

Chapter 2

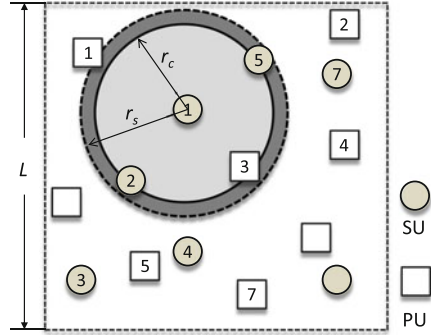
QoS-based Broadcast Protocol Under Blind Information in Cognitive Radio Ad Hoc Networks

2.1 Network Model

In this book, we consider a CR ad hoc network where N SUs and K PUs co-exist in an $L \times L$ area, as shown in Fig. 2.1. PUs are distributed within the area under the probability density function (pdf) $f_G(g)$. For simplicity, in this book, we consider that PUs are evenly distributed. The SUs opportunistically access M licensed channels. In Fig. 2.1, the solid circle represents the transmission range of a SU with a radius of r_c . Other SUs within the transmission range are considered as the neighboring nodes of the corresponding SU. That is, only when a SU receiver is within the transmission range of a SU transmitter, the signal-to-noise ratio (SNR) at the SU receiver is considered to be acceptable for reliable communications. In addition, the dashed circle represents the sensing range of a SU with a radius of r_s . That is, if a PU is currently active within a sensing range, the corresponding SU is able to detect its presence. Since the sensing ranges of different SUs at different locations may include different PUs, their acquired available channels may be different [1–3]. In addition, because the available channels of a SU are obtained based on the sensing outcome within the sensing range, each SU is not allowed to communicate with other SUs outside its sensing range since it may mistakenly use an occupied channel by a PU, which results in interference to the PU. Therefore, in this book, we assume that $r_c \leq r_s$. Additionally, we assume that a time-slotted system is adopted for SUs [4], where the length of a slot is long enough to transmit a broadcast packet.

In addition, in this book, we model the PU channel activity as an ON/OFF process, where the length of the ON period is the length of a PU packet. We assume that each PU randomly selects a channel from the spectrum band to transmit a packet. Therefore, the packets on the same channel do not necessarily belong to the same PU. This is a more practical scenario, as compared to some papers which assume that each channel is associated with a different PU. Under such practical scenario, the number of active PUs is not necessarily the number of occupied channels but depends on the total number of PUs in the network and the PU traffic intensity.

Fig. 2.1 The network model of the broadcast scenario in a multi-hop CR ad hoc network



2.2 Exploring Broadcast Design in CRNs

To explore the broadcast design in CR ad hoc networks, we first investigate two straightforward broadcast schemes in multi-hop CR ad hoc networks under blind information. We observe that both broadcast schemes have drawbacks which make them unsuitable to be used in CR ad hoc networks. In the rest of the book, we use the term “sender” to indicate a SU source node or a SU who has just received a message and will rebroadcast the message. In addition, we use the term “receiver” to indicate a SU who has not received the message.

2.2.1 Random Broadcast Scheme

The first broadcast scheme is called the *random broadcast scheme*. Since a SU is unaware of the channel availability information of other SUs before broadcasts are executed, a straightforward action for a SU sender is to randomly select a channel from its available channel set and broadcasts a message on that channel in a time slot. In addition, as stated in Chap. 1, each SU sender needs to broadcast the message for multiple time slots. We denote the number of time slots that each SU sender broadcasts as S . Accordingly, for a SU receiver, without the channel availability information of the sender, it cannot constantly stay on one channel during the whole broadcast procedure since this channel may not be in the available channel set of the sender, which leads to a definite failure of the broadcast. Thus, the only fair action for the receiver is to randomly select an available channel to listen in each time slot. If the channel selected by the receiver is the same as the channel selected by the sender, the broadcast message can be successfully received. This broadcast scheme is easy to be implemented in CR ad hoc networks under blind information. However, it cannot guarantee channel rendezvous (i.e., the sender and the receiver stay on the same channel at the same time and establish a link). In other words, in each time slot, the sender tries its luck to broadcast to its neighboring nodes. Clearly, when the number of channels is large, since the probability that the sender and receiver

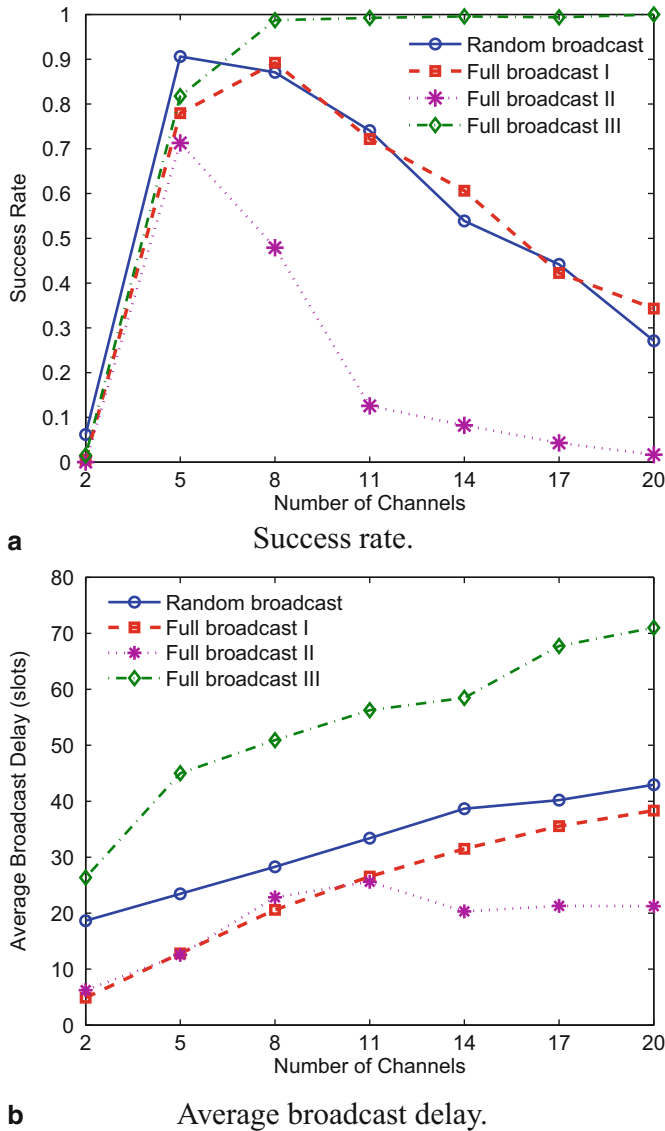


Fig. 2.2 Success rate and average broadcast delay of the random and full broadcast schemes under different number of channels when $N = 9$, $K = 20$, and $S = 20$

select the same channel is low, the probability that a broadcast is successful under the random broadcast scheme is fairly low.

Figure 2.2 shows the simulation results of the random broadcast scheme under different number of channels when $N = 9$, $K = 20$, and $S = 20$. The SUs form a 3×3 grid network. We assume that the PU traffic is discrete-time, where the PU packet

inter-arrival time X follows the biased-geometric distribution [5]. Additionally, other parameters are listed as follows:

Side length of the simulation area $L = 10$ (unit length);

Radius of the sensing range $r_s = 2$ (unit length);

Radius of the transmission range $r_c = 2$ (unit length);

The normalized PU arrival rate $\lambda_p = 0.5$;

The PU packet length $L_p = 10$ (time slots).

As mentioned in Chap. 1, the success rate is defined as the probability that all nodes in a network successfully receive the broadcast message and the average broadcast delay is defined as the average duration from the moment a source node starts a broadcast until the moment the last node in the network receives the broadcast message. It is shown in Fig. 2.2 that the random broadcast scheme leads to very low success rate when the number of channels is large, which is not suitable to be used in multi-hop CR ad hoc networks when the number of channels is large.

