Effects of Heterogeneous Frequency Changes in Cognitive Radio Femtocell Networks

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***Abstract*—Recently, cognitive radio (CR) technology is proposed to be combined with femtocell networks, which enables femtocells to access the available spectrum bands in an opportunistic manner. In practice, the available spectrums in CR femtocell networks are heterogeneous and range from hundreds of megahertz to several gigahertz. These heterogeneous spectrums have very different path-losses which may result in significantly different transmission and sensing ranges. Therefore, the change of operating frequency in CR femtocell networks introduces unique challenges. Although the effects of operating frequency change are studied in pure CR networks, issues related to the femtocell network and impacts on the sensing range are never addressed. In this paper, we introduce some unique challenges resulting from frequency changes in CR femtocell networks, such as femtocell under-utilization and interference due to the change of the transmission range, and detection error and false alarm due to the change of the sensing range. In addition, we propose a power control scheme to address the issue of the transmission range change. We also propose a detection sensitivity selection scheme to reduce the effect of the sensing range change. Simulation results show significant performance improvement of our propose schemes. To the best of our knowledge, this is the first paper that investigates the impact of frequency changes on both transmission range and sensing range in CR femtocell networks.**

I. Introduction

The low-powered, short-ranged, and low-cost femtocells are proposed as a promising technology for offloading the exponentially increasing traffic in cellular networks [1]–[3]. However, densely deployed femtocells may increase the demand of the radio spectrum and create severe interference to macrocell users. To overcome these issues, cognitive radio (CR) [4], [5] and femtocell technologies are proposed to be combined together [6]–[9]. This combined network is called CR femtocell network, where the CR femto-base stations (FBSs) are considered as secondary users (SUs) and are capable of accessing licensed spectrum of both the cellular band and other available spectrums (e.g., TV white space) in an opportunistic manner. Similar to SUs in conventional CR networks, when a primary user (PU) appears on a channel used by a CR FBS, the CR FBS needs to vacate the channel immediately and select a different channel so that all of the femtocell users (FUEs) can continue their communications. This process is known as *spectrum handoff* in CR networks [10]–[12].

Choosing channels from heterogeneous frequency bands during spectrum handoffs introduces unique challenges in CR femtocell networks. These challenges are caused by the change of two different ranges during a spectrum handoff. First, there are challenges caused by different transmission ranges. Each frequency band has different path-loss, therefore, a different transmission range for a *constant transmission power*. This difference in transmission ranges introduces two new issues in CR femtocell networks. When the operating frequency of a CR FBS changes from a low frequency to a high frequency, the coverage area of a CR femtocell shrinks due to larger path-loss at the high frequency. As a result, a number of FUEs within the uncovered area will either lose their connections or be forced to perform inter-cell handoffs. Therefore, the femtocell utilization becomes low. However, as CR femtocells are deployed to offload traffic from macrocell networks, low femtocell utilization is undesirable. On the other hand, when a CR FBS changes its operating frequency from a high frequency to a low frequency, its coverage area expands due to smaller path-loss at low frequencies. This expanded area can support more FUEs. However, this coverage area expansion can also cause interference to neighboring CR FBSs and their FUEs.

Second, there are challenges caused by different sensing ranges. The sensitivity that a SU can detect the existence of a PU also depends on the path-loss between a PU and the SU (i.e., CR FBS in CR femtocell networks). Therefore, for a given detection sensitivity, the sensing area of a CR FBS also changes with the change of the operating frequency. This change of sensing range can introduce two new issues in CR femtocell networks. When a CR FBS senses a frequency higher than its operating frequency, the sensing area becomes smaller than the transmission area due to high path-loss. As a result, if there is any PU within the transmission area that is not covered by the sensing area, it cannot be detected and the CR FBS may cause interference to this PU. Similarly, when the CR FBS senses a lower frequency channel than its operating frequency, the sensing area expanded. Therefore, the CR FBS may sense some channels as unavailable when they are actually available within its transmission range, thus, cause false alarm.

