

ADDRESSING THE HIDDEN INCUMBENT PROBLEM IN 802.22 NETWORKS*

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ABSTRACT

In the context of IEEE 802.22 networks, the hidden incumbent problem refers to a situation in which a consumer premise equipment (CPE) is within the protection region of an operating incumbent but it fails to report the existence of the incumbent to its base station (BS). In such a scenario, CPEs within the incumbent’s transmission range may not be able to decode the BS signal because of the strong interference from the incumbent signal. Moreover, the CPEs cannot report the existence of the incumbent as their transmission will cause interference to the incumbent. Therefore, these CPEs are unable to report the existence of the incumbent to the BS, and hence the BS fails to detect the presence of the incumbent. To address this problem, IEEE 802.22 prescribes that the BS broadcasts explicit outband control signals on a set of candidate channels and CPEs search for control signals on those candidate channels so that they can send the hidden incumbent detection messages to the BS via one of the candidate channels. In this paper, we present a systematic way of designating the candidate channel sets for the hidden incumbent detection (HID) protocol in 802.22 networks. The proposed approach has two noteworthy features: (1) it allows the BS and the CPE to choose different sets of candidate channels in a distributed manner without message exchanges; and (2) it significantly reduces the size of the set of candidate channels for each 802.22 entity, thus lowering the control overhead of the HID protocol.

1. INTRODUCTION

IEEE 802.22 defines the air interface for a wireless regional area network (WRAN) that uses fallow segments of the TV broadcast bands [4]. 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). In 802.22, incumbent services refer to TV broadcasting services or services for Part 74 devices¹ (wireless microphones) operating in TV bands, and secondary users refer to IEEE 802.22 entities (BS and CPEs). Cognitive Radio (CR) technology enables unlicensed (secondary) users in WRANs to utilize licensed (incumbent) spectrum bands on a non-interference basis to incumbent users [1].

The *hidden incumbent* problem refers to a situation in which a CPE is within the protection region of an operating incumbent but fails to report the existence of the incumbent to its BS. The BS transmits in the incumbent’s band but is unaware of the fact that the incumbent is using the same band. In such a scenario, CPEs within the incumbent’s transmission range may not be able to decode the BS signal because of the strong interference from the incumbent signal. Moreover, the CPEs cannot report the existence of the incumbent as their transmission will cause interference to the incumbent. Therefore, the BS fails to detect the presence of the incumbent.

The IEEE 802.22 standard defines an *explicit outband signaling* mechanism for hidden incumbent detection (HID). When a CPE lies in the protection region of an operating incumbent, it searches for control signals on multiple outband candidate channels where the BS periodically broadcasts outband control signals. In this approach, the CPE’s set of candidate channels is the same as the BS’s. However, it is possible to reduce the size of the candidate channel set to lower the control overhead. We show that it is possible for the BS and the

* This research was supported in part by the National Science Foundation under grants CNS-0627436, CNS-0716208, and CNS-0746925.

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

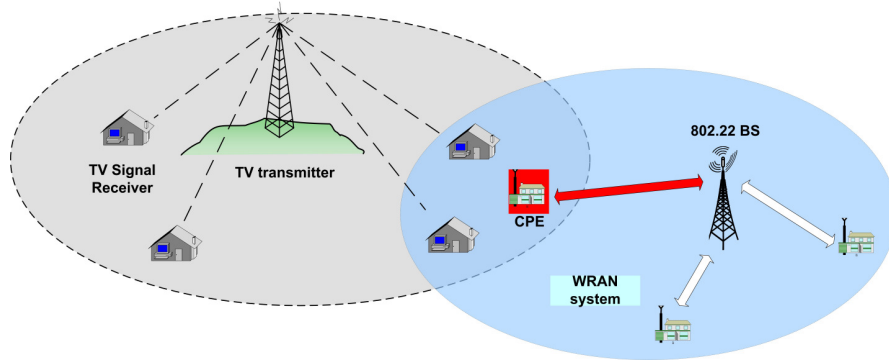


Figure 1: Illustration of the hidden incumbent problem.

CPE to have different candidate channel sets while still guaranteeing the delivery of HID messages. In this paper, we propose a systematic way of designating the candidate channel sets for the hidden incumbent detection (HID) protocol in 802.22 networks. The proposed scheme has two noteworthy features: (1) it enables a BS and a CPE under the control of the BS to each choose a different candidate channel set in a distributed manner without message exchanges; and (2) it significantly reduces the required number of candidate channels, thus lowering the control overhead.