2.2.2 Full Broadcast Scheme

The second broadcast scheme is called the *full broadcast scheme* under which each SU visits all the available channels in the spectrum. Unlike the random broadcast scheme where the channel in each time slot is randomly selected by a SU, in the full broadcast scheme, a SU sender broadcasts on all its available channels sequentially. Similarly, a SU receiver listens to its available channels sequentially. In addition, we use three different channel hopping sequences for the full broadcast scheme: (1) the channel hopping sequence under which the order for each SU to visit all the available channels is random (denoted as Full broadcast I); (2) the channel hopping sequence under which each SU visits all the available channels sequentially (denoted as Full broadcast II); and (3) the jump-stay channel hopping sequence [6] (denoted as Full broadcast III). The jump-stay channel hopping sequence can be constructed under blind information with guaranteed rendezvous. Furthermore, similar to the random broadcast scheme, each SU sender also broadcasts for a finite number of time slots, S .

Figure 2.2 shows the simulation results of the full broadcast scheme using different channel hopping sequences under different number of channels when $N = 9$, $K = 20$, and $S = 20$. Compared with the random broadcast scheme, the full broadcast scheme using the first two channel hopping sequences also suffers a low success rate when the number of channels is large. This is because that these channel hopping sequences in the full broadcast scheme also cannot guarantee channel rendezvous. Moreover, the Full broadcast II scheme leads to an extremely low success rate when the number of channels is large, as compared to the Full broadcast I scheme. In addition, both the random broadcast scheme and the full broadcast scheme using the first two hopping sequences have a long average broadcast delay when the number of channels is large. On the other hand, the Full broadcast III scheme leads to a high success rate, as compared to other schemes. However, from Fig. 2.2b, this scheme

has an extensively long average broadcast delay (almost as twice as the average broadcast delay in other scenarios). Hence, it is not suitable for broadcast scenarios where short broadcast delay is often required. Due to the low success rate in Full broadcast II and the long broadcast delay in Full broadcast III, in the rest of the book, we only use the random broadcast scheme and the Full broadcast I as the benchmarks to compare with our proposed schemes.

From the above discussion, it is known that these straightforward broadcast schemes have limitations to be used in multi-hop CR ad hoc networks. By investigating these broadcast schemes, we gain two useful insights for designing an efficient broadcast protocol in multi-hop CR ad hoc networks. First of all, from Fig. 2.2, it is shown that the first three schemes suffer a very low success rate when the number of channels is large because these schemes cannot guarantee channel rendezvous. Thus, a channel hopping sequence that can guarantee channel rendezvous without the channel availability information of other SUs is required to achieve a high success rate. Secondly, all these broadcast schemes are quite costly in terms of the average broadcast delay when the number of channels is large, which is not desirable for efficient broadcasts. This is because that a SU needs to use all the available channels in the spectrum for broadcasting in these schemes. If a SU only uses a subset of its available channels for broadcasting, the broadcast delay may be reduced. However, since fewer channels are used, the success rate may also be affected. Therefore, given that the success rate is not sacrificed, properly reducing the number of channels for broadcasting can result in shorter average broadcast delay.

2.3 The Basic Scheme

In this chapter, we present the basic scheme of our proposed protocol. As mentioned in Chap. 2.2, the straightforward broadcast schemes are not suitable for CR ad hoc networks. Therefore, based on the insights that we gain from these schemes, the main idea of our proposed QB²IC protocol is to intelligently design the channel hopping sequences for both the SU sender and the SU receiver to guarantee channel rendezvous, given that the sender and the receiver have at least one channel in common. In addition, the SU sender broadcasts on a subset of its available channels in order to reduce the average broadcast delay.

2.3.1 The Single-Hop Scenario

First of all, we consider the single-hop broadcast scenario. We propose a novel channel hopping strategy for SUs to guarantee channel rendezvous. There are several existing work on single-hop channel rendezvous for CR networks [6–9]. A common feature of these prior proposals is that all SUs in a network have to follow the same mechanism to construct the channel hopping sequence for rendezvous regardless

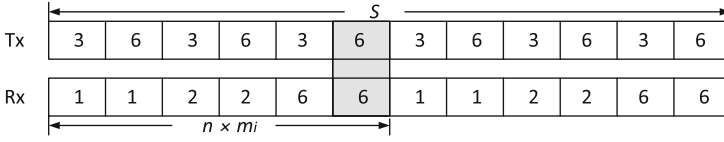


Fig. 2.3 An example of the QoS-based broadcast protocol

of transmitters or receivers. However, as stated in Chap. 1, in [7–9], the proposed channel hopping schemes cannot guarantee channel rendezvous in all scenarios under blind information. In [6], even though the proposed channel hopping sequence in the asymmetric model can guarantee channel rendezvous within $6MP(P - G)$ time slots, where P is the smallest prime number larger than M and G is the number of common channels between two SUs, $6MP(P - G)$ is usually a very large number when M is large. Therefore, this scheme may lead to very long broadcast delay when M is large. In fact, the communication pair can follow different mechanisms to construct the channel hopping sequences for channel rendezvous, which is ignored in all prior proposals. Thus, in this book, we use the channel hopping sequences generated by different methods for the sender and the receiver to guarantee channel rendezvous. Compared with the previous proposals in [6–9], our proposed channel hopping sequences can guarantee rendezvous in all scenarios under blind information within M^2 time slots, which is more favorable in broadcast scenarios. Under our proposed basic QB²IC scheme, a SU sender first randomly selects n channels from its available channel set. Then, it hops and broadcasts periodically on the selected n channels for S time slots. This channel hopping sequence with a length of S time slots is named as *the broadcast sequence*. The values of n and S are determined by the QoS requirements of the network. On the other hand, for each receiver, it first forms a random sequence that consists of its every available channel with a length of n time slots for each channel, namely *the receiving sequence*. Then, it hops and listens following the receiving sequence periodically. Denote the number of available channels of SU_i as m_i . Hence, the length of the receiving sequence of SU_i is $n \times m_i$. Figure 2.3 shows an example of the proposed QoS-based broadcast protocol. If the available channel set of the sender is $\{1, 2, 3, 6\}$, it randomly selects two channels (e.g., $\{3, 6\}$) to broadcast for S slots (i.e., $n = 2$). Each receiver listens for two time slots on each available channel of its available channel set (e.g., $\{1, 2, 6\}$) periodically. Thus, if $S = 12$, the broadcast sequence for the sender is $\{3, 6, 3, 6, 3, 6, 3, 6, 3, 6, 3, 6\}$. In addition, the receiving sequence for the receiver is $\{1, 1, 2, 2, 6, 6, \dots\}$. Hence, a successful broadcast is performed when both SUs hop on channel 6.