All of these issues are very important and unique in CR femtocell networks. They have not been considered before. Only very few existing papers have considered the impact of operating frequency change during a spectrum handoff on the transmission range in CR networks [13]–[16]. However, the impact is different in CR femtocell networks where FUEs are not cognitive because of the new consideration of femtocell

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utilization.

In this paper, We first discuss existing papers on related work and explain why solutions for conventional CR networks cannot be applied in CR femtocell networks. Then, we propose a power control scheme and a detection sensitivity selection scheme to address the above mentioned new issues. The proposed power control scheme is equally effective on addressing both the femtocell utilization problem and interference problem. Similarly, the proposed detection sensitivity scheme helps to reduce both the detection error and false alarm caused by sensing frequency changes. Both of our proposed schemes are easy for implementation. Simulation results show better performance of our proposed schemes, as compared to conventional CR femtocell networks.

The rest of the paper is organized as follows. System model, related work, and contributions are introduced in Section II. In Section III, the proposed power controlled scheme and detection sensitivity selection scheme are described. Performance evaluation for both proposed schemes is given in Section IV, followed by the conclusions in Section V.

II. System Model, Related Work, and Contributions

A. System Model

We consider a communication system that includes multiple primary networks and a femtocell-based heterogeneous network. Primary networks consist of macrocell networks, TV networks, macrocell users, and TV users. Users in primary networks are known as PUs. We consider an extension of the conventional femtocell concept under which FBSs are equipped with cognitive radios. Each cognitive radio femtocell has a number of FUEs. FUEs act as traditional femtocell users and have no cognitive capabilities. The network architecture of such a CR femtocell network is shown in Fig. 1.

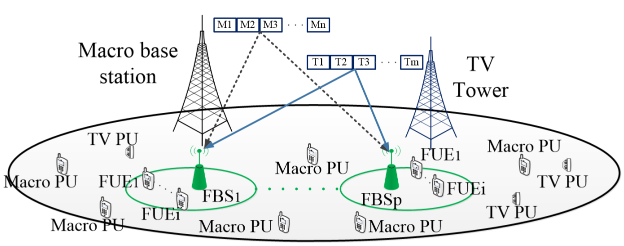


Fig. 1. A cognitive radio femtocell network.

In this model, PUs use the licensed spectrum whenever necessary. CR FBSs actively sense the spectrum and allocate the available spectrum resources to FUEs which are not being used by any PU. CR FBSs maintain a list of the available spectrum based on the sensing outcome and update it in a time-to-time manner. Whenever a FUE becomes active within the femto-coverage area, the CR FBS assigns an available channel from the list to the FUE. If a PU appears on the channel the FUE is using, the CR FBS will ask the FUE to perform a spectrum handoff. To support multiple FUEs, a CR FBS may access different spectrum bands from different networks based on their availabilities. Therefore, the CR femtocell network acts as a multi-carrier multi-radio system with heterogeneous channels.

B. Related Work and Contributions

Existing work on CR femtocell networks is mainly focused on addressing the problem of interference, spectrum allocation and management, and spectrum sharing. Almost no existing paper has considered the effect of operating frequency changes during spectrum handoffs. Additionally, although research on spectrum handoffs is rich in conventional CR networks, only a few papers have discussed the issues of the frequency change in CR networks during spectrum handoffs.

Effects of heterogeneous spectrum during spectrum handoffs in pure CR networks are considered in [13]–[15]. The problem of cell outage during a low frequency to a high frequency change is discussed in [14]. Performing inter-cell handoffs is considered as a solution for overcoming this cell outage issue. However, though a low frequency to a high frequency change has similar effects in CR femtocell networks, the proposed solution cannot be used in CR femtocell networks. The reason behind this is the femtocell utilization. If FUEs perform inter-cell handoffs, CR femtocells will have low cell utilization, therefore, low traffic offloading, which is not desirable in CR femtocell networks. In addition, an optimal operating frequency selection scheme is proposed in [15]. However, choosing a different frequency channel other than the operating channel may cause cell outage or interference problems, which is not considered in the paper. In [13], a cross-layer protocol for spectrum mobility and handoff is proposed for CR ad-hoc networks. This protocol considers when and how to make a decision for a spectrum handoff and an inter-cell handoff. The effect of the coverage range expansion is studied in [16] for femtocell networks. However, the infrastructure-based CR femtocell network needs further investigations to address the issue of frequency change in order to provide good cell utilization and at the same time to avoid interference to neighboring CR FBSs and FUEs. Moreover, none of the existing work considers the effects of frequency changes on the sensing range.

