candidate channels. BS  $x$ 's grand candidate channel set is

$$G(x) = \bigcup_{y \in N(x)} C(y).$$

For channel  $i$  and BS  $y$ , let  $r_i^y$  denote the probability that BS  $y$  schedules data transmissions on channel  $i$  in a given time interval. The value of  $r_i^y$  for any channel  $i$  is determined by the BS  $y$  itself. When  $r_i^y = 0$ , this means that channel  $i$  is a candidate channel for BS  $y$  or channel  $i$  is not allocated to BS  $y$ . Neighboring BSs exchange information on each other's  $r_i^y$  value using inter-cell beacons<sup>3</sup>.

We define the *channel accessibility* of channel  $i$  for the renter BS  $x$ , represented by notation  $\varphi_x(i)$ , as the probability that BS  $x$  can access channel  $i$  with no incumbent or self-interference in a given time interval. We can compute  $\varphi_x(i)$  using the following equation:

$$\varphi_x(i) = \alpha_i \prod_{y \in N(x)} (1 - r_i^y).$$

We define the set of *accessible candidate channels* for the BS  $x$  as

$$R(x) = \{i | \varphi_x(i) > \eta, i \in G(x)\}, \quad (1)$$

where  $\eta$  is an adjustable parameter.

To comply with CASS's channel selection rule, BS  $x$  selects channel  $s$  such that

$$s = \arg \min_{i \in R(x)} \{p_{int}(i)\}, \quad (2)$$

where  $p_{int}(i)$  is the probability of interfering with incumbent signals on channel  $i$ . Let  $t$  denote the expected length of secondary user packets. If  $v_i$  is known,  $p_{int}(i)$  can be calculated as

$$p_{int}(i) = 1 - \int_t^\infty \frac{1}{v_i} \cdot e^{-\frac{u}{v_i}} du = 1 - e^{-\frac{t}{v_i}}. \quad (3)$$

CASS's channel selection technique minimizes the probability of interfering with incumbent signals (as prescribed by (3)) subject to the constraint on channel accessibility (as prescribed by (1)).

<sup>3</sup>In 802.22, a *quiet period* in every 802.22 frame is used for 802.22 entities to exchange inter-cell beacons. Information about the cell's candidate channel sets and active channel sets is contained in the beacons.

#### D. The Channel Contention Procedure

In ODSC's CCN-based channel contention procedure, the probability that the contention source wins the contention process is equal to the probability that it wins all of the pair-wise contentions, which is  $(1/2)^n$  ( $n$  is the number of contention destinations or the number of pair-wise contentions). This implies that a contention source is unlikely to win the needed channels when there are a large number of contention destinations. To address this problem, instead of using CCN, CASS employs the *Contention Priority Number (CPN)* to resolve pair-wise contentions.

1) *Contention priority number*: In CASS, the winner of a pair-wise contention is determined by comparing the contention source's CPN with the contention destination's CPN. Before we explain how the CPN is determined, we describe how a BS's "occupancy timeshare" on a channel is defined. In the  $k^{th}$  incumbent idle time period on channel  $i$ , the contention source BS  $x$  calculates its occupancy timeshare value on this channel,  $S_x(i)$ , using the following equation:

$$S_x(i) = \max\left(\sum_{j=1}^k m_x^j(i), 1\right),$$

where  $m_x^j(i)$  is the number of frames in the  $j^{th}$  incumbent idle time period during which channel  $i$  is allocated to BS  $x$ . Similarly, a contention destination BS  $y$  calculates its occupancy timeshare value on this channel represented by  $S_y(i)$ . In CASS, we use the occupancy timeshare values,  $S_x(i)$  and  $S_y(i)$ , to represent the CPNs of BS  $x$  and BS  $y$  on channel  $i$ , respectively.

2) *Contention resolution rule*: CASS's contention resolution rule is straightforward: the contention source BS wins the pair-wise contention if it has a *smaller CPN* than the contention destination BS. This rule guarantees that the contention source acquires the needed channels if its occupancy timeshare on those channels is smaller than those of contention destinations. The contention destination BS  $y$  uses the following rule to resolve the pair-wise contention with BS  $x$ .