Based on the above rules, if the SU sender selects all its available channels and the length of the broadcast sequence S is equal to $n \times M$, the channel rendezvous is guaranteed within S time slots when the sender and each receiver have at least one channel in common. Therefore, the broadcast is ensured to be successful in the single-hop scenario. Thus, if n is sufficiently large, the probability that at least one channel selected by the sender are also in the available channel set of each receiver is high. However, on the other hand, since each SU is only equipped with one radio, it

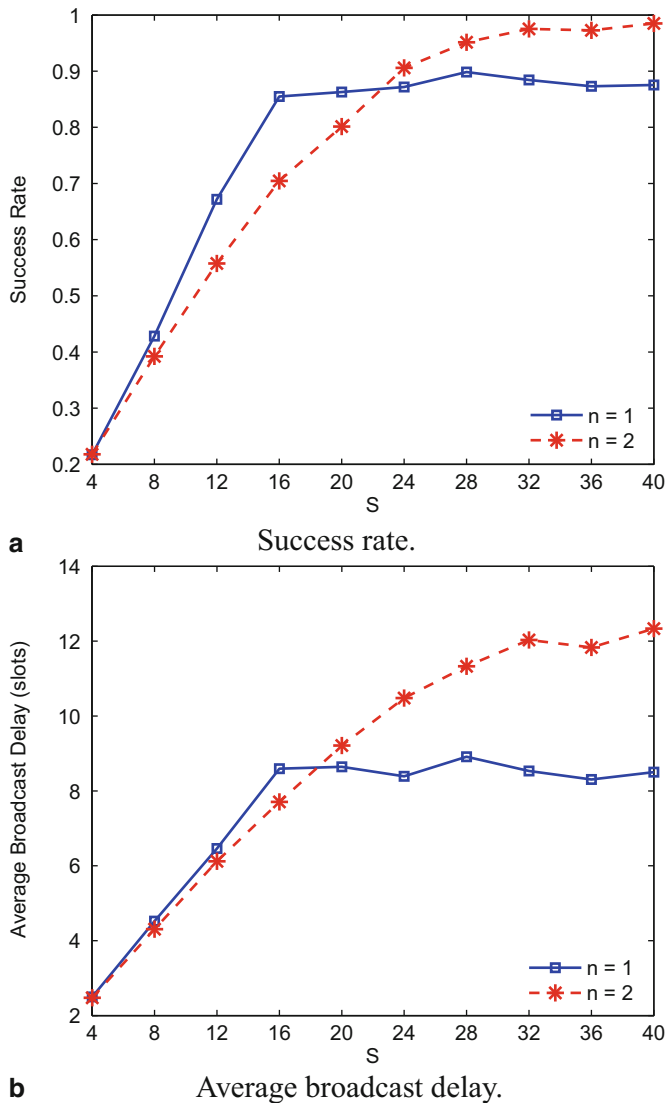


Fig. 2.4 The trade-off between the success rate and average broadcast delay under different n and S

cannot broadcast on n ($n > 1$) channels simultaneously. Hence, it takes a long time to finish broadcasting on all n channels when n is large.

From the above analysis, there exists a trade-off between the success rate and the average broadcast delay for different values of n and S . Figure 1 shows the simulation results of the success rate and the average broadcast delay for a single-hop broadcast scenario when $K = 40$ under various values of n and S . The PU traffic and other parameters are the same to generate Fig. 2.2. It is illustrated that higher success rate

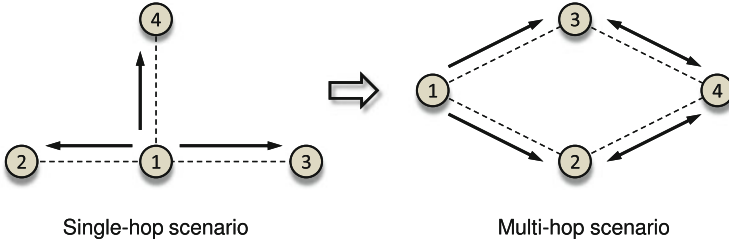


Fig. 2.5 Two different topologies of two 4-SU networks

often indicates longer average broadcast delay. Therefore, if the QoS requirements (i.e., the minimum required success rate and the maximum allowed average broadcast delay) are given, proper n and S can be selected.

2.3.2 The Multi-Hop Scenario

Next, we investigate the basic scheme of the proposed protocol in the multi-hop broadcast scenario. We consider two 4-SU networks as shown in Fig. 2.5. The first topology of the 4-SU network is a single-hop scenario where SU_1 is the source node. The second topology is a multi-hop scenario evolved from the first topology when SU_1 moves away from SU_4 . Since we want to consider the broadcast collision issue, the multi-hop scenario is studied in such a grid topology instead of a simple chain topology, as shown in Fig. 2.5. Without loss of generality, we assume that SU_1 is the source node and other nodes are by default receivers. Each receiver first follows the proposed receiving sequence to hop through and listen on the channels. When a receiver successfully receives the broadcast message, it becomes a sender who needs to rebroadcast the message. Therefore, it follows the rules of the senders and generates the proposed broadcast sequence to rebroadcast.

Our proposed QB^2IC protocol has special advantages when applied to multi-hop scenarios in CR networks, as compared to traditional ad hoc networks. In traditional ad hoc networks, if a node (e.g., SU_4) receives multiple copies of a message from its parent nodes (e.g., SU_2 and SU_3) simultaneously, a broadcast collision occurs and all copies of the message are discarded. Unfortunately, in traditional ad hoc networks, such broadcast collision is unavoidable in multi-hop scenarios if the parent nodes broadcast at the same time. However, under our proposed QB^2IC protocol, since the receiver can only listen to one channel at a time, as long as the parent nodes do not select the same channel to broadcast, such broadcast collision can be avoided. In fact, when the number of channels is large and different SUs obtain different available channels, the probability that two parent nodes select the same channel at the same time is fairly low.

In addition, under our proposed QB^2IC protocol, the success rate of the broadcast for the whole network can be improved in the multi-hop scenario. This is because

that a SU may not only receive the broadcast message from its parent node, but also receive the message from its child node (e.g., SU_2 can receive the message from SU_4 if SU_4 receives the message from the path $SU_1 \rightarrow SU_3 \rightarrow SU_4$). This is usually different from the broadcast schemes in traditional MANETs where nodes receive broadcast messages from their parent nodes. More importantly, if the channels used for broadcast in different paths are different, the probability that one of the channels is in the available channel set of the receiver is increased, as compared to the scenario where a SU only receives the message from its parent nodes. Thus, by utilizing the diversity of users and channels, the success rate of the whole network can be increased. Figure 2.6 shows the performance comparison between the single-hop scenario and the multi-hop scenario shown in Fig. 2.5 when $n = 1$. It is illustrated that the improvement of the success rate under the multi-hop scenario is up to 30 %, while the multi-hop scenario only costs up to 20 % additional average broadcast delay. Therefore, under our proposed QB²IC protocol, the success rate is benefited in the multi-hop scenario due to the diversity of users and channels.

2.4 The Enhanced Scheme

In this chapter, we first conduct an analysis on the channel availability of different SUs. Then, based on the results of this analysis, an enhanced QB²IC scheme for multi-hop CR ad hoc networks is presented.

2.4.1 Analysis of the Channel Availability

Based on the considered network model, the available channels of a SU are determined by the active PUs within its sensing range. Thus, first of all, we derive the average number of available channels of a SU. The size of the simulation area and the sensing range is denoted as A_L and A_S , respectively. Since PUs are evenly distributed in the considered simulation area, the probability that p PUs are in a sensing range is

$$\Pr(p) = \binom{K}{p} \left(\frac{A_S}{A_L}\right)^p \left(\frac{A_L - A_S}{A_L}\right)^{K-p}, \quad (2.1)$$

where $\binom{K}{p}$ represents the total combinations of K choosing p . In addition, we denote the probability that a PU is active as ρ . Therefore, given that there are p PUs in a sensing range, the probability that there are b PUs active is

$$\Pr(b|p) = \binom{p}{b} \rho^b (1 - \rho)^{p-b}. \quad (2.2)$$

Furthermore, given that there are p PUs and b active PUs within a sensing range, the probability that there are c available channels is denoted as $\Pr(c|p, b)$. Since

