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INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

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Toward Reliable Contention-aware Data Dissemination in Multi-hop Cognitive Radio Ad Hoc Networks

Mubashir Husain Rehmani* , Aline Carneiro Viana† , Hicham Khalife‡ , Serge Fdida§

Thème COM — Systèmes communicants
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Abstract:
This paper introduces a new channel selection strategy for reliable contention-aware data dissemination in multi-hop cognitive radio network. The key challenge here is to select channels providing a good tradeoff between connectivity and contention. In other words, channels with good opportunities for communication due to (1) low primary radio nodes (PRs) activities, and (2) limited contention of cognitive ratio nodes (CRs) acceding that channel, have to be selected. Thus, by dynamically exploring residual resources on channels and by monitoring the number of CRs on a particular channel, SURF allows building a connected network with limited contention where reliable communication can take place. Through simulations, we study the performance of SURF when compared with three other related approaches. Simulation results confirm that our approach is effective in selecting the best channels for efficient and reliable multi-hop data dissemination.

Key-words: multi-hop cognitive radio networks, opportunistic forwarding, dynamic channel selection, data dissemination.

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Dissémination fiable de données dans les réseaux radio cognitifs multi-sauts

Résumé : Nous présentons dans cet article une nouvelle stratégie de sélection de fréquences pour la dissémination fiable des données dans le réseau radio cognitifs multi-sauts. Le principal défi ici est de sélectionner des fréquences offrant un bon compromis entre la connectivité et les contentions. En d'autres termes, il s'agit de sélectionner les fréquences offrant de bonnes opportunités de communication en raison de (1) la faible activité des nœuds radio primaire (PR), et (2) la contention limitée entre les nœuds ratios cognitifs (CR) opérant sur ces fréquence. Ainsi, en explorant dynamiquement les ressources résiduelles sur les fréquences des primaires et en contrôlant le nombre de CR sur une fréquence particulière, notre stratégie SURF permet de construire un réseau connecté à contention limitée où des communications fiables peuvent être effectuées. Grâce à une large étude basées sur des simulations, nous étudions les performances de SURF par rapport à trois autres approches. Les résultats de simulation confirment que notre stratégie permet la sélection des meilleures fréquences adaptées à une dissémination fiable et efficace des données dans un réseau radio cognitifs multi-sauts.

Mots-clés : Réseaux radio cognitifs multi-sauts, routage opportuniste, sélection dynamique de fréquence, dissémination de données

1 Introduction

Data dissemination is a classical and a fundamental function in any kind of network. In wireless networks, the characteristics and problems intrinsic to the wireless links bring several challenges in data dissemination in the shape of message losses, collisions, and broadcast storm problem, just to name a few. However, in the context of Cognitive Radio Network (CRN) [1], reliable data dissemination is much more challenging than traditional wireless networks. First, in addition to the already known issues of wireless environments, the diversity in the number of channels each cognitive node can use adds another challenge by limiting node's accessibility to its neighbors. Second, cognitive radio nodes have to compete with the Primary Radio (PR) nodes for the residual resources on many channels and use them opportunistically. Besides, during communication CR nodes should communicate in such a way that it should not degrade the reception quality of PR nodes by causing CR-to-PR interference. In addition, CR nodes should immediately interrupt its transmission whenever a neighboring PR activity is detected [5].

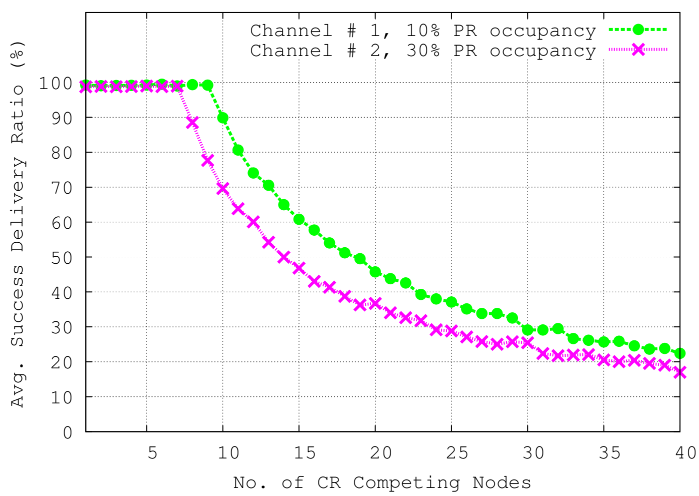


Figure 1: CR nodes competing for the same channel.

