Energy Detection Performance Analysis for UWB Radar Sensor Networks

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Abstract

Ultra wideband radar sensor networks have intensive military and commercial applications. However, how to mitigate the interference to the existing systems and increase the spectrum utilization for UWB radar sensor networks should also be studied carefully. While energy detection has been extensively studied in the past, hidden terminal and exposed node problems are ignored through assuming that the environment is the same for transmitters and receivers. In this paper, considering hidden terminal and exposed node problems, we make a theoretical analysis on the performance of commonly used energy detection methods, such as ideal method, transmitter-independent method, and transmitter/receiver-cooperated method, in terms of detection probability. Corresponding analytical models are provided. Performance theoretical curves are acquired to compare the characteristics for individual energy detection methods under various scenarios. Moreover, the upper bound for detection probability is achieved and is compared under various system traffic intensity and sensing capability. The theoretical results gotten in this paper can supply a reference on the choosing of energy detection method according to system scenario, such as traffic load, sensing capability, and so forth.

1. Introduction

Ultra-wideband (aka UWB, ultra-wide band, ultraband, etc.) is a radio technology that can be used at very low energy levels for short-range high-bandwidth communications by using a large portion of the radio spectrum. Within the past forty years, advances in analog, digital electronics, and ultra-wideband (UWB) signal theory have enabled system designers to propose some practical UWB communication systems such as in [1]. Currently, numerous companies and government agencies are investigating the potential of UWB to deliver on its promises. A wide range of UWB applications have been demonstrated [2, 3]. The application of ultra wideband (UWB) to radar systems has a long history of development [3, 4]. With the capability of excellent range resolution and penetration, UWB radar sensors attached more extensive investigation in recent years.

Today's wireless networks are regulated by a fixed spectrum assignment policy, that is, the spectrum is regulated by governmental agencies and is assigned to license holder or services on a long-term basis for larger geographical regions. In addition, according to Federal Communications Commission (FCC) [5], temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85%. UWB communications transmit in a way that doesnot interfere largely with other more traditional narrowband and continuous carrier wave uses in the same frequency band. However first studies show that the rise of noise level by a number of UWB transmitters puts a burden on existing communications services. This may be hard to bear for traditional systems designs and may affect the stability of such existing systems.

In order to ensure that UWB radar sensor networks working smoothly, one of the important requirements is to sense the spectrum holes successfully and then to mitigate the interference to the existing systems. The most efficient detection method is to detect the primary users that are receiving data within the communication range of an secondary user. In reality, however, it is difficult for a secondary user to have a direct measurement of a channel between a primary receiver and a primary transmitter. Thus, the most recent work focuses on primary transmitter detection based on local observations of secondary users. Generally, the spectrum sensing techniques can be classified into matched filter [6], energy detector, and cyclostationary feature detector [7].

When the structure of primary signal is known to secondary user, the optimal detector is a matched-filter followed by a threshold test [8]. The optimal way for any signal detection is a matched filter, since it maximizes received signal-to-noise ratio. However, implementing this type of coherent detector is difficult since a secondary user needs to have a priori knowledge of primary user signal at Physical and MAC layers, for example, modulation type and order, pulse shaping, packet format. Moreover, extra dedicated circuitry to achieve synchrony with each type of primary licenses would be needed. Therefore, there may be cases in practice where matched-filter detector is ruled out due to the lack of knowledge about primary signal's structure.

From other aspect, modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hoping sequences, or cyclic prefixes that result in built-in periodicity. Even though the data is a stationary random process, these modulated signals are characterized as cyclostationary. This can be used for detection of a random signal with a particular modulation type in a background of noise and other modulated signals [9].

One common method for detection of unknown signals is energy detection, which measures the energy in the received waveform over an observation time window [10, 11]. In [12], energy detection of unknown deterministic signals is studied. Detection performance in terms of detection probability and false alarm probability is formulated. In [13, 14], multiband/wavelet approach and blind adaptive minimum output energy detection were proposed for capturing the AM-FM components of modulated signals immersed in noise and for DS/CDMA [15] over multipath fading channel separately. Performance of energy detection under channel randomness has been considered in [16, 17]. In order to improve spectrum sensing, several authors have recently proposed collaboration among secondary users [18, 19]. A group of unlicensed deices were exploited for spectrum sensing, which leads to more efficient spectrum utilization from a system-level point of view while decreasing computational complexity of detection algorithms at individual nodes.

However, energy detection has been extensively studied in the past; hidden terminal and exposed node problems are ignored through assuming that the environment is the same for transmitters and receivers. While this assumption does not always hold, especially in high-node density scenarios. In this paper, considering hidden terminal and exposed node problems, we make a theoretical analysis on the performance of energy detection in terms of detection probability. An analytical model is provided for ideal energy detection, transmitter-independent energy detection for CSMA [20]/ALOHA [21]/Schedule-based systems and transmitter/receiver-cooperated energy detection. Theoretical curves are acquired to compare the characteristics for individual energy detection methods under various situations. Moreover, the upper bound for detection probability is achieved and compared under various system traffic and sensing error. The theoretical results we acquired can supply a reference on the method selection.

The remainder of this paper is organized as follows. In Section 2, we summarize motivations for our work. We summary all definitions used through this paper in Section 3. Sections 4 and 5 describe our theoretical analysis on different energy detection methods. Theoretical results are given in Section 6. Section 7 concludes this paper.