The rest of the paper is organized as follows. We provide technical background in Section 2 and describe our candidate channel set designation scheme in Section 3. We discuss related work in Section 4 and conclude the paper in Section 5.

2. PRELIMINARIES

In this section, we provide the technical background that will facilitate the understanding of the various concepts presented throughout the paper.

2.1. Explicit Outband Signaling for Hidden Incumbent Detection

We use an example to explain the hidden incumbent problem. In a WRAN system as shown in Figure 1, the BS is in service on channel x , and some CPE inside the interference range of the incumbent system (e.g., the cell composed of a TV transmitter and several TV signal receivers) may not be able to decode the BS signal because of strong interference from the incumbent transmitter (TV transmitter). Thus, this CPE cannot report the existence of the incumbent system to the BS, and the BS fails to detect the presence of the “hidden”

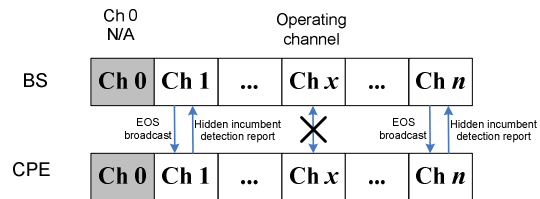


Figure 2: An example of the explicit outband signaling scheme for hidden incumbent detection.

incumbent system. In such a situation, some incumbent users (e.g., TV signal receivers inside the overlapping area in Figure 1) will experience interference from the WRAN system.

To address this problem, the 802.22 standard suggests that a BS periodically broadcast the *explicit outband signal* (EOS) in a set of other unoccupied channels, referred to as *the set of candidate channels*. The EOS that includes the information of the BS’s current service channel is a control signal broadcasted by the BS on the outband candidate channels. When some CPEs cannot decode the BS’s current service channel, the CPEs try to sense those outband candidate channels in an attempt to locate the BS signal. If CPEs receive an explicit outband broadcast signal, the CPEs can recognize the current service channel ID of the BS. If the current service channel was already sensed and was found to be not decodable at a CPE, then the CPE sends a HID report to the BS via an outband channel in the upstream link. After receiving the report, the BS changes its service channel to some other available band because the BS notices the existence of the hidden incumbent in the current service band.

Figure 2 illustrates an example of the HID protocol prescribed in 802.22. Suppose channel x is the current operating channel between the BS and the CPE, channel 0 is sensed as not available (N/A), and channels 1, 2, ..., $x-1$, $x+1$, ..., n are candidate channels, free of incumbent signals. When channel x is unavailable due to the hidden incumbent interference, the CPE senses those candidate channels where the BS broadcasts EOS. In this example, the CPE detects the EOS on channel 1 and sends HID reports to the BS on the same channel. Note that the set of candidate channels of the BS is identical to the set of candidate channels sensed by the CPE.

2.2. Problem Statement

Suppose there are n licensed channels available to an 802.22 WRAN cell, labeled as 0, 1, ..., $n-1$. Let A denote the set of all channels, and thus

$$A = \{0, 1, \dots, n-1\}.$$

Suppose channel x is an operating channel of the WRAN cell. Let $C(i)$ denote the set of candidate channels of an 802.22 entity i , which satisfies:

$$C(i) \neq \emptyset \text{ and } C(i) \subseteq A \setminus \{x\}.$$

If the operating channel x is temporarily unavailable due to incumbent signal interference, then BS i invokes the explicit outband signaling process on the set $C(i)$. At the same time, CPE j under the control of BS i also scans all the channels in $C(j)$ searching for the BS's control signals. To guarantee the detection of the EOS and the delivery of HID reports, the following two properties need to be satisfied:

$$C(i) \cap C(j) \neq \emptyset. \quad (1)$$

$$C(i) \subseteq A \setminus \{x\} \text{ and } C(j) \subseteq A \setminus \{x\}. \quad (2)$$

In the 802.22 standard, the set of candidate channels used by CPE j is the same as the one used by its BS i , i.e., we have

$$C(j) = C(i).$$

The most naïve solution to the hidden incumbent problem is to let the BS broadcast the EOS on all channels that are free of incumbent signals, and the CPEs to sense those channels. We can significantly reduce the control overhead, if it is possible for the BS to broadcast the EOS in fewer channels and the CPEs to sense fewer channels. In this paper, we propose a HID protocol that requires a significantly reduced number of candidate channels (compared to the number required by 802.22), while guaranteeing that the BS and the CPE have at least one channel in common that can be used for uplink and downlink communications.