In multi-hop cognitive radio ad hoc networks, where coordination between CRs is hard to achieve and no central entity for regulating the access over channels is to be envisaged, reliable data dissemination is even more complex. In this perspective, the first step in having efficient data dissemination is to know *how to select best channels*. Thus, differently from most works in the literature dealing with single-hop communication [13, 2], we go a step further here and build up a channel selection strategy for multi-hop communication in CRN. The objective of every cognitive radio node is to select the best channel ensuring a maximum connectivity and consequently, allowing the largest data dissemination in network. This corresponds to the use of channels having not only low primary radio nodes (PRs) activities, nevertheless the reliability of the dissemination process is achieved by limiting the contention of cognitive ratio nodes (CRs) acceding selected channels.

The effect of CR contentions on dissemination is highlighted in Fig. 1 that shows the evolution of the average success delivery ratio at receivers of a single source, with the number of competing CRs. It is clear that the performance of a channel with low PR activity decreases with the number of CR competing for the available resource. Nevertheless, a channel with higher PR activity can be a good choice if CR contention is low. The challenge here is then how to find a good tradeoff between connectivity and contention.

In this paper, we propose a channel selection strategy, named SURF. The goal of SURF is to ensure reliable contention-aware data dissemination and is specifically designed for multi-hop cognitive radio ad hoc networks. Usually channel selection strategies provide a way to nodes to select channels for transmission. On the contrary, SURF endue CR nodes to select best channels not only for transmission but also for overhearing. As a result, both sender and receiver tuned to the right channel for effective and reliable data dissemination. Additionally, by dynamically exploring residual resources on channels and by monitoring the number of CRs on a particular channel, SURF allows building a connected network with limited contention where reliable communication can take place. To counter this issue, we define the "Tenancy Factor β", which enables SURF algorithm to avoid channels with high CR contention.

Through simulations, we show that SURF builds, as expected, a highly connected network suitable for reliable dissemination. Moreover, SURF outperforms existing algorithms. In fact, we compared our solution with two variants of Selective Broadcasting (SB) strategy [7], the closest technique to SURF available today. The simplicity and decentralized nature of our solution makes it usable in ad hoc CRNs deployed to convey emergency messages and alerts. It can also be employed in commercial applications to disseminate short publicity messages.

The remainder of this paper is organized as follows: we discuss connectivity vs. contention trade-off in Section 2. We give general overview of SURF in Section 3. Section 4 deals with detailed description of SURF. Section 5 provides comprehensive analysis of SURF. Performance analysis is done in section 6, then the major advantages of SURF are highlighted in section 7. Section 8 discuss related work and finally, section 9 concludes the paper.

2 Cognitive radio ad hoc networks: connectivity VS. contention trade-off

In a highly dynamic/opportunistic cognitive radio network, cognitive users compete for residual resources (a.k.a spectrum holes) left by the activity of the legacy users more formally called primary radio users. Every cognitive node, using an intelligent selection strategy, selects the appropriate channel for transmitting with the major constraint of not degrading the service of ongoing primary radio communications. Indeed, primary radios have the absolute priority over the communication channels. In an opportunistic multi-hop cognitive radio network where coordination between CRs is hard to achieve and no central entity for regulating the access over channels is to be envisaged, the objective of every cognitive radio is to select the channel ensuring a maximum connectivity. Such spectrum band has the highest number of active cognitive radios hence allows quick and effective data dissemination in the network.