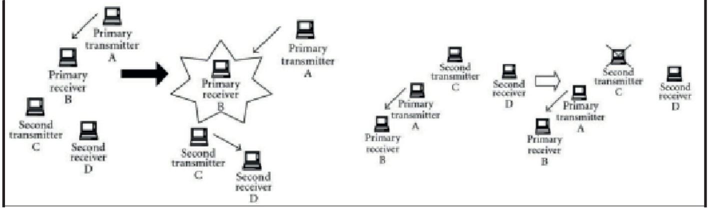
2. Our Motivations

Two nodes are said to be hidden from one another (out of signal range) when both attempt to send information to the same receiving node, resulting in a collision of data at the receiver node. On the other hand, overhearing a data transmission from neighboring nodes can inhibit one node from transmitting to other noes. Those are very well-known hidden terminal problem and exposed node problem for contention-based MAC protocols [22]. The hidden terminal problem causes failure communication with collision, while exposed node problem decreases frequency utilization due to unnecessarily blocking of some communications. RTS-CTS method is one of the most popular solutions to the hidden terminal problem, such as in IEEE80.2.11 [23]. In existing systems, hidden terminal problem and exposed node problem also should be considered for energy detection, since the strength of received signal is various at transmitter side and receiver side. To the best of our knowledge, it is the first paper to study the influence of hidden and exposed problems on energy detection capability.

2.1. Hidden Terminal Problem

As shown in Figure 1, in a primary system there are two primary users (PUs) A and B. When communication is processing between A and B, there are two secondary users (SUs) C and D appeared in the same region. According to most of existing energy detection methods, before deciding working spectrum, C will sense spectrum hole around it. Since C is hidden from A, C cannot detect the transmission between A and B, then C will decide to pick up the same spectrum band to process communication to D, which will destroy the communication between A and B as shown in Figure 1(a). This is the hidden terminal problem for energy detection. This hidden problem breaks one of the most important rules: the SUs should not generate unacceptable interference to PUs.

Figure 1 (a) The illustration of hidden terminal problem and (b) The illustration of exposed node problem.



2.2. Exposed Node Problem

As shown in Figure 1(b), in a primary system there are two PUs A and B. When communication is processing between A and B, there are two SUs C and D appeared in the same region. According to most of existing energy detection methods, before deciding working spectrum, secondary user C will sense spectrum hole around it. Since C is exposed to A, C will detect the transmission between A and B, then C will decide to block its transmission or pick up different spectrum band to process communication to D, even though in fact the communication between C and D on the same frequency band will not cause any interference to primary receiver B. This is the exposed node problem for energy detection. This exposed problem breaks another most important rules: in order to enhance the spectrum utilization, allow more SUs to work on spectrum holes of primary systems.

3. Main Definitions

We classify the frequency band/channel state into three categories.

(i)*Idle* : When both secondary transmitter and receiver do not sense any signal, we claim the channel is idle. In this case, secondary communication pair can utilize the channel for communications.

(ii)*Busy* : Once a secondary transmitter senses the beacon from a primary receiver and/or a secondary receiver senses the beacon from a primary transmitter, we claim a channel is busy. In this case, secondary communication pair should not utilize the busy channel for communications, since their communication might destroy primary users' or be destroyed by primary users'.

(iii)*Fake Busy* : Just when a secondary transmitter senses the beacon from a primary transmitter and/or a secondary receiver senses the beacon from a primary receiver, we claim that the channel is fake busy. In this case, secondary communication pair still can utilize the channel for communication, since there is no any unacceptable interference among them.

Generally, network topology, traffic type, and communication capability of primary user system determine channel state. In this paper, we exploit p_{id}, p_{bs}, and p_{fd} to express the chance of channel state might be at certain point of time. They always satisfy $p_{\mathrm{id}}+p_{\mathrm{bs}}+p_{\mathrm{fd}}=1$. The definitions are

(i)p_{id} is the probability of a channel being *Idle* ;

(ii)p_{bs} is the probability of a channel being *Busy* ;

(iii)p_{fbs} is the probability of a channel being *Fake Busy* .

During energy detection, the sensed signal can come from primary transmitters and, for some cases, from primary receivers, which are not determined. We use p_{tx} and p_{rx} to stand the probability that the sensed signal coming from primary transmitters and from primary receivers.

During energy detection, the sensed signal can come from primary transmitters and, for some cases, from primary receivers, which are not determined. We use P_{tx} and P_{rx} to stand the probability that the sensed signal coming from primary transmitters and from primary receivers.

The sensing probabilities are defined as:

$$\begin{aligned}
&P\{\text{no signal sensed} \mid \text{no signal exsiting}\} = P_{00};\\
&P\{\text{signal sensed} \mid \text{signal exsiting}\} = P_{11};\\
&P\{\text{no signal sensed} \mid \text{signal exsiting}\} = P_{10};\\
&P\{\text{signal sensed} \mid \text{no signal exsiting}\} = P_{01}.
\end{aligned}$$

Studies in [12, 16, 17] showed that the detection probability and false alarm probability were the functions of signal-to-noise ratio $(\mathrm{SNR})\ \gamma$. Hence we note those sensing probabilities as $P_{00}(\gamma)$, $P_{01}(\gamma)$, $P_{10}(\gamma)$, and $P_{11}(\gamma)$.