- If the contended channel is one of the channels in BS  $y$ 's candidate channel set, BS  $x$  acquires the contended channel directly.
- If the contended channel is contained in BS  $y$ 's active channel set, it compares  $S_y(i)$  with  $S_x(i)$  to determine the outcome of the pair-wise contention: if  $S_x(i) < S_y(i)$ , BS  $x$  wins the pair-wise contention, and BS  $y$  gives up the channel  $i$ ; otherwise, BS  $y$  wins.

If BS  $x$  wins all of the pair-wise contentions, it adds channel  $i$  to its active channel set. Each contention destination removes the contended channel  $i$  from its available channel list. In the next quiet period, BSs involved in the channel contention process send beacons to its neighboring BSs to notify them about the change in channel allocation.

#### IV. PERFORMANCE EVALUATION

In this section, we compare CASS with 802.22's inter-BS resource sharing mechanisms via simulation results. All of the scenarios we considered involve multiple overlapping cells. In each cell, there is one BS and ten CPEs. Every BS requires

TABLE I  
Default Simulation Parameter Values.

Simulation Parameters	Values
Total licensed spectrum band	54–806 MHz
Bandwidth of a licensed channel	8 Mbps
Number of licensed channels	10
BS transmission radius	30 Km
TV transmission receiving radius	30 Km
Modulation method	QPSK
Effective Antenna height of the BS	30 m
Effective antenna height of the CPE	9 m
Channel switch delay	10 ms
802.22 frame size	40 ms

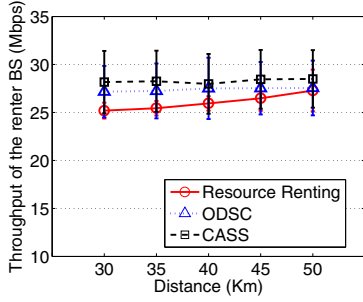


Fig. 3. Throughput of BS  $b$  vs. distance  $d$  in the 3-BS scenario.

five channels to satisfy the QoS of its admitted workload. BSs of overlapping cells are synchronized by the periodic transmission of inter-cell beacons. The simulation parameter values were chosen to be consistent with those used in the simulation experiments in [5], and they are given in Table I. The 802.22 Working Group has suggested that a variation of the Hata model is the most appropriate propagation model for studying 802.22 [4]. The Hata model [10] represents the urban area propagation loss as a standard formula and supplies correction equations to model suburban and open rural areas. In our simulations, we use a variation of the Hata model for open rural areas. We simulated three inter-BS spectrum sharing protocols: 802.22 Resource Renting, 802.22 ODSC, and CASS. Note that Resource Renting is a pure non-exclusive spectrum sharing protocol; ODSC is a pure exclusive spectrum sharing protocol; and CASS can operate in either spectrum sharing mode, switching from one mode to the other when the channel conditions warrant it. We created our own event-driven simulator in C, and each simulation result is the average value of ten simulation runs.

We use the notation  $\lambda_i$  to denote the number of incumbent signal arrivals on channel  $i$  during one superframe<sup>4</sup>, assuming that the incumbent signals follow a Poisson arrival process—hereafter, we’ll simply refer to this value as the incumbent transmission rate. We assume that there is at most one incumbent transmitter per channel per cell.

#### A. The 3-BS Scenario

We simulated a scenario with three overlapping 802.22 cells. The topography of the cells is shown in Fig. 1. The distance between two neighboring BSs is  $d$  Km. In this simulation

experiment, the initial channel assignments are given as: BS  $a$ ’s active channel set is  $\{1, 2, 3, 4, 9\}$  and its candidate channel set is  $\{10\}$ . BS  $c$ ’s active channel set is  $\{1, 2, 3, 4, 10\}$  and its candidate channel set is  $\{9\}$ . BS  $b$  has only an active channel set  $\{5, 6, 7, 8\}$ , and it is in spectrum shortage. The grand candidate channel set of BS  $b$  is  $G(b) = \{9, 10\}$ . Let  $\lambda_i = 0, i = 1, 2, \dots, 9$ , and  $\lambda_{10} = 1/2$ .

Fig. 3 shows a plot of the throughput of BS  $b$  (renter) vs. the distance between neighboring BSs,  $d$ . As expected, when  $d$  is small ( $< 50$  Km), CASS and ODSC outperformed Resource Renting. When the distance between neighboring BSs is small, the SIR measured at the 802.22 entities (BS and CPEs) of the renter cell is low due to self-interference. In such a situation, a non-exclusive spectrum sharing scheme, such as Resource Renting, would be expected to perform poorly. When  $d = 50$  Km, Resource Renting’s performance was comparable to that of ODSC because the effects of self-interference were insignificant at this distance.