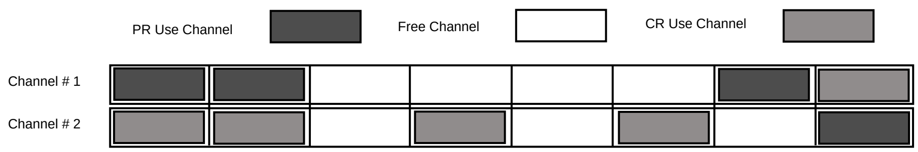


Figure 2: PR and CR Nodes occupancy over channels

Intuitively, one may think that the best strategy for *all* CRs is to dynamically switch to the less occupied channel (by PRs). Thus, satisfying the objective of verifying priority constraints imposed by PRs. Nevertheless, such strategy leads to many classical problems already well known in wireless networking. First, forcing all CRs in a geographic area to be active over the same channel makes all nodes compete for the same resource thus generating contention and collision problems. Second, such approach wastes the valuable additional capacity on different channels that the cognitive radio concept offers. Indeed, it was already shown in traditional wireless networking that networks with high contention, where repetitive collisions are frequent, suffer from close to zero throughput [8]. A typical example is described in Fig. 2. Initially, channel 1 has more primary radio activities and should be avoided by the CR transmitters. However, if enough CRs switch to channel 2 to communicate, channel 1 quickly becomes less occupied and able to carry higher throughputs than channel 2. Therefore, taking into account contention issues due to CR transmissions is necessary when selecting spectrum bands for CR communications.

Any proposed strategy for channel selection in CRN has to optimize the connectivity vs. contention trade-off. We propose hereafter a channel selection strategy that monitors the number of active CR nodes on a particular channel. As a result, *we are able to build a well connected network while dynamically exploiting residual resources on many channels*. We detail how our proposed strategy named SURF handles this trade-off in the following sections.

3 SURF: General overview

SURF channel selection strategy is specifically designed for ad hoc cognitive radio networks. The general goal of our strategy is to ensure a reliable data dissemination over a multi-hop CRN. Such technique can be used to convey emergency alarms and alerts or to deliver low priority data such as advertisement messages in a cognitive radio multi-hop context. Recall that in order to achieve our goal and ensure coverage and reliability, the connectivity vs. contention trade-off should be optimized.

SURF strategy is exclusively implemented by every CR node and is used for transmission and/or overhearing. As detailled hereafter, using the decentralized algorithm proposed by SURF, every CR sender judiciously selects the *best* frequency band for sending messages and every CR receiver tunes to the right channel (selected by the sender) to retrieve the sent data.

With SURF, each CR node looks first for the less PR-occupied channel to help deciding autonomously which channel to use. In addition to PR occupancy, we also consider CR neighbors competing for the same channel resource. More precisely, every CR node classifies available channels based on the observed PR-occupancy over these channels. This classification is then refined by identifying the number of active CRs over each band. The best channel for transmission is the channel that has the lowest PR activity and a reasonable ongoing CR activity. Indeed, choosing a channel with few CRs yields to a disconnected network. The challenge in our strategy is in finding the number of active CRs on every channel that gives the best connectivity with limited contention. Practically, every CR after classifying available channels, switches dynamically to the best one and broadcasts the stored message.

Additionally, CRs with no messages to transmit implement the SURF strategy in order to tune to the *best* channel for data reception. Clearly, using the same strategy implemented by the sender allows nodes in the close geographic areas to select the same channel as sender for overhearing with high probability. Intuitively, it is likely that CRs in the sender's vicinity have the same PR occupancy, hence channels available to a CR sender is also available to its neighbors with high probability [16]. Therefore, SURF controls the number of CR receivers, thus a connected topology with low contention is created. Once a packet is received, every CR receiver undergoes again the same procedure to choose the appropriate channel for conveying the message for its neighbor.