The probability of correct decision (P_{cd}) is the probability that a SU makes a correct decision on utilizing or not utilizing a particular frequency band when sensing a particular frequency band is *Idle* /*Fake Busy* or *Busy* , defined as:

$$\begin{aligned}
&P_{\mathrm{cd}}\\
&= P\{\text{communication is blocked} \mid \text{channel is Busy}\}\\
&\times P\{\text{channel is Busy}\}\\
&+ P\left\{\text{communication is processed} \mid \text{channel is } \frac{\text{Idle}}{\text{Fake Busy}}\right\}\\
&\times P\left\{\text{channel is } \frac{\text{Idle}}{\text{Fake Busy}}\right\}.
\end{aligned}$$

4. Generic Environment for Secondary Transmitter and Receiver

While energy detection has been extensively studied in the past, hidden terminal and exposed node problems are ignored through assuming that the environment is often same for transmitters and receivers. However, this assumption cannot always hold in the real world. In this section, we use the generic model, in which the signal sensed by secondary transmitters (STs) might not be identical for secondary receivers (SRs). Moreover, in real world, there is always error for signal sensing, that is, $0 < P_{00}$, P_{11}, P_{01}, $P_{10} < 1$. In this case, for real system design, we evaluate the performance in terms of detection probability for ideal energy detection method, transmitter-independent energy detection method, and transmitter/receiver-cooperated energy detection method.

4.1. Ideal Energy Detection

In this case, the primary transmitter (PT) and primary receiver (PR) have the capability to send out special messages such as beacons to indicate they are doing communications. Moreover, for energy detection, not only ST but also SR participate the sensing task. Based on the detection results both from STs and SRs, the secondary communication pairs decide their working frequency bands.

We define a 2×2 matrix ($S = \begin{pmatrix} s_{r1} & s_{r2} \\ s_{t1} & s_{t2} \end{pmatrix}$) to express that the detection results for secondary communication pairs. s_{r1} and s_{r2} are the detection results referring to PR and PT individually at the SR side. Similarly, s_{t1} and s_{t2} are the detection results referring to PT and PR individually at the ST side. The value for s_{r1}, s_{r2}, s_{t1}, and s_{t2} can be 1 or 0 based on signals detected or not. There are totally 16 statuses for S (see Table 1). Note that the signal strength s_{t1} and the signal strength s_{r2} reflect the hidden problem degree and exposed problem degree individually. Therefore, combining the detection at STs and SRs, the detection errors caused by hidden problem and exposed problem can be solved successfully at the same time.

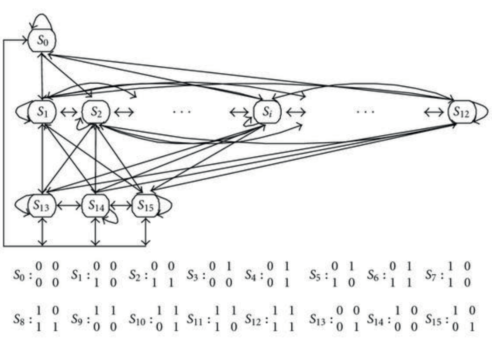
Table 1 Channel state classification according to S for ideal energy detection.

Channel State	S
Idle	$\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$
Fake Busy	$\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$
	$\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix},$
Busy	$\begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix},$
	$\begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix},$
	$\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}.$

We use the Markov chain to model the channel state switching (see Figure 2). Based on the definition on detection probability (P_{cd}), we derive (3) as following:

$$\begin{aligned} P_{\mathrm{cd}} &= (P_{\mathrm{id}} + P_{\mathrm{fbs}}) p_{00}(y_{r2}) p_{00}(y_{t1}) \\ &\quad + \frac{1}{9} P_{\mathrm{bs}} [p_{01}(y_{t1}) + p_{01}(y_{r2}) + p_{10}(y_{r2}) p_{11}(y_{t1}) \\ &\qquad + p_{11}(y_{r2}) p_{10}(y_{t1}) + 3 p_{11}(y_{r2}) p_{00}(y_{t1}) \\ &\qquad + 3 p_{11}(y_{r2}) p_{11}(y_{t1}) + 3 p_{11}(y_{r2}) p_{11}(y_{t1})]. \end{aligned}$$

Figure 2 **The Markov Chain for channel state switching for ideal energy detection.**



Note the following.

(i)Even though PT, PR, ST and SR participate spectrum sensing, incorrect decision is still possible that for sensing errors of STs and SRs.

(ii)Although both ST and SR implement energy detection according to messages exchanged between PTs and PRs, detection performance in terms of detection probability P_{cd} has nothing with $p(y_{r1})$ and $p(y_{t2})$. That is, only the detection capability referring to PRs of STs, and detection capability referring to PTs of SRs together determines the performance of this ideal energy detection method. This implies that, during detection, to ensure the detection performance the STs only need to monitor the signal from PRs, and the STs need to monitor the signal from PTs. Consequently, the overhead brought by energy detection for STs and STs can be safely reduced through making STs/SRs ignore the signal from PTs/PRs.

(iii)Moreover, assuming sensor nodes can correctly detect whether there is transmission processing around them on a particular frequency band, that is, $p_{00}=1$, $p_{11}=1$, $p_{01}=0$, and $p_{10}=0$. In this case according to (3), we have $P_{\text{cd}}=1$, which are consisting with our above analysis. For this reason, this ideal energy detection method is an optimal detection way for UWB radar sensor networks.

However, it is too good to be true in real world since overhead caused by transmitting beacons both form primary transmitters and receivers is too heavy to be acceptable or feasible for some systems that utilize certain MAC methods, in which there is no confirmation/response from receivers during data transmission process.