Fig. 3 shows that CASS outperforms both Resource Renting and ODSC irrelevant of the value of  $d$ . We can explain this result by recalling the fact that CASS attempts to select a channel that is most underutilized by the incumbent users by requiring the renter BS to consider spectrum sensing results during the channel selection process; in contrast, the other two spectrum sharing schemes do not consider spectrum sensing results. When either Resource Renting or ODSC is used, the likelihood that an incumbent signal appears in the active channel(s) is higher compared to CASS. Obviously, the appearance of incumbent signals in an active channel degrades the renter cell’s throughput as this requires costly channel switches. When CASS is used, BS  $b$  selects channel 9 from its grand candidate channel set because  $\lambda_9 < \lambda_{10}$ . In practice, a renter BS can use the following procedure to utilize spectrum sensing results when selecting a channel: (i) Using a compiled record of recent spectrum sensing data and a maximum likelihood estimator, estimate the expected incumbent idle time for each channel (see [8] for details); (ii) Using (3) and the values obtained in the first step, calculate the probability of interfering with incumbent signals for each channel; and (iii) Select a channel using (2).

#### B. The 9-BS Scenario

We simulated a network topography with 9 overlapping cells in a  $100 \times 100$  Km area. All channels are randomly assigned to the BSs. Fig. 4(a) shows plots of average throughput per cell vs. the number of incumbent transmitters per cell. The incumbent transmission rate was fixed to  $1/4$  for all incumbent transmitters. The performance gap is seen between Resource Renting and ODSC. In such a high self-interference environment, non-exclusive spectrum sharing schemes are inferior to exclusive spectrum sharing schemes. Fig. 4(b) shows plots of average throughput per cell vs. incumbent transmission rate.

Fig. 4(c) shows plots of the average throughput per cell vs. the channel switch delay. In the corresponding simulation experiments, we included four active incumbent transmitters that have the same transmission rate, viz  $1/16$ . In inter-BS spectrum sharing, the channel switch delay is the biggest contributing factor to the control overhead. A recent study

<sup>4</sup>An 802.22 superframe is composed of 16 frames.



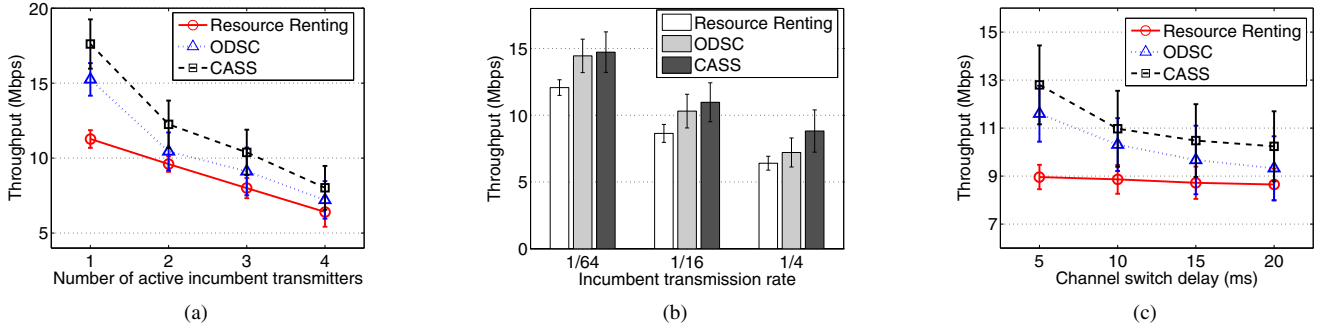


Fig. 4. Simulation results of the scenario with 9 overlapping cells.

has found that the channel switch latency for most popular wireless cards is between 5 ms and 20 ms [9]. In Fig. 4(c), we used the same range of values for the channel switch delay. As the channel switch delay increases, the control overhead caused by channel switch events during the channel contention procedures increases, thereby degrading the performance of ODSC and CASS.