4 Detailed description of SURF

4.1 Considered Scenario

We consider an infrastructureless multi-hop cognitive radio ad hoc network in which only CR nodes collaborate. In the assumed configuration, no cooperation or feedback from primary nodes is expected. Consequently, CR nodes can only rely on information obtained or inferred locally to undergo transmission or reception decisions.

Moreover, we consider that CR nodes are capable to switch over the available channels easily. For the sake of simplicity, we assume that every channel is divided into equal time slots. Each slot can be exclusively used either by a primary radio or by a cognitive radio when no primary activity is present over that slot. Hence, every channel is composed of $\tau_t = \tau_o + \tau_a$ time slots, where τ_o and τ_a are the slots occupied by PR nodes and the available slots, respectively. A total of C frequency channels are available in the network. These channels can either be used by PR or CR nodes. Due to PR nodes' localized and timely activity, the total frequency channels vary with time and location, which results in a non-uniform, scattered and diverse set of channels available to CR nodes.

We consider CR nodes equipped with a single transceiver, where a single channel can be selected at a time and used *exclusively* for transmission or overhearing. It is worth noting here that, contrarily to other approaches in the literature where the costly assumption of having CR nodes equipped with multi-transceivers is used, *our assumption is highly realistic today* and is already considered in some cognitive radio devices and prototypes [4]. In these devices, physical constraints limit the access of CR nodes to a limited set of available channels. Indeed, covering all the spectrum bands is a highly costly process, thus we assume that every cognitive radio device can handle a predefined number of channels. We denote the set of spectrum channels each CR can exploit by Acs such that $Acs \in C$ and $|Acs| < |C|$. We shall investigate the impact of the size of Acs on the performance of our strategy later in the paper (Section 5.3).

In the considered scenario described above, SURF strategy provides every CR with a way to select the appropriate channel for transmission and reception.

4.2 PR and CR Occupancy

We consider that the spectrum sensing block provides the spectrum opportunity map as described in [15], which is then used by CR nodes to calculate the PR and CR occupancy. The spectrum sensing block is responsible for obtaining awareness about the spectrum usage and presence of primary users; whereas spectrum opportunity map identifies whether primary users have been detected or not for each channel. PR occupancy is thus, denoted here by $PR_o^{(i)}$ and is defined as the time slots percentage of the channel i occupied by PR nodes, i.e. the ratio between the number of PR nodes and the total number of time slots τ_t.

Practically, our estimation of the PR occupancy follows a conservative approach. In fact, computing the PR occupancy based on the total number of primary radios assumes these nodes are permanently active. Intuitively, given the higher priority of PRs in accessing spectrum bands, considering that PR are always active gives them additional guarantees at the price of a lesser space for CRs activity. The remaining available percentage of the channel i, i.e. $1 - PR_o^{(i)}$, gives then the space available for channel sharing among CR nodes, named $CR_{as}^{(i)}$. The CR occupancy $CR_o^{(i)}$ is then obtained from the available space for CR activities on a particular channel i, $CR_{as}^{(i)}$, as described hereafter.

Since we are considering non-cooperative infrastructureless architecture, there is no centralized authority that helps CR nodes for their channel selection. Therefore, there is no way to prevent collision and message losses when the number of CR nodes competing for the same channel increases. Additionally, CR nodes have to rely on *locally* inferred information in a distributed manner to select channels with a higher number of 1-hop CR receivers. To allow nodes to select channel having a good compromise between the number of CR receivers and the number of competing CR transmitters, we use the *Tenancy Factor*, named β, to compute the CR occupancy $CR_o^{(i)}$ of each channel i. β provides the upper bound in terms of number of CR neighbors on a particular channel, where the communication is still performed with a good probability of success. The goal here is then to maximize the chances of selecting channels that have a a good number of CR neighbors (close to *Tenancy Factor* β).