In this work, we consider the effects of frequency changes on both the transmission range and sensing range. The summary of our contributions is as follows:

- The effect of operating frequency change on the transmission range is studied for the first time in CR femtocell networks.
- The effect of frequency change on the sensing range is also studied for the first time.
- An effective power control scheme is proposed which can maintain the received signal strength (RSS) at the cell boundary in a way that the CR femtocell can provide good cell utilization and at the same time avoid interference with neighboring cells and their users.
- An adaptive detection sensitivity selection scheme is proposed which can reduce the effect of drastic change on the sensing range and consequently reducing detection error rate and false alarm rate.

- A realistic simulation scenario is developed for evaluating the performance of the proposed schemes in terms of femtocell utilization, probability of interference, detection error rate, and false alarm rate.

III. Proposed Power Control Scheme and Detection Sensitivity Selection Scheme

In this section, the proposed power control scheme is introduced, followed by the proposed detection sensitivity selection scheme. Both of the proposed schemes are equally effective for a low-to-high frequency change and a high-to-low frequency change during a spectrum handoff.

In the proposed power control scheme, the transmission power is controlled in a way that the RSS at the CR femtocell boundary remains the same as the RSS at the conventional femtocell boundary for any operating frequency. In this way, both the low femtocell utilization introduced by the low-to-high frequency change and the interference introduced by the high-to-low frequency change during a spectrum handoff can be avoided. The RSS at the femtocell boundary can be calculated as

$$P_{rx} = P_{tx} + G_f + G_u - PL, \quad (1)$$

where P_{tx} is the transmitting power of a FBS, G_f is the antenna gain of the FBS, G_u is the antenna gain of the FUE, and PL is the path-loss at the femtocell boundary. In the proposed scheme, we use the ITU-RP.1238-7 indoor path-loss model [17] to calculate the path-loss, PL, at the femtocell boundary as

$$PL = 20log_{10}(f) + Nlog_{10}(r_f) + L_f(n) - a(n), \quad (2)$$

where the operating carrier frequency $f = 1700$ MHz by assuming that the conventional femtocell operates on the LTE radio spectrum, r_f is the radius of a femtocell, N is the distance power coefficient, L_f is the floor/wall penetration loss, $a(n)$ is the shadow fading, and n is the number of floors/walls. From conventional femtocell networks, we know that femtocells are designed to provide indoor coverage. Hence, femtocells have a small but enough coverage to cover a home, usually 10 meters to 15 meters in radius [2].

Whenever a CR FBS performs a spectrum handoff either from a low frequency to a high frequency or from a high frequency to a low frequency, it needs to adapt its transmission power so that the RSS at the femtocell boundary does not change drastically. This can be obtained as

$$P_{newtx} = P_{rx} - G_f - G_u + PL_{opt}, \quad (3)$$

where PL_{opt} is the path-loss for the new operating frequency, f_{opt}, which can be calculated using equation (2).