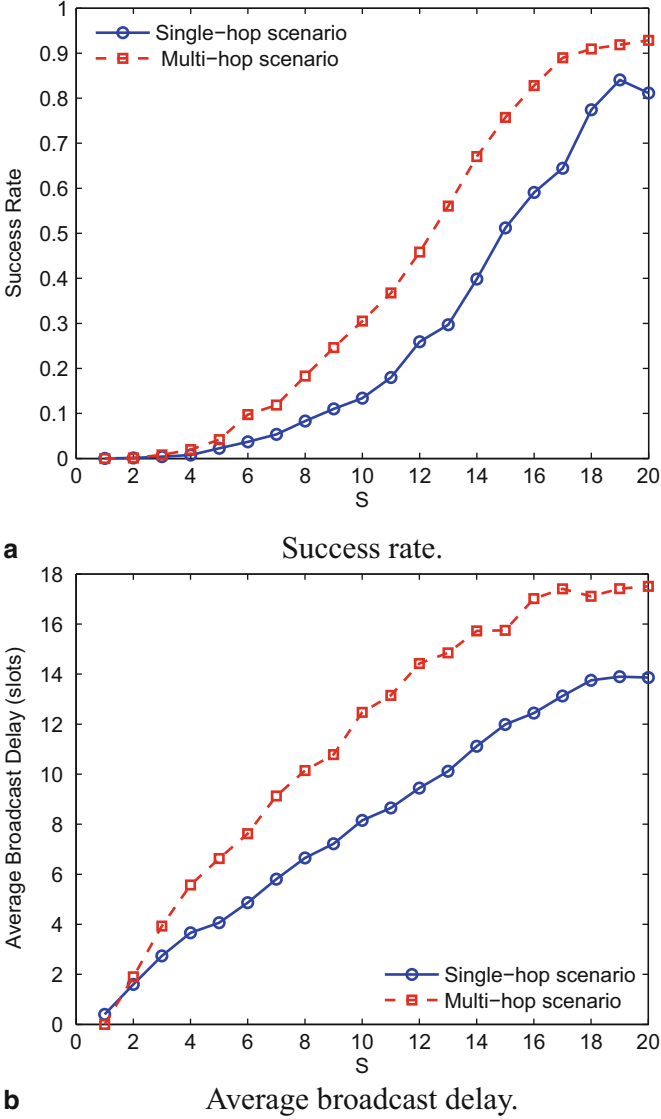
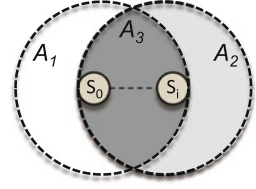


Fig. 2.6 Comparison between the single-hop and the multi-hop scenarios

the number of available channels is only related to the number of active PUs, c is independent of p . In addition, since an active PU randomly selects a channel from M channels in the spectrum, $\Pr(c|p, b)$ is equivalent to the probability that there are exactly c empty boxes given that b distinguishable balls are randomly put into a total of M distinguishable boxes and a box can have more than one ball (because we do

Fig. 2.7 Two neighboring SUs whose sensing ranges overlap



not limit a channel to only one PU). Thus, $\Pr(c|p, b)$ can be expressed as:

$$\Pr(c|p, b) = \frac{\binom{M}{c}(M-c)!S(b, M-c)}{M^b}, c \in [\max(0, M-b), M], \quad (2.3)$$

where $S(b, M-c)$ is the Stirling number of the second kind. In addition, $S(b, M-c)$ is defined as

$$S(b, M-c) = \frac{1}{(M-c)!} \sum_{i=0}^{M-c} (-1)^i \binom{M-c}{i} (M-c-i)^b. \quad (2.4)$$

Thus, the probability that there are c available channels and there are p PUs and b active PUs in the sensing range of a SU is the product of (2.1), (2.2), and (2.3). Then, the average number of available channels of a SU, $E[c]$, is written as

$$E[c] = \sum_{p=0}^K \sum_{b=0}^p \sum_{c=\max(0, M-b)}^M \frac{c \binom{M}{c} (M-c)! S(b, M-c)}{M^b} \left(\frac{p}{b}\right) \rho^b (1-\rho)^{p-b} \left(\frac{K}{p}\right) \left(\frac{A_S}{A_L}\right)^p \left(\frac{A_L - A_S}{A_L}\right)^{K-p}. \quad (2.5)$$

In addition, another important parameter is the average number of common channels between two neighboring SUs. Figure 2.7 illustrates an example of two neighboring SUs whose sensing ranges overlap, where d is the distance between the two SUs. Assume that SU_i and SU_j can hear each other. As shown in Fig. 2.7, the sensing ranges of the two SUs are divided into three areas. A_3 (the dark area) represents the area of the overlapping part, while A_1 (the white area) and A_2 (the gray area) represent the areas of the sensing ranges of SU_i and SU_j without A_3 , respectively.

Define $A^* = A_1 + A_2 + A_3$. Therefore, based on basic geometry, A^* can be obtained as follows:

$$A^* = (2\pi - 2\alpha)r_s^2 + d\sqrt{r_s^2 - \left(\frac{d}{2}\right)^2}, \quad (2.6)$$

where $\alpha = \cos^{-1} \frac{d}{2r_s}$. Thus, the channels that are used by the active PUs within A^* are those that cannot be used by either SU_i or SU_j . In other words, the common channels between two neighboring SUs are those that are not used by the active PUs

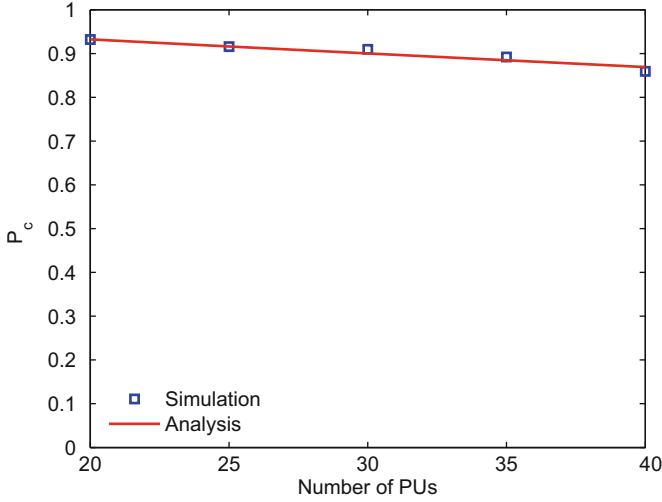


Fig. 2.8 The ratio of the average number of common channels between two neighboring SUs to the average number of available channels of one SU when $\rho = 0.9$

within A^* . Thus, similar to the derivation process for $E[c]$, the average number of common channels between two neighboring SUs, $E[u]$, is obtained from

$$E[u] = \sum_{y=0}^K \sum_{z=0}^y \sum_{u=\max(0, M-z)}^M \frac{u \binom{M}{u} (M-u)! S(z, M-u)}{M^z} \binom{y}{z} \rho^z (1-\rho)^{y-z} \binom{K}{y} \left(\frac{A^*}{A_L}\right)^y \left(\frac{A_L - A^*}{A_L}\right)^{K-y}, \quad (2.7)$$

where y and z are the number of PUs and active PUs within A^* , respectively.

Then, we define the ratio of the average number of common channels between two neighboring SUs to the average number of available channels of a SU as

$$P_c = \frac{E[u]}{E[c]}, \quad (2.8)$$

P_c measures the similarity of the available channel sets between two neighboring SUs. If $P_c = 1$, this means that the available channels between two neighboring SUs are exactly the same. On the other hand, if $P_c = 0$, this means that the available channels between two neighboring SUs are completely different. Figure 2.8 shows the simulation and analytical results of P_c when $r_c = r_s$ and both SUs are at the border of each other's sensing range. Since the sensed available channels of two SUs might be the most distinct when they are apart the most, Fig. 2.8 shows the lower bound of P_c . Figure 2.8 indicates that the simulation and analytical results coincide and also implies that even though the available channels of different SUs are different, the similarity of available channels between neighboring SUs is high ($> 85\%$).

2.4.2 The Enhanced QB²IC Scheme

The above analysis of the channel availability indicates that neighboring SUs have very similar available channel sets. Thus, inspired by this observation, we propose an enhanced QB²IC scheme to further improve the performance.

The main idea of our enhanced scheme is that each SU selects the first θ channels from its available channel set based on the indexes of the channels to form a new available channel set. Based on the downsized available channel set, each SU follows the basic scheme to broadcast. Since the available channel sets of neighboring SUs are similar, the downsized available channel sets of neighboring SUs are also similar. In this way, if the threshold θ is properly selected, the success rate does not degrade significantly. However, since the number of the channels that each receiver needs to listen is reduced, the average broadcast delay can be greatly reduced.