Figure 3 shows algorithm how CR nodes calculate CR occupancy according to the tenancy factor β and the number of CR neighbors competing for the channel. When the number of CR neighbors, i.e. $CR_n^{(i)}$, on a particular channel i is lower than β, the chances of the channel with number of neighbors close to β to be selected increases. The best channel in terms of channel availability is the one with CR neighbors equal to β. When CR neighbors are higher than β, the higher number of neighbors decreases the chances of the channel to be selected.

if $CR_n^{(i)} < \beta$
then $CR_o^{(i)} \leftarrow \frac{CR_{as}^{(i)}}{(\beta - CR_n^{(i)})}$
else if $CR_n^{(i)} = \beta$
then $CR_o^{(i)} \leftarrow CR_{as}^{(i)}$
else $CR_n^{(i)} > \beta$
then $CR_o^{(i)} \leftarrow \frac{CR_{as}^{(i)}}{CR_n^{(i)}}$
end if

Figure 3: Algorithm for CR occupancy's computation

4.3 Channel Selection

$SURF$ strategy classifies channels by assigning a weight $P_w^{(i)}$ to each observed channel i in the Acs set. Thus, every cognitive radio running SURF, locally computes the $P_w^{(i)}$ using the following equation:

$$\forall i \in C : P_w^{(i)} = e^{-PR_o^{(i)}} \times CR_o^{(i)} \tag{1}$$

$P_w^{(i)}$ describes the availability level of a channel (i) and is calculated based on the occupancy of PR (i.e. $PR_o^{(i)}$) and CR (i.e. $CR_o^{(i)}$) nodes over this channel (c.f. Section 4.2). If a CR node finds two or more channels having identical higher values of P_w, it firstly tries to select the one that has lower $PR_o^{(i)}$ among them. If they also have identical values of $PR_o^{(i)}$, then the CR node randomly selects one channel among the channels with identical and higher values of P_w.

Practically, the computed availability in Eq. 1 exponentially decreases with the PR occupancy and linearly increases with the available space for CR activities. These two behaviors are directly related to the two objectives the SURF strategy needs to satisfy. The major objective of protecting the ongoing PR activity is mapped into an exponential decrease of a channel weight as a function of the PR occupancy. The higher the PR occupancy over a spectrum band the exponentially lower the weight will be. Thus, SURF gives high importance to not degrading the service of ongoing primary communications. The second objective of ensuring a maximum connectivity is implemented in the second term of Eq.1. More precisely, the $CR_o^{(i)}$ obtained through Algorithm (cf. Figure3) increases with available space for CRs activity, while carefully considering the connectivity versus contention trade-off.

5 SURF Comprehensive Analysis

In this section, we investigate how SURF reacts to different CRN conditions (i.e. PR activity, available channels, etc) when different values of β are used. The goal is thus, to well understand the β effect and to be able to select the good one for the SURF performance's evaluation (cf. Section 6).

5.1 Methodology

We study the SURF behavior for different values of β when varying PR activity, set of available channels Acs, and total number of channels C in the network. We then evaluate three performance issues: (i) the average number of CR neighbors per hop, which is the potential 1-hop receivers at each channel of the transmitter's Acs set; (ii) the average number of CR receivers per hop, which is the CRs that correctly received the sent packet (i.e., the average number of CR nodes that have selected for overhearing the same channel than the transmitter selected for sending and, even if unreliable links are considered, have correctly received the packet), and (iii) the average loss ratio per hop, which is the number of lost packets over the total number of transmitted packets. Since, the system we explore is highly complex and many parameters can be modified, for results tractability and clarity, we modify each of a single parameter while fixing all the others. The influence of β over those performance issues is monitored by first varying the PR occupancy (cf. Section 5.2), second by varying the available channel set (cf. Section 5.3), and finally, under a dynamic environment where both the available channel set and PR occupancy vary, simultaneously (cf. Section 5.4).