Now, we adapt the detection sensitivity of a CR FBS in order to minimize the effect of frequency variation during a spectrum handoff. The detection sensitivity is defined as the minimum signal-to-noise ratio (SNR) at which the primary signal can still be accurately (e.g., with a probability of 0.99) detected by the cognitive radio. The detection sensitivity is expressed as

$$\lambda = \frac{P_{PU} * PL(D)}{N_p}, \quad (4)$$

where P_{PU} is the transmission power of the primary signal, $PL(D)$ is the path-loss for the interference range of the CR, and N_p is the noise power [18], [19]. In dB, (4) can be expressed as

$$\lambda = P_{PU} + PL(D) - N_p. \quad (5)$$

Therefore, the sensing range of SU transmitters has to cover the maximum interference range in order to avoid interference at PU receivers. For the simplification of the calculation, we consider the interference range and the transmission range the same. Therefore, $PL(D) = PL$, where $D = r_f$. Now, we can calculate the sensing range as

$$r_s = 10^{\frac{\lambda + N_p - P_{PU} - 20log_{10}(f_{opt}) - L_f(n) + a(n)}{N}}. \quad (6)$$

The required detection sensitivity, λ_{new}, is obtained under the sensing range, r_s, which is

$$\lambda_{new} = P_{PU} + 20log_{10}(f_{new}) + Nlog_{10}(r_s) + L_f(n) - a(n) - N_p, \quad (7)$$

where f_{new} is equal to the operating frequency, f_{opt}, if a channel with a carrier frequency higher than or equal to the operating frequency is sensed. Otherwise, f_{new} is equal to the new sensing frequency, f_s. This adaptive detection sensitivity scheme allows a CR FBS to sense a certain range despite of the sensing frequency variation. The flow chart of our proposed power control scheme and the detection sensitivity selection scheme is presented in Fig. 2.

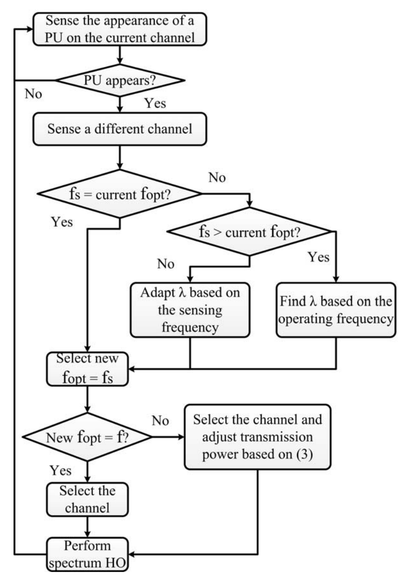


Fig. 2. Flow chart for the proposed power control and the detection sensitivity selection scheme.

IV. Performance Evaluation

In this section, we evaluate the performance of our proposed power control scheme and detection sensitivity selection scheme using simulations. We use Net Logo 5.0.5 to simulate our proposed algorithm in an indoor environment [20]. A single-floored two-bedroom apartment is designed to have a CR FBS which has the capacity of supporting up to eight FUEs. The CR FBS has six neighboring CR femtocells and all of them are within the coverage area of primary networks containing a macrocell and a TV tower. We consider 30 users, where each user has a probability of 0.7 to enter or exit the apartment in a random manner. All users are placed randomly and they follow a modified version of the Random Waypoint mobility model. The mobility model is modified in such a way that users only use the door to get in/out of the apartment and none of them can cross the walls. The power control scheme and the adaptive detection sensitivity scheme are evaluated under the spectrum handoff scenario of a low-to-high frequency change and a high-to-low frequency change. The simulation parameters are given in Table I [2], [15], [17].

TABLE I
SIMULATION PARAMETERS

Transmission power of PUs	45 dBm
Transmission power of conventional FBS	10 dBm
Operating frequency	100 MHz to 3500 MHz
Range of femtocell (radius)	15 m
Wall penetration loss	5 dB
Outdoor penetration loss	2 dB to 10 dB
Distance power coefficient, N	28
Antenna gain of PUs	15 dB
Antenna gain of FBS, G_f	2 dB
Antenna gain of FUEs, G_u	0 dB
Shadow fading, $a(n)$	28
Number of FUEs, m	8
Number of PUs, n	30
The probability that a PU is active, σ_p	0.1 (ON/OFF process)

A. Performance Evaluation of the Power Control Scheme

To evaluate the performance of the proposed power control scheme, we investigate the following two performance metrics: 1) *femtocell utilization:* the probability that a FUE stays connected to the femtocell while within the coverage area of the serving femtocell; 2) *the probability of interference:* the probability that a CR FBS interferes with neighboring CR FBSs and FUEs. In addition, we compare the performance of our proposed power control scheme with conventional CR femtocell networks, where no power control is used.