However, there again exists a trade-off between the success rate and the average broadcast delay when selecting the threshold θ . As shown in Fig. 2.9, when θ increases, the success rate increases but the average broadcast delay also increases. Thus, if the QoS requirements are given, a proper θ can be selected.

2.5 Performance Evaluation

In this chapter, we evaluate the performance of the proposed QB²IC protocol. Since there is no existing comparable broadcast scheme under blind information for multi-hop CR ad hoc networks, we compare our proposed broadcast schemes with the random broadcast scheme and the full broadcast scheme with the first channel hopping sequence introduced in Chap. 2.2. As mentioned in Chap. 2.2, we also assume that the PU traffic is discrete-time, where the PU packet inter-arrival time X follows the biased-geometric distribution whose probability mass function (pmf) is given by [10, 11]:

$$\Pr(X = x) = \begin{cases} 0 & x < l \\ \lambda_p(1 - \lambda_p)^{(x-l)} & x \geq l, \end{cases} \quad (2.9)$$

where x is the number of time slots between packet arrivals, $l \geq 0$ represents the minimum number of time slots between two adjacent packets, and λ_p is the probability that a PU packet arrives during one time slot (i.e., λ_p is the normalized arrival rate of PU packets). Thus, the probability that a PU is active can be written as $\rho = \frac{L_p}{L_p + \frac{1-\lambda_p}{\lambda_p}}$,

where L_p is the fixed PU packet length [12]. It is noted that the PU traffic model is used to obtain simulation results. In fact, our proposed QB²IC broadcast protocol does not rely on specific PU traffic models. In addition, denote σ as the probability that a transmission is successful. That is, if $\sigma = 1$, it means that there is no transmission error and a transmission is always successful. Moreover, the default parameters used to obtain the simulation results are listed in Table 2.1. For the topology of the

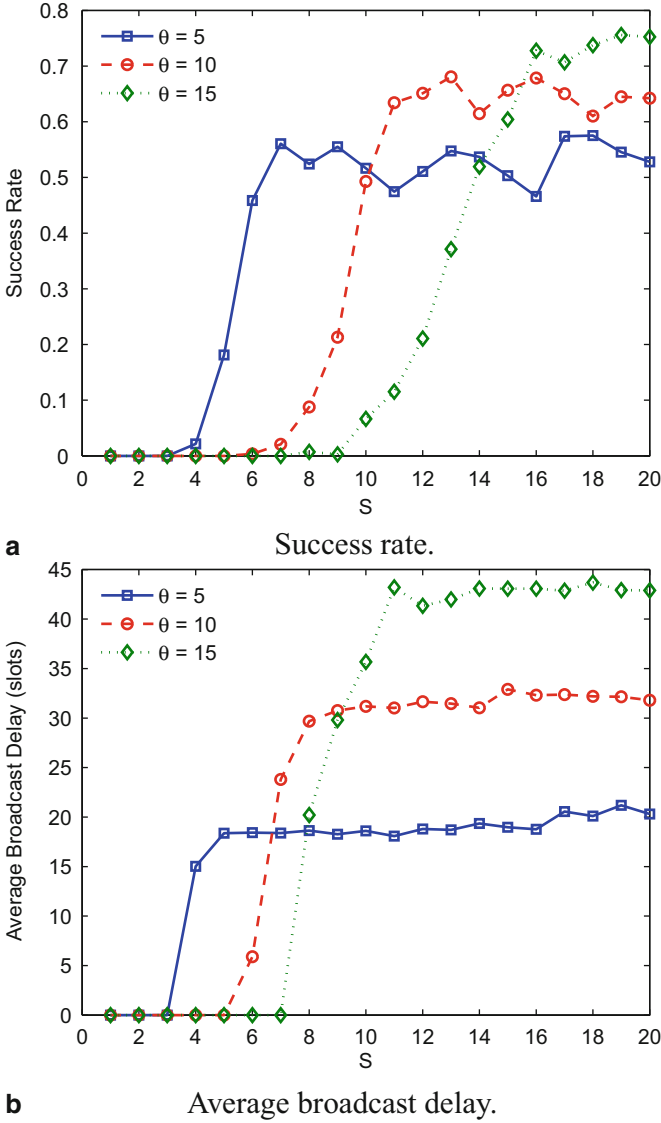


Fig. 2.9 Success rate and average broadcast delay of the proposed enhanced QB²IC scheme under various θ

CR ad hoc network, we assume that SUs form a 4×4 grid network with the distance between two adjacent SUs equal to r_c .

Figure 2.10 depicts the performance results of the two proposed QB²IC schemes (for the enhanced scheme, $\theta = 10$), the random broadcast scheme, and the full broadcast scheme under different S when $K = 40$, $M = 20$, $n = 1$, and $\sigma = 1$. It is shown that when S is large (e.g., $S = 19$), the basic scheme outperforms the other

Table 2.1 Simulation parameters

Number of SUs N	16
Number of PUs K	40
Number of channels M	20
Side length of the simulation area L	10 (unit length)
Radius of the sensing range r_s	2 (unit length)
Radius of the transmission range r_c	2 (unit length)
Number of selected channels n	1
The normalized PU arrival rate λ_p	0.5
The PU packet length L_p	10 (time slots)
The probability of a successful transmission σ	1

three broadcast schemes in terms of higher success rate. However, the enhanced scheme can greatly reduce the average broadcast delay while obtaining satisfactory success rate. Both the proposed QB²IC schemes outperform the random broadcast scheme and the full broadcast scheme in terms of higher success rate and shorter average broadcast delay.

Figures 2.11 and 2.12 show the impact of the number SUs and the number of PUs on the network performance, respectively, where the secondary network is a grid network when $S = 20$. On the other hand, Fig. 2.13 depicts the impact of the number of SUs on the network performance where the secondary network is not a grid network. In Fig. 2.11, SUs form a 2×2 network for $N = 4$ and a 3×3 network for $N = 9$. It is shown that the average broadcast delay increases as the number of SUs in the network increases. This is because that the increase of the number of hops leads to a longer broadcast delay. However, the success rate of the basic QB²IC scheme does not decrease significantly when the number of SUs increases. This is because that the multi-hop scenario benefits the success rate due to the diversity of channels. On the other hand, as shown in Fig. 2.12, the success rate decreases when the number of PUs increases. This is because that the number of common channels between neighboring nodes decreases when the total number of PUs increases, which leads to a lower success rate.

We also investigate the impact of the number of SUs on the network performance where the secondary network is not a grid network. Fig. 2.13 shows the results of the basic broadcast scheme where the SUs are randomly distributed in the simulation area. In Fig. 2.13a, it is shown that when the number of SUs increases, the success rate of the whole network also increases. This is because that if the number of SUs within the same area is large, the diversity of senders and channels increases. Thus, the number of potential senders of a SU increases. Therefore, in our proposed QB²IC protocol, the probability that one of the channels used by these senders is in the available channel set of the receiver is increased. Hence, the probability that all nodes in the network can successfully receive the broadcast message also increases. Due to the same reason, in Fig. 2.13b, it is shown that the average broadcast delay does not increase significantly when the number of SUs increases. That is, when the