3. THE HIDDEN INCUMBENT DETECTION PROTOCOL

In this section, we describe the proposed hidden incumbent detection (HID) protocol.

3.1. Construction of the Candidate Channel Sets

Our scheme utilizes quorum systems [3, 8, 10] to construct sets of candidate channels that satisfy (1) and (2).

Definition 1: Given a finite universal set $U = \mathbf{Z}_m$ of m elements, a *quorum system* S under U is a collection of non-empty subsets of U , which satisfies the intersection property:

$$p \cap q \neq \emptyset, \forall p, q \in S.$$

Each $p \in S$ (which is a subset of U) is called a *quorum*. Here, \mathbf{Z}_m denotes the set of nonnegative integers less than m .

In the following definitions, we define three types of quorum systems.

Definition 2: Given a finite universal set $U = \mathbf{Z}_m$ of m elements, a *singleton* quorum system S is a quorum system under U that has exactly one quorum q .

For example, $S = \{\{0, 1, 2\}\}$ is a singleton quorum system under \mathbf{Z}_3 . The size of the quorum in a singleton quorum system can range from 1 to m .

Definition 3: Given a finite universal set $U = \mathbf{Z}_m$ of m elements, a *majority* quorum system S is a quorum system under U , in which each quorum p in S contains more than half of the elements in U .

For example,

$$S = \{\{0, 1, 2\}, \{1, 2, 3\}, \{2, 3, 0\}, \{3, 0, 1\}\}$$

is a majority quorum system under \mathbf{Z}_4 . A quorum q in a majority quorum system must satisfy the relation:

$$|q| \geq \lceil m+1 \rceil / 2.$$

Definition 4: A set $D = \{a_1, a_2, \dots, a_k\} \subset \mathbf{Z}_m$ is called a relaxed cyclic (m, k) -difference set if for every $d \neq 0 \pmod{m}$ there exists at least one ordered pair (a_i, a_j) , where $a_i, a_j \in D$, such that $a_i - a_j \equiv d \pmod{m}$.

Definition 5: A group of sets $B_i = \{a_1+i, a_2+i, \dots, a_k+i\} \pmod{m}$, $i \in \{0, 1, \dots, m-1\}$ is a *cyclic* quorum system if and only if $D = \{a_1, a_2, \dots, a_k\}$ is a relaxed cyclic (m, k) -difference set.

For example, $D = \{0, 1, 3\}$ is a relaxed cyclic $(7, 3)$ -difference set under \mathbf{Z}_7 since each $d \in \{1, \dots, 6\}$ is

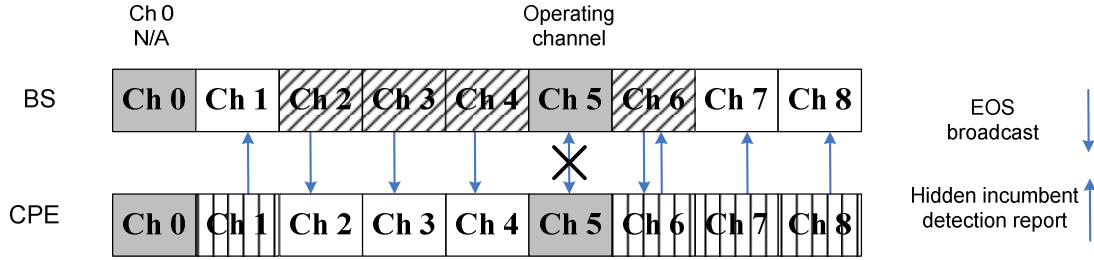


Figure 3: An example of the HID protocol using a cyclic quorum system. The cyclic quorum system S is constructed over Z_9 , where $S = \{\{0,1,2,4\},\{1,2,3,5\},\{2,3,4,6\},\{3,4,5,7\},\{4,5,6,8\},\{5,6,7,9\},\{6,7,8,1\},\{7,8,0,2\},\{8,0,1,3\}\}$. The BS picks the quorum $p = \{2,3,4,6\}$, and the CPE picks the quorum $q = \{6,7,8,1\}$ as their candidate channel sets. The BS and the CPE perform a two-way handshake on their common channel, viz Ch6, which is selected as the new operating channel.