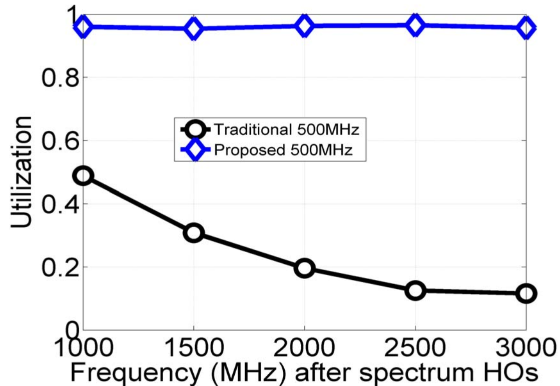
1) Femtocell Utilization: While a CR FBS performs a spectrum handoff from a low frequency to a high frequency, the transmission range of the CR FBS shrinks. As a result, some FUEs may lose their connections to the FBS. Therefore, to continue their communications, femto-to-macro handoffs are performed. Because of this shrunk transmission area, the utilization of femtocell decreases when a CR FBS changes its operating frequency from a low frequency to a high frequency. In our proposed power control scheme, the transmission power is controlled in a way that the transmission range of the femtocell remains constant. Therefore, our proposed power control scheme shows better femtocell utilization as compared to the conventional CR femtocell networks. In both cases, the femtocell utilization is calculated as the total duration a FUE is connected to a CR FBS divided by the total duration that the FUE is within the coverage area of the home FBS. The femtocell utilization of the proposed scheme and the conventional scheme is shown in Fig. 3. The figure shows results of femtocell utilization during a low operating frequency to different high frequency changes. From the figure, it is shown that the femtocell utilization of our proposed scheme is much better than the traditional scheme.

2) The Probability of Interference: A high-to-low frequency change extends the transmission coverage area because of the low path-loss. This extended transmission area may generate interference to other FUEs and other FBSs (i.e., neighboring femtocells). As a result, we consider the probability of interference to a neighboring CR FBS to evaluate the performance of a high-to-low frequency change during a spectrum handoff. The probability of interference under the conventional femtocell networks and the proposed scheme is shown in Fig. 4 for a high operating frequency to a low frequency change. From the figure, it is shown that the probability of interference is high during a spectrum handoff from a high frequency to a very low frequency. However, the probability of interference is very low and almost constant under the proposed scheme, which indicates that the frequency change does not increase the probability of interference under the proposed power control scheme.

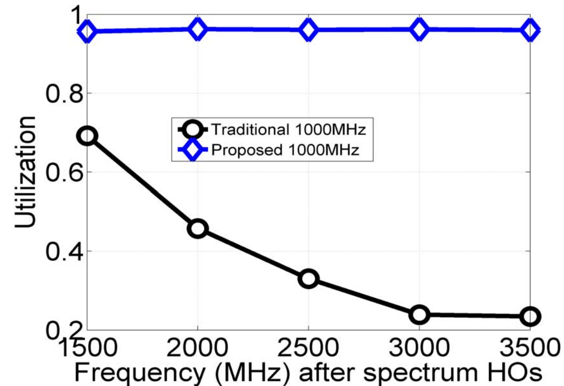
B. Performance Evaluation of the Detection Sensitivity Selection Scheme

To evaluate the performance of the proposed detection sensitivity selection scheme, we consider two different performance metrics: 1) *detection error rate:* the probability that a PU is within the sensing area of a CR FBS, but cannot be detected by the CR FBS; 2) *false alarm rate:* the probability that a CR FBS senses the presence of a PU which is not within the sensing range of a CR FBS. We compare our proposed scheme with conventional CR femtocell networks, which do not use any detection sensitivity scheme. In addition, we also compare the results by using only the power control scheme and by using both power control and detection sensitivity schemes together.