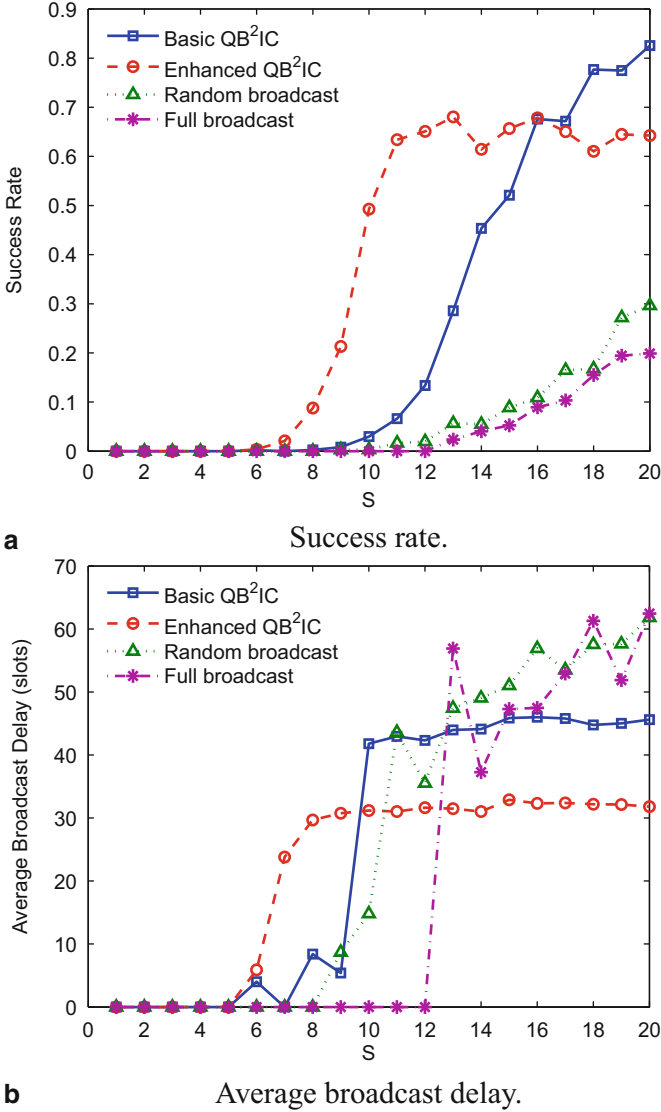


Fig. 2.10 Success rate and average broadcast delay of the proposed QB²IC schemes with the random and full broadcast schemes under various S

number of SUs increases by 10 times, the average broadcast delay only increases by 40 % for the basic scheme and 51 % for the enhanced scheme. To sum up, it is shown that our proposed basic and enhanced broadcast schemes are scalable when the CR ad hoc network size increases.

Figure 2.14 shows the impact of the number of channels on the network performance when $K = 30$ and $N = 9$. For the length of the broadcasting sequence, we

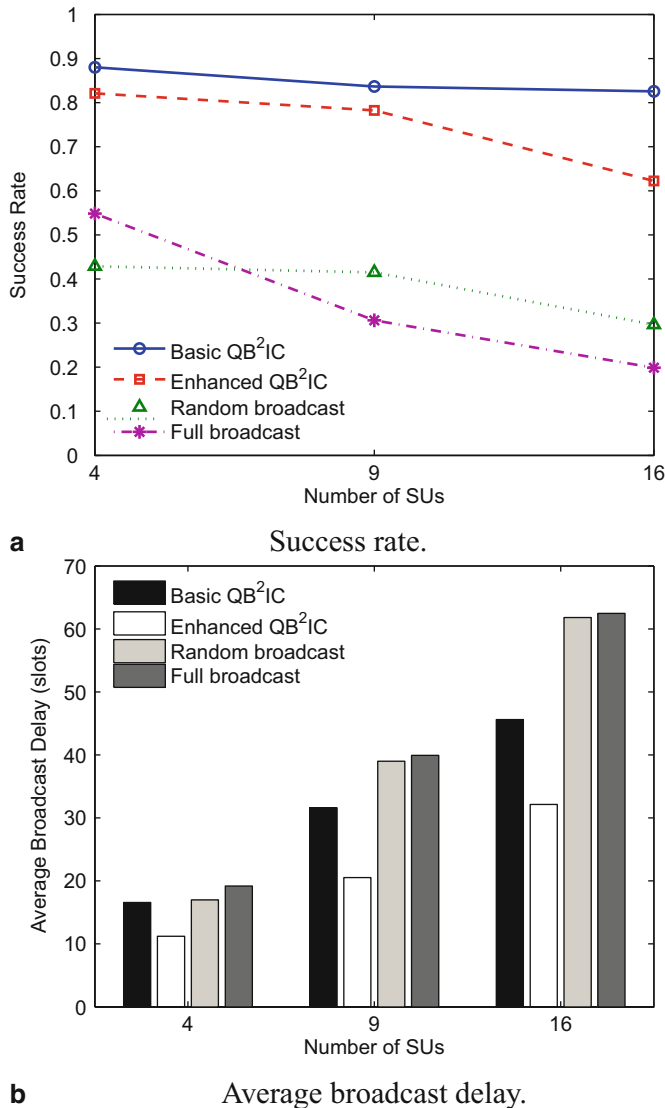


Fig. 2.11 The impact of the number of SUs on the network performance where the secondary network is a grid network

set $S = 2M$. In addition, for the enhanced scheme, we let $\theta = M/2$. As stated in Chap. 2.3, the number of channels leads to a trade-off in terms of the success rate and broadcast delay. On one hand, a large M ensures that the probability that two parent nodes select the same channel at the same time is low. Therefore, as shown in Fig. 33, expect the full broadcast scheme, the success rate of the other three broadcast schemes increases as the number of channels increases. In addition, both

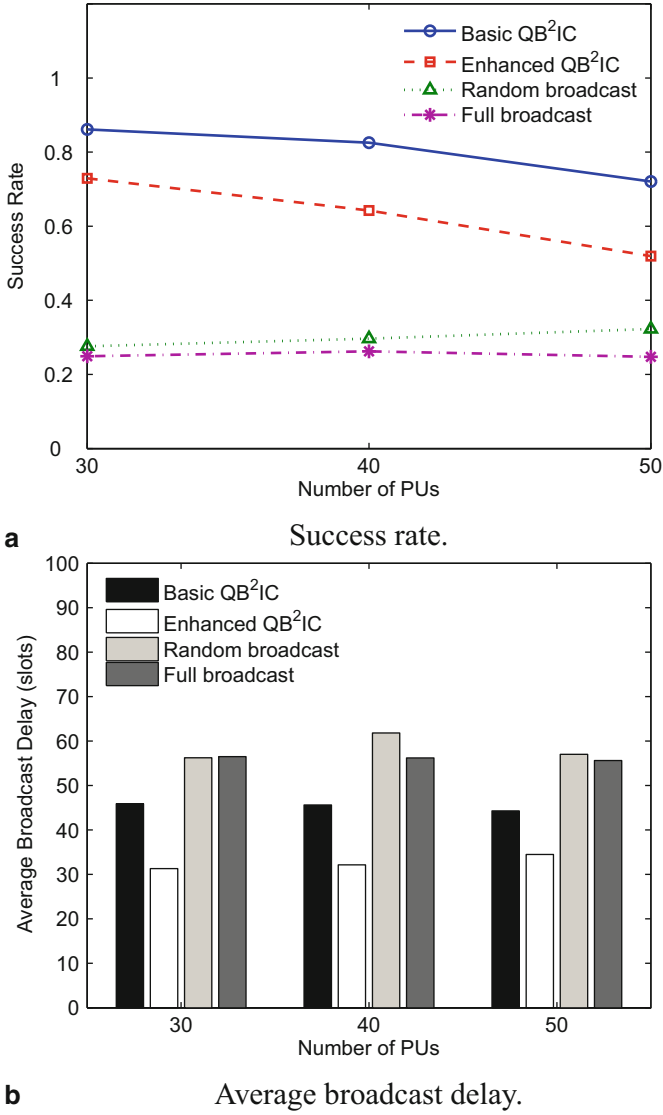


Fig. 2.12 The impact of the number of PUs on the network performance

our proposed basic and enhanced schemes have very similar and high success rates (i.e., >0.95). However, the random and full broadcast schemes result in relatively low success rates. On the other hand, a large M also leads to a long broadcast delay. Hence, as shown in Fig. 2.14b, the average broadcast delay of all four schemes increases as the number of channels increases. Moreover, our proposed enhanced scheme outperforms other the three broadcast schemes in terms of shorter average broadcast delay.