congruent to the difference of two elements in D . Given $D, S = \{B_0, B_1, \dots, B_6\}$ is a cyclic quorum system under Z_7 , where $B_i = \{0+i, 1+i, 3+i\} \bmod 7, i \in \{0, 1, \dots, 6\}$. In [7], Luk and Wong conducted an exhaustive search to find all the cyclic quorum systems under Z_m for $m = 4, \dots, 111$.

Using one of the quorum systems defined above, the candidate channel set for an 802.22 entity i can be constructed using the following steps.

1. Given the set of available channels, $A = \{0, 1, \dots, n-1\}$, construct a quorum system S over U , where $U = A$.²
2. The 802.22 entity i obtains the local spectrum sensing results and determines the set of incumbent-free channels³. Let $F(i)$ denote such a set, where $F(i) \subseteq A$.
3. The 802.22 entity i searches for a quorum, q , that is a subset of $F(i)$, from the quorum system S . If such a quorum q exists, entity i determines its candidate channel set, $C(i)$, as q ; otherwise, it determines $C(i)$ as $F(i)$. The rule for determining $C(i)$ is given as follows:

$$C(i) = \begin{cases} q, & \text{if there exists } q \subseteq F(i); \\ F(i), & \text{otherwise.} \end{cases} \quad (3)$$

Using the above construction method, a BS and its CPEs can significantly reduce the number of candidate channels that need to be maintained in order to perform the HID protocol. For instance, a BS i picks a set of candidate channels, $C(i)$, corresponding to quorum $p \in$

S . Similarly, a CPE j picks a set of candidate channels, $C(j)$, corresponding to quorum $q \in S$. Since $p \cap q \neq \emptyset$, $C(i)$ and $C(j)$ must have at least one overlapped channel (i.e., a channel in common). As a result, BS i and CPE j can perform the HID protocol using one of the channels common to $C(i)$ and $C(j)$.

3.2. Selection of the New Operating Channel

When the operating channel x between a BS i and a CPE j becomes unavailable (due to the appearance of an incumbent signal), the BS and the CPE starts the process of hidden incumbent detection to find a new operating channel as follows.

- BS i and a CPE j determine their corresponding candidate channel sets, $C(i)$ and $C(j)$, respectively, according to (3).
- If $C(i)$ and $C(j)$ are constructed based on two quorums in S whose corresponding channel sets are incumbent free, there must be at least one incumbent-free channel common to both $C(i)$ and $C(j)$. The first channel in which the CPE detects the BS's EOS is selected as the new operating channel between the BS and the CPE.
- Otherwise, either $C(i)$ is equal to $F(i)$ or $C(j)$ is equal to $F(j)$.
 - If $C(i)$ and $C(j)$ have common channel(s), the new operating channel between the BS and the CPE is selected as the first channel in which the CPE detects the BS's EOS.
 - If $C(i)$ and $C(j)$ do not have a common channel, it implies that there is no incumbent-free channel common to the BS and the CPE at the current time. In this case, the HID protocol cannot be executed.

² The desired property of the candidate channel set determines the particular quorum system that should be used.

³ An incumbent-free channel set is a set of channels that are free of incumbent signals based on the local spectrum sensing results.

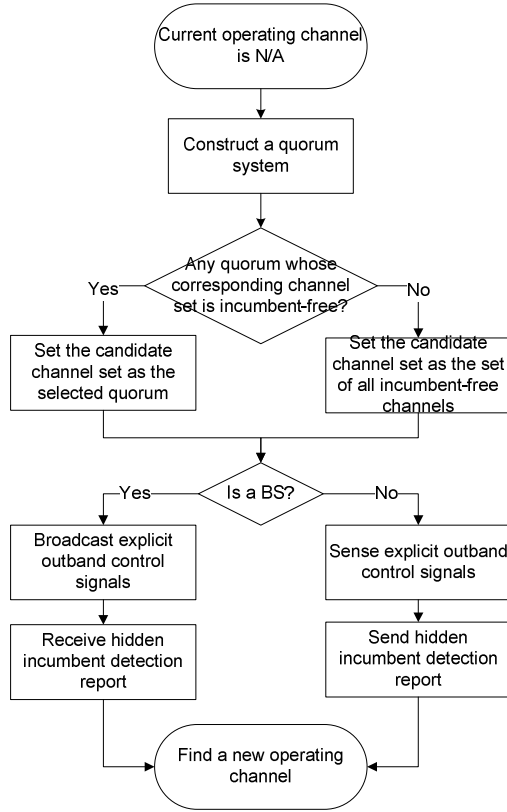


Figure 4: The process of hidden incumbent detection.