1) Detection Error Rate: When a CR FBS senses a channel with a frequency lower than the operating frequency, it can only sense an area smaller than its current transmission area. As a result, any PU within the area that is not covered by the sensing range is most likely to be undetected. The detection error rate is high in conventional CR femtocells for this reason and this may cause collision not only between PUs and FUEs, but also between FUEs from different CR femtocells. The simulated results of the detection error rate are shown in Fig. 5, where the detection error rate is obtained under the conventional CR femtocell networks (without power control and sensitivity detection, shown as "traditional"), the proposed adaptive sensitivity selection scheme (shown as "DS"), the proposed power control scheme (shown as "power control"), and the proposed power control and adaptive sensitivity detection scheme together (shown as "combined"). The performance is shown for operating frequencies 500MHz and 1000MHz, and sensing frequencies are 1000MHz to 3000MHz and 1500MHz to 3500MHz, respectively. From the figure, it is shown that the performance of the conventional CR femtocell network and the power control scheme are almost similar, which indicates that controlling transmission power of a CR FBS does not have much effects on the sensing range. It is also shown in the figure that both the detection sensitivity

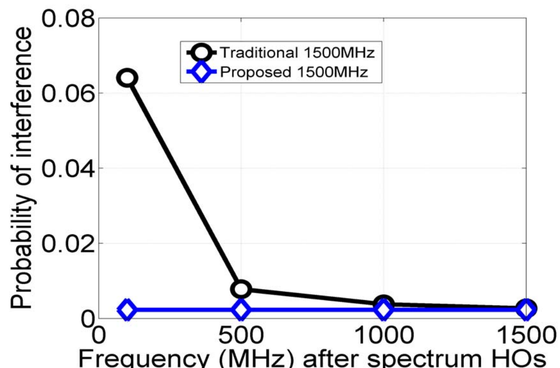


(a) Femtocell utilization for operating frequency 500MHz

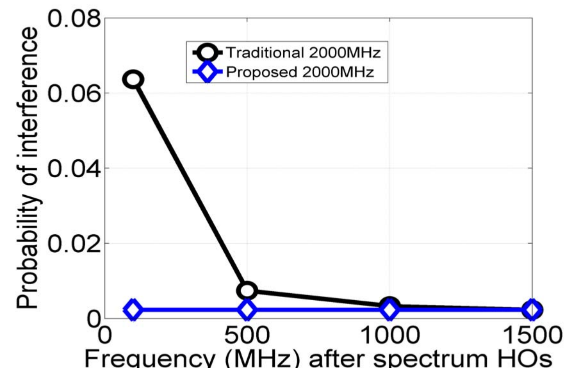


(b) Femtocell utilization for operating frequency 1000MHz

Fig. 3. Comparison of the femtocell utilization.



(a) The probability of interference for operating frequency 1500MHz



(b) The probability of interference for operating frequency 2000MHz

Fig. 4. Comparison of the probability of interference.

scheme and the combination scheme show better results than the conventional one.

2) False Alarm Rate: False alarm happens when a CR FBS senses the presence of a PU, which is not within the interference range. In CR femtocell networks, when the CR FBS senses a channel with frequency lower than the operating frequency, its sensing range extended. In this case, as the CR FBS senses larger area than its transmission area, it may sense some available channels as unavailable and cause false alarm. The rate of false alarm for a high-to-low frequency change is shown in Fig. 6 for operating frequencies 2000MHz and 2500MHz. From the figure, it is shown that when a CR FBS senses a lower frequency than the operating frequency, the rate of false alarm is higher in conventional CR femtocell networks than in the CR femtocell network using our proposed detection sensitivity scheme. It is also shown in the figure that using both the power control scheme and the detection sensitivity scheme can achieve better performance than others.