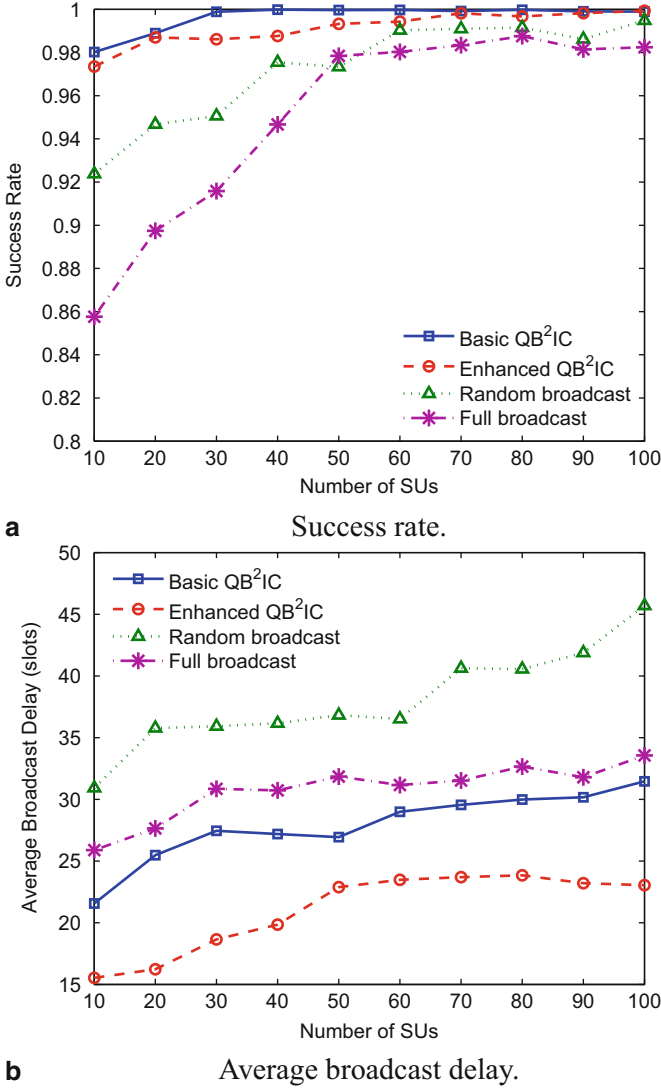


Fig. 2.13 The impact of the number of SUs on the network performance where the secondary network is *not* a grid network

In this chapter, we study the impact of the channel availability variation on the network performance. Note that during a broadcast process, the channel availability of the sender and receiver may change due to either PU activity (i.e., a new PU may claim one of the available channels during a broadcast) and PU mobility (i.e., a new active PU may move into the sensing range of a SU). This channel availability change may also affect the network performance. Therefore, the robustness of the proposed

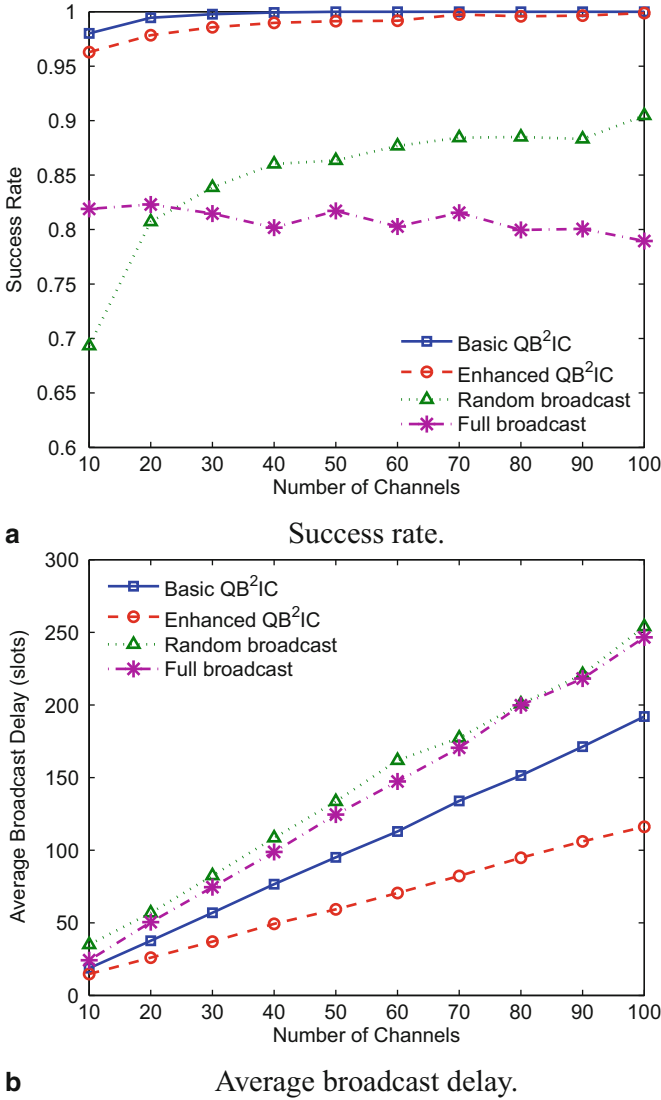


Fig. 2.14 The impact of the number of channels

broadcast scheme against the channel availability variation needs to be investigated. Figure 2.15 depicts the impact of the channel availability change due to PU activity on the basic broadcast scheme when $n = 2$, $S = 40$ and $M = 20$. We let the PU packet arrival rate change from 5 to 50 pkt/s and the PU packet length is 50 slots. This means that the probability that a PU is active, ρ , varies from 0.35 to 0.85. It is shown that the impact of the PU activity on the network performance is quite limited. When PUs are very densely deployed (i.e., 40 PUs within a 10×10 area) and PU

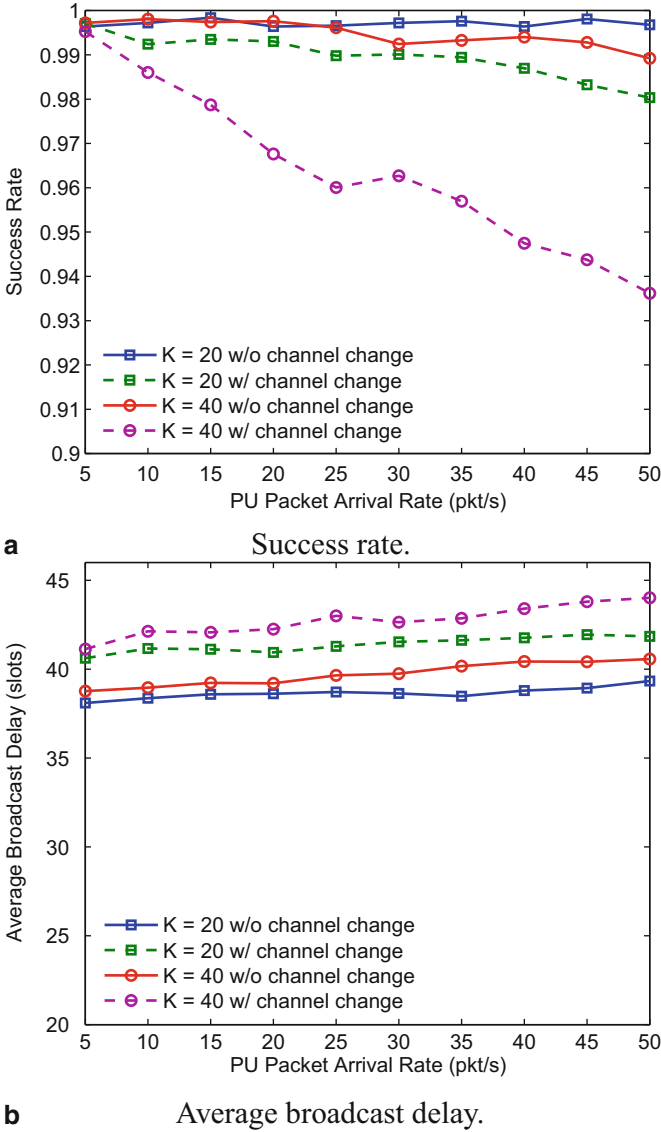


Fig. 2.15 The impact of the channel availability change due to PU activity

traffic is very heavy (i.e., $\rho = 0.85$), the decrease of the success rate is only up to 5 % and the increase of the average broadcast delay is only up to 9 %.