We run simulations over a cognitive radio specific simulator written in C++. Within the network, we consider that two nodes can communicate if they use at least one common channel and if they are within the transmission range of each other. In order to simulate message losses, a probability $P_s^{(i)}$ of successfully sending a message is assigned to each channel i and equals to:

$$P_s^{(i)} = \frac{\tau_a^{(i)}}{CR_n^{(i)}} \qquad \forall i \in C \tag{2}$$

while loss ratio equals to $1 - P_s^{(i)}$. In fact, equation (2) states that the probability of sending a message is dependent on the available slots τ_a and the number of CR nodes competing for the channel i.e. $CR_n^{(i)}$. We consider 1% of message losses, if $CR_n^{(i)} < \tau_a$. It is worth noting here that no retransmission in implemented in our simulations.

Results are generated from an average of 1000 simulations, along with 95% of confidence intervals. For all results, unless otherwise specified, we consider 30 PR nodes and τ_t=6 total time slots for each channel. To ensure total network connectivity, the transmission range is set to *R* = 250m and the average CR neighbor density d_{avg} before Acs computation, is set to 20. We consider Acs size of [5,4,3] for 5 total number of channels ($Ch = 5$), and [15,12,8] for 15 total channels ($Ch = 15$). The number of CR nodes is fixed to *N=70* and randomly deployed within a square area of a^2 =707x707m^2 [3]. Because the total number of CRs is fixed, it is straightforward to notice that the number of average CR neighbors per channel decrease as the Acs size decrease. *TTL* is introduced to disseminate the message in the whole network. It is the maximum number of hops required for a packet to traverse the whole network and is set to $\lceil \frac{2a}{R} \rceil$, i.e. $TTL = 6$ in our simulation scenario. The total number of PRs are uniformly distributed among the existing channels.

5.2 Impact of PR Occupancy

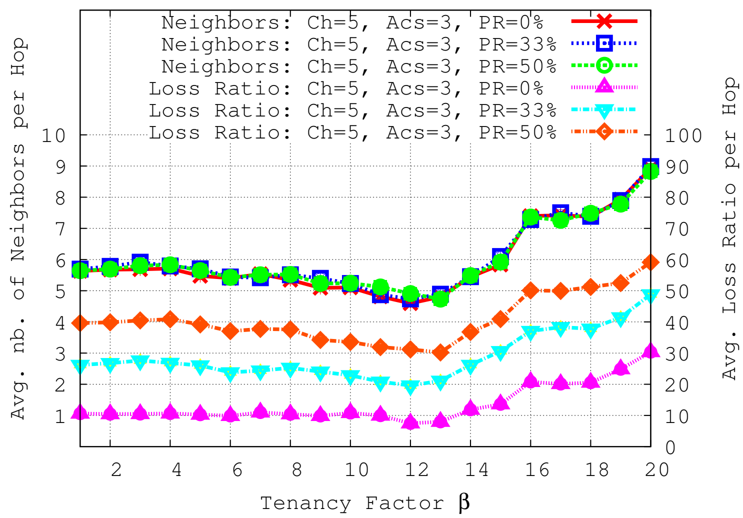


Figure 4: Tenancy factor β, average number of neighbors per hop, and average loss ratio per hop, in a CRN with 70 CR nodes for varying PR occupancy (i.e. fixed time slots occupied by PR nodes) and fixed Acs, for channels=5.

Higher (cf. lower) PR occupied channels give lower (cf. higher) space for CR communication. Thus, to investigate the impact of PR occupancy over the analysed performance issues, we varied the PR occupancy from 0%, 33%, and 50% by changing the slots occupied by PR nodes to 0, 2, and 3, respectively. We then fixed the total number of channels Ch to 5 and the size of the Acs set per node to 3, which results in an average density of approximately 8 CR neighbors per channel of the Acs set.