4.2. Transmitter-Independent Energy Detection

In transmitter-independent energy detection method, only STs process spectrum sensing task. Therefore, the matrix S is reduced into a scalar whose value can be 0 or 1. When a ST senses there is no primary communication pairs doing communication, that is, $S=0$, it will decide to use this channel for its communication, otherwise it will not. Generally, there are two categories of primary system based on whether there is confirmation/response from primary receivers. In CSMA/CA primary systems, since besides RTS control packets and data packets transmitted by PTs, another control packets—CTS and ACK are transmitted by PRs [23]. The decision can be done according to the detection with PTs or PRs, in this case, P_{cd} is modified as follows:

$$\begin{aligned}P_{\text{cd}} &= p_{\text{tx}}\Big\{p_{\text{id}}p_{00}(y_{t2})+\frac{1}{3}p_{\text{fbs}}\left[p_{00}(y_{t2})+2p_{10}(y_{t2})\right]\\ &\qquad +\frac{1}{2}p_{\text{bs}}p_{11}(y_{t2})\Big\}\\ &\quad +p_{\text{rx}}\Big\{(p_{\text{id}}+p_{\text{fbs}})p_{00}(y_{t1})+\frac{2}{3}p_{\text{bs}}p_{11}(y_{t1})\Big\}.\end{aligned}$$

Compared with ideal energy detection methods, the following is observed.

(i)P_{cd} is not only the functions of $P_{y_{t1}}$, but also the functions of $P_{y_{t2}}$ when the detected signal is coming from PTs.

(ii)Assuming CRs can correctly detect whether there is transmission processing around them on a particular frequency band, that is, $p_{00}=1$, $p_{11}=1$, $p_{01}=0$ and $p_{10}=0$, in this specific case, $P_{\text{cd}}=p_{\text{tx}}(p_{\text{id}}+(1/3)p_{\text{fbs}}+(1/2)p_{\text{bs}})+p_{\text{rx}}(p_{\text{id}}+p_{\text{fbs}}+(2/3)p_{\text{bs}})$. Since it always has that $p_{\text{tx}}+p_{\text{rx}}=1$ hold, the upper bound of P_{cd} is given in (5). It is achieved when the detected signals all come from PRs, that is, $p_{\text{tx}}=0$ and $p_{\text{rx}}=1$

$$P_{\text{cd,max}}=p_{\text{id}}+p_{\text{fbs}}+\frac{2}{3}p_{\text{bs}}.$$

(iii)Even though only STs are exploited for energy detection in CSMA/CA-based primary system, it can be an optimal energy detection method when channel status is only *Idle* or *Fake Busy*. That is, when $p_{\text{bs}}=0$, $P_{\text{cd,max}}=1$. Otherwise, the performance of transmitter-independent energy detection methods is always $(1/3)p_{\text{bs}}$ worse than the ideal energy detection methods.

(iv)For other primary systems, such as TDMA systems, CSMA systems and ALOHA systems, in which there is no response/confirmation from receivers during data transmission processes, that is, $p_{\text{tx}}=1$ and $p_{\text{rx}}=0$, there is

$$P_{\text{cd,max}}=p_{\text{id}}+\frac{1}{3}p_{\text{fbs}}+\frac{1}{2}p_{\text{bs}}.$$

Comparing (6) with (5), note that if more signals from PRs can be detected by STs, better detection performance can be achieved under same systems scenario, that is, same $p_{\text{id}}, p_{\text{fbs}}, p_{\text{bs}}$.

4.3. Transmitter/Receiver-Cooperated Energy Detection

Considering the spectrum environment sensed by receiver and transmitter due to different location of them, receiver aiding spectrum sensing method is one of feasible mechanisms to improve the detection performance. Consequently, the detection matrix S is changed into $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$, $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$, $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$, and $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$, with only ST doing frequency sensing, it is impossible to identify wether the channel is *Busy* or *Fake Busy* when $S=\begin{pmatrix} 0 \\ 1 \end{pmatrix}/\begin{pmatrix} 1 \\ 0 \end{pmatrix}$. Hence, there are two alternative ways to infer the channel state. One is claiming the channel is *Idle* when $S=\begin{pmatrix} 0 \\ 0 \end{pmatrix}$, claiming that the channel is *Fake Busy* when $S=\begin{pmatrix} 0 \\ 1 \end{pmatrix}$, $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$, and $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$ (see Table 2).

Table 2 Channel state classification according to S for transmitter/receiver-cooperated method.

Channel State	S
Idle	$\begin{pmatrix} 0 \\ 0 \end{pmatrix}$
Busy	$\begin{pmatrix} 0 \\ 1 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \end{pmatrix}$

Then, P_{cd} is calculated through

$$\begin{aligned}
P_{\mathrm{cd}} &= p_{\mathrm{tx}}\Big\{p_{\mathrm{id}}p_{00}(y_{r2})p_{00}(y_{t2}) \\
&\quad +\frac{1}{3}p_{\mathrm{fbs}}[p_{00}(y_{r2})p_{00}(y_{t2})+2p_{00}(y_{r2})p_{10}(y_{t2})] \\
&\quad +\frac{1}{6}p_{\mathrm{bs}}[p_{11}(y_{t2})+4p_{11}(y_{r2})+2p_{10}(y_{r2})p_{01}(y_{t2}) \\
&\qquad +2p_{10}(y_{r2})p_{11}(y_{t2})+p_{01}(y_{r2}) \\
&\qquad +p_{00}(y_{r2})p_{01}(y_{t2})]\Big\} \\
&\quad +p_{\mathrm{rx}}\Big\{p_{\mathrm{id}}p_{00}(y_{r1})p_{00}(y_{t1}) \\
&\quad +\frac{1}{3}p_{\mathrm{fbs}}[p_{00}(y_{r1})p_{00}(y_{t1})+2p_{10}(y_{r1})p_{00}(y_{t1})] \\
&\quad +\frac{1}{6}p_{\mathrm{bs}}[4p_{11}(y_{t1})+p_{11}(y_{r1})+2p_{01}(y_{r1})p_{10}(y_{t1}) \\
&\qquad +2p_{11}(y_{r1})p_{10}(y_{t1})+p_{10}(y_{r1})p_{01}(y_{t1})]\Big\}.
\end{aligned}$$

The other one is claiming the channel is *Idle* when $S=\begin{pmatrix} 0 \\ 0 \end{pmatrix}$, claiming the channel is *Fake Busy* when $S=\begin{pmatrix} 0 \\ 1 \end{pmatrix}/\begin{pmatrix} 1 \\ 0 \end{pmatrix}$, and claiming the channel is Busy when $S=\begin{pmatrix} 1 \\ 0 \end{pmatrix}/\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ and $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$ (see Table 3).