Using the selected incumbent-free operating channel, the CPE can send back hidden incumbent detection messages to the BS. An example of the HID protocol using a cyclic quorum system is shown in Figure 3. In the example, there are eight channels in total, and the cyclic quorum system is constructed over \mathbf{Z}_9 . A flow chart of the HID protocol is given in Figure 4.

3.3. Comparisons

We compare three hidden incumbent protocols: the first protocol is the one prescribed in 802.22 and the other two employ the proposed quorum system-based approach for selecting candidate channels. Suppose channel x is an operating channel between a BS i and a CPE j , and their candidate channels sets are $C(i)$ and $C(j)$, respectively.

3.3.1 Hidden incumbent detection in 802.22

Since $C(i) = C(j) \subseteq A \setminus \{x\}$, each of the two candidate channels sets, $C(i)$ and $C(j)$, form a singleton quorum

system over $U = A \setminus \{x\}$. In the worst case, the BS has to broadcast EOS on all $(n-1)$ channels in $A \setminus \{x\}$ and the CPE has to sense all $(n-1)$ channels in $A \setminus \{x\}$ since $C(i) = C(j)$.

3.3.2 Hidden incumbent detection using a majority quorum system

Suppose we use a *majority* quorum system in the proposed HID protocol. In this approach, the size of a candidate channel set is equal to the cardinality of a quorum in the majority quorum system over $U = \mathbf{Z}_n$, which is approximately $(n+1)/2$.

3.3.3 Hidden incumbent detection using a cyclic quorum system

Suppose we use a *cyclic* quorum system in the proposed HID protocol. It was proven in [5] that any quorum q in a cyclic quorum system under $U = \mathbf{Z}_m$ must have a cardinality of $|q| \geq \sqrt{m}$. Thus, the minimum cardinality of a quorum in the cyclic quorum system under $U = \mathbf{Z}_n$ is approximately \sqrt{n} . This means that the minimum size of a candidate channel set is approximately equal to \sqrt{n} .

Above analysis highlights the difference between the HID protocol prescribed by 802.22 and the protocol proposed in this paper. The difference is in the way that the candidate channels are selected. The proposed protocol enables a BS and its CPEs to select a fewer number of candidate channels, thereby lowering the control overhead of the overall network. The above analysis shows that an HID protocol employing a majority quorum system can reduce the size of the candidate channel set by half $((n+1)/2)$ as discussed in Section 3.3.2), while one that employs a cyclic quorum system can reduce the size of the candidate channel set to its square root (\sqrt{n} as discussed in Section 3.3.3).

4. RELATED WORK

The research community's interest in the air interface for dynamic spectrum access has intensified in recent years. In [9], Sengupta et al. proposed 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 the Utility Graph Coloring (UGC) which is a centralized algorithm designed to maximize system utility (i.e., spectrum reuse). In an 802.22 proposal [2], Ang et al. proposed an on-demand explicit outband signaling scheme to save energy. A BS does not broadcast

outband signals periodically, but instead broadcasts the outband signals only after it receives the outband tone signals sent by the CPEs. These CPEs send the outband tone signals when they detect incumbent signals. In [6], Kim et al. proposed a modest modification of the 802.22 approach that uses a number of extra candidate channels to broadcast the current channel list and to report the CPE's sensing results. The objective of this approach is to better detect hidden incumbent systems.

5. CONCLUSION

This paper described a hidden incumbent detection (HID) protocol that employs a novel method of constructing candidate channels. Compared to the HID protocol prescribed in the 802.22 standard, the proposed approach significantly reduces the size of the candidate channel set by utilizing quorum systems to select the candidate channels. This reduction in the size of the candidate channel set leads to reduced control overhead in the 802.22 network. As explained in the previous discussions, the degree of reduction depends on the specific quorum system that is employed.

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