## V. RELATED WORK

In concept, 802.22's non-exclusive spectrum sharing mechanisms are somewhat similar to channel borrowing schemes proposed for cellular telephone networks [7]. In a channel borrowing scheme, a BS of one cell borrows channels from adjacent BSs. However, there is one important difference between 802.22's non-exclusive spectrum sharing and channel borrowing in cellular telephone networks—the former is a distributed process whereas the latter is a centralized process. 802.22 cells will be likely managed by different wireless service providers, and thus there will be no central entity that has the authority to manage channel assignments between 802.22 cells. For this reason, 802.22 carries out spectrum sharing (through channel borrowing) in a distributed manner. In contrast, channel assignment and sharing in cellular telephone systems are carried out in a centralized manner since cells in a given region are typically controlled by a centralized base station controller.

The research community's interest in the air interface for dynamic spectrum access has intensified in recent years. In [11], Sengupta et al. propose improvements for 802.22's air interface. Specifically, they formulated the 802.22 channel assignment problem as a vertex coloring problem, and proposed a coloring algorithm called Utility Graph Coloring (UGC) that is a centralized algorithm designed to maximize system utility (i.e., spectrum reuse). In [3], the authors studied techniques to maximize throughput in dynamic spectrum access networks under incumbent protection constraints.

## VI. CONCLUSION

The primary objective of 802.22 inter-BS spectrum sharing is to address the two major challenges in self-coexistence: minimize self-interference (among cells) and enable cells to acquire enough resources to satisfy the QoS of their admitted workloads (in opportunistic spectrum sharing environments).

In this paper, we identified the drawbacks of 802.22's spectrum sharing mechanisms and proposed a new inter-BS spectrum sharing protocol called *Coexistence-Aware Spectrum Sharing* (CASS). Our simulation results show that CASS outperforms 802.22's spectrum sharing mechanisms. The major contributions of this paper include the following: (1) CASS gives us some level of insight on how to determine whether non-exclusive spectrum sharing or exclusive spectrum sharing should be employed; (2) CASS uses a channel selection strategy that incorporates spectrum sensing information to help satisfy incumbent coexistence requirements and improve network throughput; (3) CASS employs a channel contention procedure that was designed to avoid the drawbacks of ODSC's channel contention procedure.

## ACKNOWLEDGMENT

This work was partially sponsored by NSF through grants CNS-0627436, CNS-0716208, and CNS-0746925.

## REFERENCES

- [1] C. M. Cordeiro, K. Challapali, D. Birru, and N. S. Shankar, "IEEE 802.22: The First Worldwide Wireless Standard Based on Cognitive Radios," *IEEE DySPAN*, Nov. 2005.
- [2] D. Grandblaise and W. Hu, "Inter Base Stations Adaptive On Demand Channel Contention for IEEE 802.22 WRAN Self Coexistence," IEEE docs: IEEE 802.22-07/0024r0, Jan. 2007.
- [3] S. Huang, X. Liu, and Z. Ding, "Opportunistic Spectrum Access in Cognitive Radio Networks", *IEEE INFOCOM*, April 2008.
- [4] IEEE 802.22 Working Group, "Reviews of Channel Model," IEEE docs: 22-05-0070-00-0000, Aug. 2005.
- [5] IEEE 802.22 Working Group, "ETRI FT Philips Samsung Proposal," IEEE docs: 22-06-0005-01-0000, Jan. 2006.
- [6] IEEE 802.22 Working Group, <http://www.ieee802.org/22/>.
- [7] H. Jiang, and S. S. Rappaport, "CBWL: A New Channel Assignment and Sharing Method for Cellular Communications Systems", *IEEE Trans. on Vehicular Technology*, Vol. 43(2), May 1994, pp. 313–321.
- [8] H. Kim and K. G. Shin, "Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in Cognitive Radio Networks", *IEEE Trans. on Mobile Computing*, Vol. 7(5), Jan. 2008, pp. 533–545.
- [9] A. Mishra, V. Shrivastava, D. Agrawal, S. Banerjee, and S. Ganguly, "Distributed Channel Management in Uncoordinated Wireless Environments", *ACM Mobicom*, Sept. 2006, pp. 170–181.
- [10] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Upper Saddle River, NJ: Prentice Hall, 2001.
- [11] S. Sengupta, S. Brahma, M. Chatterjee and S. Shankar, "Enhancements to Cognitive Radio Based IEEE 802.22 Air-Interface," *IEEE ICC*, June 2007, pp. 5155–5160.
- [12] S. J. Shellhammer, "Estimation of Packet Error Rate Caused by Interference using Analytic Techniques - A Coexistence Assurance Methodology," IEEE docs: P802.19-05/0028r1, Sept. 2005.