Table 3 channel state classification according to S for transmitter/receiver-cooperated method.

Channel State	S
Idle	$\begin{pmatrix} 0 \\ 0 \end{pmatrix}$
Fake Busy	$\begin{pmatrix} 0 \\ 1 \end{pmatrix}/\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
Busy	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}/\begin{pmatrix} 0 \\ 1 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \end{pmatrix}$

In this case, the P_{cd} is calculated through

$$
\begin{aligned}
p_{\mathrm{cd}} = p_{\mathrm{tx}}\Big\{ & p_{\mathrm{id}}[p_{00}(y_{r2})p_{00}(y_{t2}) + p_{00}(y_{r2})p_{01}(y_{t2})] \\
& + \frac{1}{3}p_{\mathrm{fbs}}[p_{00}(y_{r2})p_{00}(y_{t2}) + 2p_{00}(y_{r2})] \\
& + \frac{1}{3}p_{\mathrm{bs}}[2p_{11}(y_{r2}) + p_{01}(y_{r2})]\Big\} \\
+ p_{\mathrm{rx}}\Big\{ & p_{\mathrm{id}}[p_{00}(y_{r1})p_{00}(y_{t1}) + p_{01}(y_{r1})p_{00}(y_{t1})] \\
& + \frac{1}{3}p_{\mathrm{fbs}}[p_{00}(y_{r1})p_{00}(y_{t1}) + 2p_{00}(y_{t1})] \\
& + \frac{1}{3}p_{\mathrm{bs}}[2p_{11}(y_{t1}) + p_{01}(y_{t1})]\Big\}.
\end{aligned}
$$

The following is discussed based above formulas.

(i)Compared with transmitter-independent energy detection methods, since both STs and SRs participate in the detection process, the detection performance is the same whatever the detection is based on the signal from PTs or from PRs. It is a good news for UWB radar sensor networks that are coexisting with primary systems, in which no response/confirmation from PRs during data transmission processes.

(ii)Assuming sensor nodes can correctly detect whether there is a transmission processing around them on a particular frequency band, that is, $p_{00} = 1$, $p_{11} = 1$, $p_{01} = 0$ and $p_{10} = 0$, the upper bound for detection probability is:

$$
\begin{aligned}
p_{\mathrm{cd,max}} &= p_{\mathrm{id}} + \frac{1}{3}p_{\mathrm{fbs}} + \frac{5}{6}p_{\mathrm{bs}}, \\
p_{\mathrm{cd,max}} &= p_{\mathrm{id}} + p_{\mathrm{fbs}} + \frac{2}{3}p_{\mathrm{bs}}.
\end{aligned}
$$

Note that when $p_{\mathrm{bs}} < 4p_{\mathrm{fbs}}$, the performance of treating $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ as *Fake Busy* is worse than treating $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ as *Busy* .

(iii)Using transmitter/receiver-cooperated energy detection methods, it can acquire better performance for TDMA primary systems, ALOHA systems and CSMA systems. However, for CSMA/CA systems, the transmitter/receiver-cooperated energy detection method treating $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ as *Busy* achieves better performance when $p_{\mathrm{tx}} \geq (4p_{\mathrm{fbs}} - p_{\mathrm{bs}}) / 4p_{\mathrm{fbs}}p_{\mathrm{bs}}$, and treating $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ as *Fake Busy* can always achieve better performance.

(iv)Even though only PTs and PRs are exploited for energy detection, it can be an optimal energy detection method when channel status only be *Idle* or *Fake Busy* . That is, when $p_{\mathrm{bs}} = 0$, $p_{\mathrm{cd,max}} = 1$. Otherwise, the performance is always $(1/3)p_{\mathrm{bs}}$ worse than the one of ideal energy detection method.

5. Identical Environment for Secondary Transmitter and Receiver Scenario

When the environments for secondary transmitters and receivers are same. In this case, all possible values for S are shown in Table 4. We will obtain p_{cd} for various energy detection methods separately.

Table 4 channel state classification according to S for ideal method.

Channel State	S
Idle	$\begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$
Busy	$\begin{pmatrix} 0 & 1 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}.$

5.1. Ideal Energy Detection

Since the situation for STs and SRs is the same, it is valid to make a correct decision only according to the detection by STs or SRs. Moreover, for ideal energy detection, PTs and PRs have the capability to send message out, which can be detected by secondary users. In this case, the detection probability P_{cd} is as follows:

$$\begin{aligned} P_{cd} &= p_{id}p_{00}(y_1)p_{00}(y_2) \\ &\quad + \frac{1}{3}p_{bs}[p_{01}(y_1) + p_{11}(y_1) \\ &\qquad + p_{01}(y_2) + p_{00}(y_1)p_{11}(y_2) \\ &\qquad + p_{10}(y_1)p_{11}(y_2) + p_{11}(y_1)p_{00}(y_2)]. \end{aligned}$$

p_{y1} is the detect probability according to the signal from PRs, and p_{y2} is the detect probability according to the signal from PTs. Compared with ideal energy detection performance in generic environment, that is, the situation for SRs might not be identical with the one for STs, they are same when there is only *Busy* or *Ideal* status existed for channel (i.e., $p_{fbs} = 0$) and the detection results at SRs are same as the ones at STs (i.e., $p(y_{r2}) = p(y_2)$ and $p(y_{t1}) = p(y_1)$).