V. Conclusion

In this paper, we addressed the issues of frequency changes in CR femtocell networks. The proposed power control scheme addresses the issue related to the transmission range changes, while the detection sensitivity selection scheme helps to reduce the effect of the sensing frequency changes. The performance of the power control scheme is analyzed in terms of femtocell utilization and probability of interference. On the other hand, the performance of the detection sensitivity selection scheme is analyzed in terms of detection error rate and false alarm rate. Our proposed schemes can increase the femtocell utilization and at the same time, can reduce the interference from neighboring CR FBS and FUEs, the detection error rate, and the false alarm rate. Proposed schemes are compared with the conventional CR femtocell networks where the effect of heterogeneous frequency change is not considered. Simulation results show significant performance improvement as compared to the conventional CR femtocell networks.

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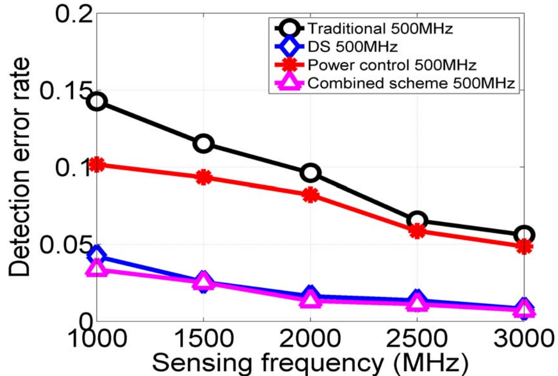
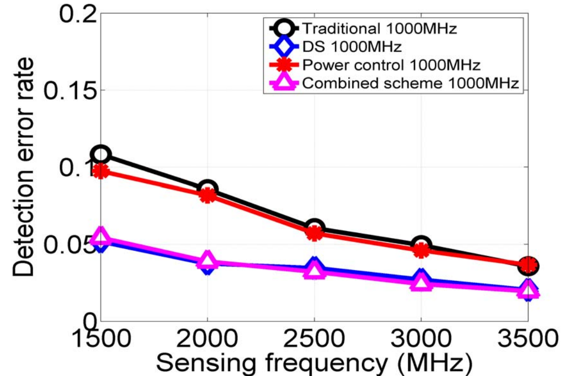
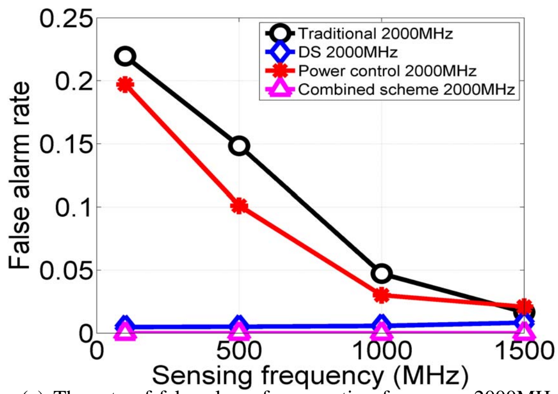


(a) Detection error rate for operating frequency 500MHz

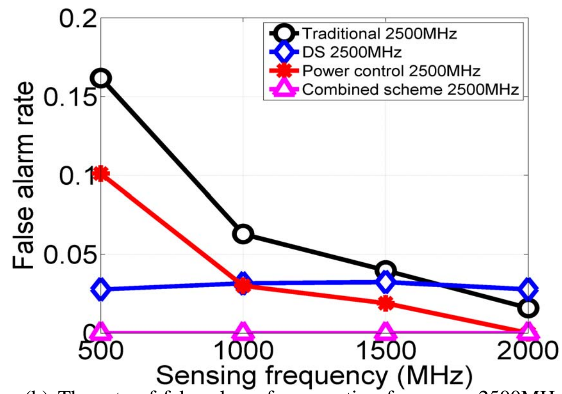


(b) Detection error rate for operating frequency 1000MHz

Fig. 5. Comparison of the detection error rate.



(a) The rate of false alarm for operating frequency 2000MHz



(b) The rate of false alarm for operating frequency 2500MHz

Fig. 6. Comparison of the false alarm rate.

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