In addition, Fig. 2.15 depicts the impact of the channel availability change due to PU mobility. We use the Random Waypoint Mobility Model to characterize the movement pattern for PUs [13–15]. Under this model, a PU begins by staying in a location for a certain period of time (e.g., a pause time which is uniformly distributed

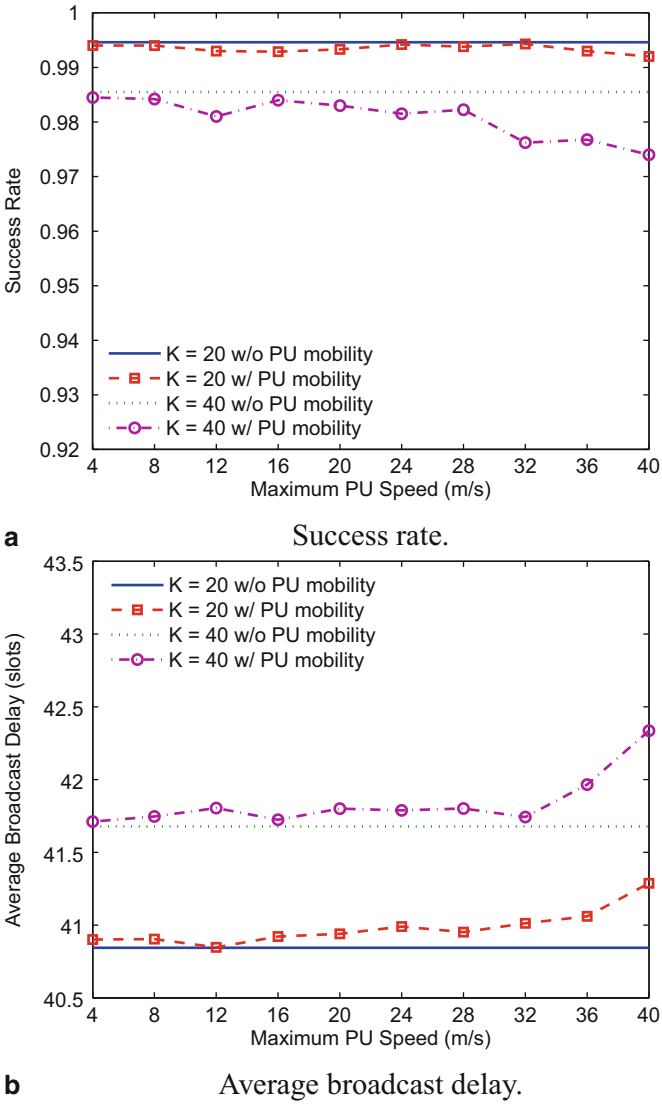


Fig. 2.16 The impact of the channel availability change due to PU mobility

between $[0, 4s]$). Once the pause period expires, the PU randomly selects a speed that is uniformly distributed between $[0, v_{max}]$ and moves for a random time that is uniformly distributed between $[0, 4s]$. Upon its arrival, the PU pauses for a random time period before starting the movement again. Figure 2.16 depicts the impact of the channel availability change due to PU mobility on the network performance. Similar to the impact of PU activity on the network performance, it is shown that the impact of the PU mobility is also quite trivial. When PUs are very densely deployed

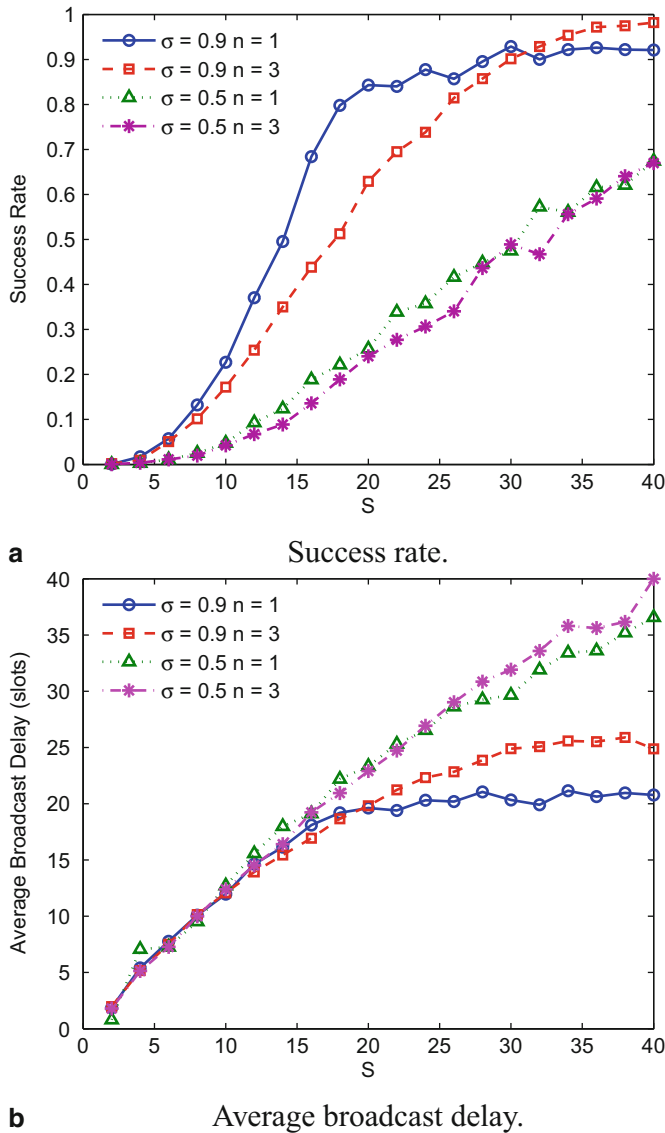


Fig. 2.17 Success rate and average broadcast delay of the basic scheme of the proposed QB²IC protocol when $N = 4$ under various n , S , and σ

(i.e., 40 PUs within a 10×10 area) and PUs move very fast (i.e., the maximum PU speed is 40 m/s), the decrease of the success rate is only up to 1 % and the increase of the average broadcast delay is only up to 2 %.

In this chapter, we investigate the impact of transmission errors on the network performance. It is known that various factors (e.g., transmission contention, channel

quality, etc.) can lead to transmission errors. These transmission errors may cause failed broadcasts. However, as stated in Chap. 1, due to the ACK implosion problem, ACK messages are not feasible to be used to prevent failed broadcasts in CR ad hoc networks. Even though ACKs are not applied to solve the transmission error problem, our proposed QB²IC protocol can still be used in a radio environment where transmission errors exist. By increasing the number of channels selected by the sender (i.e., n) or increasing the number of times that the sender broadcasts the message (i.e., S), the probability that a sender and a receiver have a channel rendezvous increases. Therefore, our proposed QB²IC protocol can still achieve satisfactory QoS requirements. Figure 2.17 shows the simulation results of the basic scheme of the proposed QB²IC protocol when $N = 4$ under various n , S , and σ , where SUs form a 2×2 grid network. It is shown that by increasing n or S , our proposed QB²IC protocol can still achieve satisfactory performance.

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