5.2. Transmitter-Independent Energy Detection

When the environment is the same for STs and SRs, using the transmitter-independent detection method the detection performance is as following:

$$\begin{aligned} P_{cd} &= p_{tx}\left\{p_{id}p_{00}(y_2) + \frac{1}{3}p_{bs}[2p_{11}(y_2) + p_{01}(y_2)]\right\} \\ &\quad + p_{rx}\left\{p_{id}p_{00}(y_1) + \frac{1}{3}p_{bs}[2p_{11}(y_1) + p_{01}(y_1)]\right\}. \end{aligned}$$

The following characteristics are observed.

(i)When the situations for STs and SRs are identical, the upper bound of detection performance is the same. It is $P_{cd,max} = p_{id} + (2/3)p_{bs}$.

(ii)Since the situations at STs and SRs are the same, it is unnecessary to exploit both secondary transmitter and receiver for better detection performance for UWB radar sensor networks. Therefore, for the special case that there is identical environment for STs and SRs, traditional energy detection method—transmitter-independent energy detection—is an optimal choice.

(iii)Since the situations at STs and SRs are same, obviously, detection probability can be enhanced. However, compared with the performance in generic environment, the upper bound is the same as the ones when only monitoring PRs' signals for energy detection, but always better than the ones when only monitoring PTs' signals. It inspired us that some wrong detections are generated for the difference between STs and SRs. That is, in that case, traditional transmitter-independent energy detection is not the best choice. If more signal from PRs can be detected by STs, even for different situation for STs and SRs, better detection performance can be achieved.

6. Theoretical Results and Performance Analysis

6.1. Surface of Detection Probability P_{cd} for Ideal Energy Detection

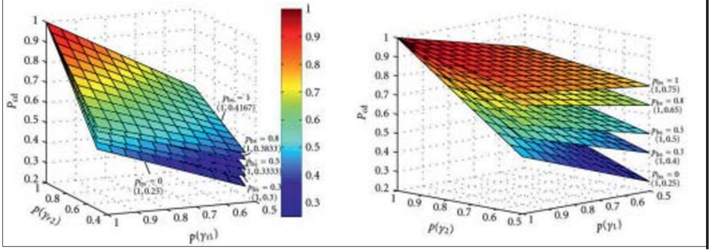
Assuming STs and SRs own same sensing capability, that is, $p_{00}(y_{r2}) = p_{11}(y_{r2})$ and $p_{00}(y_{t1}) = p_{11}(y_{t1})$. Moreover, $p_{10}(y_{r2}) = p_{01}(y_{r2}) = 1 - p_{00}(y_{r2})$ and $p_{10}(y_{t1}) = p_{01}(y_{t1}) = 1 - p_{00}(y_{t1})$. Based on (3) and (10), Figure 3 shows the surfaces for P_{cd} under various combinations of traffic load intensity p_{bs}, sensing capability of STs/SRs $p(y_{r2})/p(y_{t1})$. Here, the range for $p(y_{r2})$ and $p(y_{t1})$ is $[0.5\ 0.6\ 0.7\ 0.8\ 0.9\ 1.0]$, as well as the candidates for p_{bs} are $[0.0\ 0.3\ 0.5\ 0.8\ 1.0]$. In those two figures, p_{bs} the maximum value and minimal value of P_{cd} are shown for each surface. Note that the following.

(i)Fixing the traffic intensity of primary systems (i.e., fixing p_{bs}), with the increase of signal detection capability for STs/SRs (i.e., increasing $p(y_{r2})/p(y_{t1})$) there is higher chance to make correct decision for secondary users. It inspire us that enhance the detection capability for secondary users can reduce the interference to primary systems and increase the frequency utilization.

(ii)Fixing the signal detection capability of STs/SRs (i.e., fixing the value for $p(y_{r2})/p(y_{t1})$), when primary system is more often being truly busy (i.e., with higher value for p_{bs}) there is higher chance to make correct decision for secondary users. That is, it is more easy for secondary users to successfully monitor the primary system, which is busy exchanging information. Otherwise, more error will be made for detection.

(iii)Identical environment for STs and SRs can improve the detection performance for UWB radar sensor networks even under same situation, such as same p_{bs}, $p(y_{r2})$ and $p(y_{t1})$, since there is no chance for channel being *Fake Busy* . Therefore, the improvement due to identical environment is reduced when the detection error caused by exposed node problem is less (i.e., less chance for channel being *Fake Busy*). For example, when $p_{bs}=0.0$, the minimal successful detection probability is the same as 0.25 for generic scenario and identical scenario, while when $p_{bs}=1.0$, the minimal successful detection probability for identical environment is 44.44% ($(0.75-0.4167)/0.75=44.44\%$) higher than the one for generic environment.

Figure 3 **Detection probability P_d for ideal energy detection method for (a) generic environment for secondary transmitters/receivers scenario and (b) identical environment for secondary transmitters/receivers scenario.**



6.2. Surface of Detection Probability P_{cd} for Transmitter-Independent Energy Detection Method

Assuming there is the same sensing probability for STs, that is, $p_{00}(y_{t1})=p_{11}(y_{t1})$ and $p_{10}(y_{t1})=p_{01}(y_{t1})=1-p_{00}(y_{t1})$. When sensed signal comes from primary transmitters and receivers both, we assume that the sensing probability at STs is the same. Here, the range for $p(y_{t1})$ is [0.5 0.6 0.7 0.8 0.9 1.0], as well as the candidates for p_{bs} are $[0.0\ 0.3\ 0.5\ 0.8]$.

According to (4), Figure 4 shows the surfaces for P_{cd} under various combinations of traffic load intensity p_{bs}, p_{fbs} and sensing capability of secondary transmitter $p(y_{t1})$ when sensed signal come from PTs or PRs. In above two figures, with p_{bs}, the maximum value and minimal value for P_{cd} are shown for each surface. Note that the following.

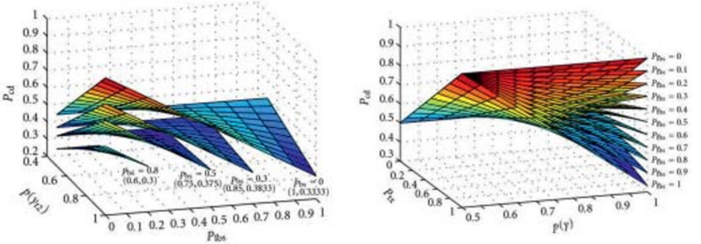
(i)From Figure 7(a), compared with ideal energy detection method, the more the chance for channel being truly occupied by primary users is, the more the detection error becomes both for generic and identical scenarios. It inspires us that the behavior of primary systems, in which the channel is less often occupied, can be easier to be monitored by secondary systems only through STs.

(ii)Also from Figure 4(a), since the channel status cannot be accurately monitored only by STs, the chance for channel being *Fake Busy* directly impacts on the detection performance. Fixing the chance for channel being truly busy, the chance for STs to successfully detect the channel status is decreased with the detection error introduced by exposed node problem becoming bigger (i.e., higher value for P_{fbs}). While, in this case, the detection performance can be improved through enhance the sensing capability for STs (i.e., higher value for $p(y_{t2})$).

(iii)When sensed signal comes from PTs or PRs (see Figure 4(b)), it is a negative influence of sensing capability for STs on the detection performance.

(iv)From Figure 4(b), if more sensed signal comes from PRs, the performance for transmitter-independent detection method can be improved when fixing channel status. Moreover the influence degree of P_{tx} on P_{cd} is changed with the chance for channel being *Fake Busy* . That is, the more the chance for channel being *Fake Busy* , the less the improvement on detection performance caused by more sensed signal coming from PRs. Even more, this positive impact becomes a negative impact when P_{Y} and P_{fbs} locate in a certain range. The turning points are: $p(y)\geq 0.9$ when $P_{fbs}=1.0$, $p(y)\geq 0.95$ when $P_{fbs}=0.9$ and $p(y)=1.0$ when $P_{fbs}=0.8$.

Figure 4 Detection Probability of P_{cd} for Transmitter Independent Energy Detection when Sensed Signal from (a) Primary Transmitter only and (b) Primary Transmitter or Receiver.



6.3. Surface of Detection Probability P_{cd} for Transmitter/Receiver-Cooperated Energy Detection

Assuming there is the same sensing probability for secondary transmitters and receivers, that is, $p_{00}(y_{t2})=p_{11}(y_{t2})$ and $p_{00}(y_{r2})=p_{11}(y_{r2})$. Moreover, $p_{10}(y_{t2})=p_{01}(y_{t2})=1-p_{00}(y_{t2})$ and $p_{10}(y_{r2})=p_{01}(y_{r2})=1-p_{00}(y_{r2})$. When sensed signal comes from PRs and PTs both, we assume the sensing probability at STs is the same. Here, the range for $p(y_{t1})$ is $[0.5\ 0.6\ 0.7\ 0.8\ 0.9\ 1.0]$, as well as the candidates for P_{bs} are $[0.0\ 0.3\ 0.5\ 0.8]$.

Based on (7), Figures 5, 6, 7, and 8 show the surfaces for P_{cd} under various combinations of traffic load intensity P_{bs}, P_{fbs} and sensing capability of STs/SRs $p(y_{t2})/p(y_{r2})$ when sensed signal come from PTs/PRs.

Figure 5 In Generic Scenario, Detection Probability of [illegible] for Transmitter/Receiver-Cooperated Energy Detection for (a) [illegible], (b) [illegible] and (c) [illegible]

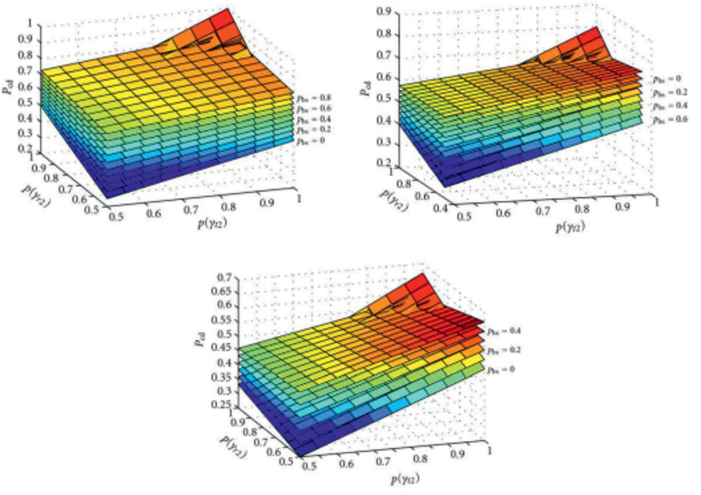


Figure 6 In Generic Scenario, Detection Probability of [illegible] for Transmitter/Receiver-Cooperated Energy Detection for (a) [illegible], (b) [illegible] and (c) [illegible]

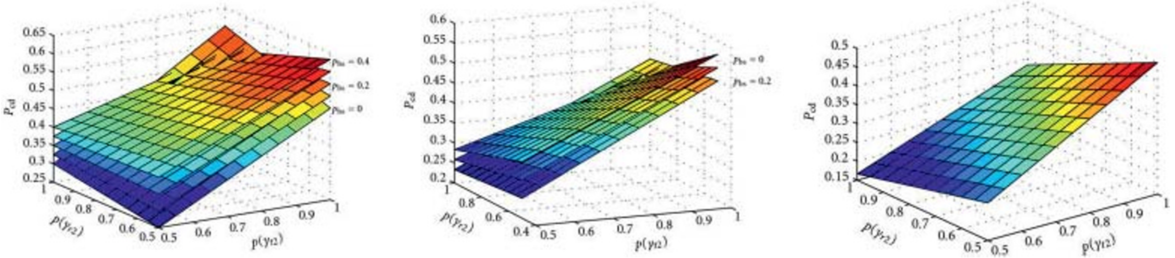


Figure 7 In Identical Scenario, Detection Probability of [illegible] for Transmitter/Receiver-Cooperated Energy Detection for (a) [illegible], (b) [illegible] and (c) [illegible]

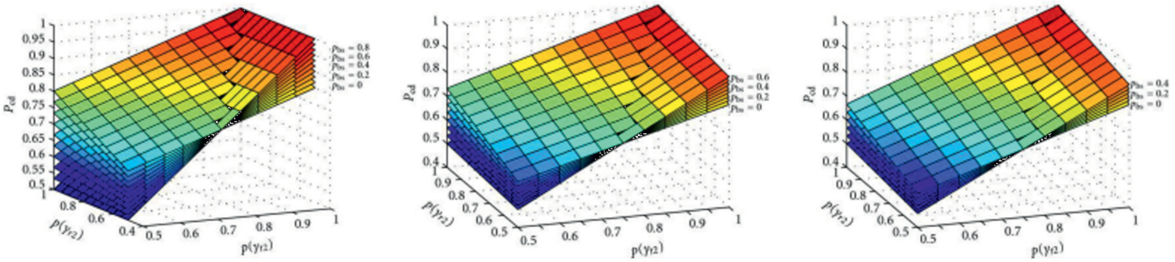
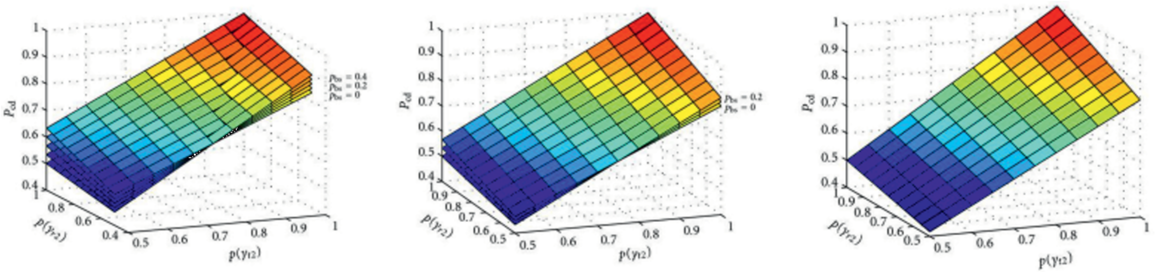


Figure 8 In Identical Scenario, Detection Probability of for Transmitter/Receiver-Cooperated Energy Detection for (a) , (b) and (c)



Note that the following.

(i)Similarly with ideal energy detection method, the more the chance for channel being truly occupied by primary users is, the less the detection error becomes both for generic and identical scenarios. It inspires us that the behavior of primary systems, in which the channel is more often occupied, can be more easy to be monitored by secondary systems both through STs and SRs.

(ii)Fixing the chance for channel being *Busy* and *Fake Busy* , the chance for secondary users to successfully detect the channel status is enhanced for utilizing more sensitive STs (i. e., higher value for $p(y_{t2})$).

(iii)There is a watershed for the influence of sensing capacity of SRs on detection performance when the environment for STs and SRs is not identical. When $P_{\text{fbs}} \le 0.5$, the detection performance can be improved through using more sensitive receivers, otherwise when $P_{\text{fbs}} \ge 0.5$, less sensitive receivers should be exploited to reduce detection errors. However, this watershed is disappeared when identical environment for STs and SRs.

(iv)Using both STs and SRs for detection, it is still impossible to accurately monitor the operation for primary users for exposed node problem and hidden terminal problem. Identical environment for secondary transmitters and receivers can improve the detection performance

7. Conclusions

While energy detection has been extensively studied in the past, hidden terminal and exposed node problems are ignored through assuming that the environment is the same for transmitters and receivers. In this paper, considering hidden terminal and exposed node problems, we make a theoretical analysis on the performance of commonly used energy detection methods, such as ideal method, transmitter-independent method and transmitter/receiver-cooperated method, in terms of detection probability. Corresponding analytical models are provided. Performance theoretical curves are acquired to compare the characteristics for individual energy detection methods under various scenarios. Moreover the upper bound for detection probability is achieved and is compared under various system traffic intensity and sensing capability. From the theoretical results, we found that it is easy to correctly detection the channel status when primary systems are heavily occupied for ideal energy detection method and tansmitter/receiver-cooperated energy detection method. Otherwise, transmitter-independent method is a better scheme to monitor the primary systems. Commonly, increasing the sensitivity of secondary users can upgrade the detection performance. However, in our analysis, it is not true for transmitter-independent method and transmitter/receiver-cooperated method under certain situations. We have concluded those special cases in this paper. Therefore, the theoretical results can supply a reference on the choosing of energy detection method according to system scenario, such as traffic load, sensing capability, and so forth.

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