Fig. 4 and Fig. 5 shows then the average number of CR neighbors and CR receivers per hop (left axes), and the loss ratio per hop (right axes) for varying values of β. In particular, those figures show how the PR occupancy impacts the CR contention and consequently, the loss ratio when different values of β are used. The number of neighbors (cf. Fig. 4) remains constant for values of β lower than 8, i.e. when $CR_n^{(i)} \geq \beta$. In this case and according to the SURF algorithm (cf. Figure 3), low values of β do not play any role in limiting network contention among CR nodes. Thus, channels are being weighted based only on the total number of available slots (i.e. $CR_{as}^{(i)}$) or CR neighbors competing for the channels (i.e. $CR_o^{(i)} = \frac{CR_{as}^{(i)}}{CR_n^{(i)}}$). On the other hand, the increase of β for values higher than $CR_n^{(i)}$, increases the chances of selecting channels that have higher number of neighbors, and consequently, higher number of receivers. This happens until a certain threshold, when the channel contention is increased and higher loss ratio is detected, affecting the number of receivers. This can be perceived for values of β higher than 8, as shown in Fig. 5. Note that, since no retransmission of lost messages is implemented, the contention among nodes is limited to their first try for transmitting a message. The same happens for loss ratio measurement, which is

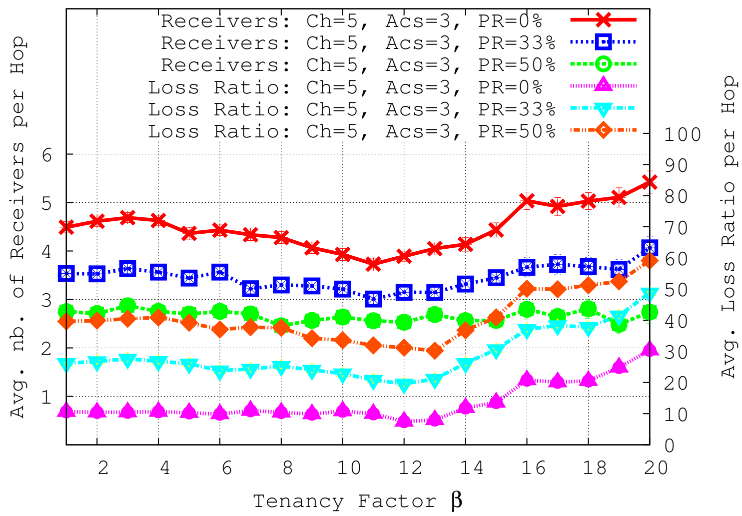


Figure 5: Tenancy factor β, average number of receivers per hop and average loss ratio per hop, in a CRN with 70 CR nodes for varying PR occupancy (i.e. fixed time slots occupied by PR nodes) and fixed Acs, for channels=5.

also limited to losses at the first transmission of each message only. This can explain why the increase in loss ratio doe not significantly decrease the number of receivers in Fig. 5.

Additionally, as expected, with the increase of PR occupancy, the average number of CR receivers per hop decreases and the average loss ratio per hop increases. This is primarily because of the lower available slots $CR_{as}^{(i)}$ to CR nodes communicating, which leads to more contention and collisions. Particularly, when there is no PR occupancy, i.e. PR occupancy=0%, the average number of receivers per hop is the highest and the average loss ratio per hop is the lowest (cf. Fig. 5), for any value of β. This is due to the fact that 0% of PR occupancy yields to higher available channel slots τ_a, which results in less CR contention. On the other hand, as the number of available channel slots τ_a decreases (e.g. PR occupancy=50%), CR nodes finds less opportunity to communicate, resulting in higher loss ratio due to higher contention.

5.3 Impact of Available Channel Set Acs

The size of the Acs set and the diversity in number of channels each cognitive node can use, limit node's accessibility to its neighbors. Thus, if the Acs set is too small compared to total channels C and diverse for each CR, the number of receivers is reduced. In Fig. 6 and Fig. 7, we evaluate this effect for total number of channels equal to $Ch = 5$ and $Ch = 15$, respectively, and, for clarity reasons, consider that all channels are unoccupied by PR nodes (i.e. PR occupancy=0%). We vary the size of the Acs set to 4 and 3 for $Ch = 5$ and to 12 and 8 for $Ch = 15$.

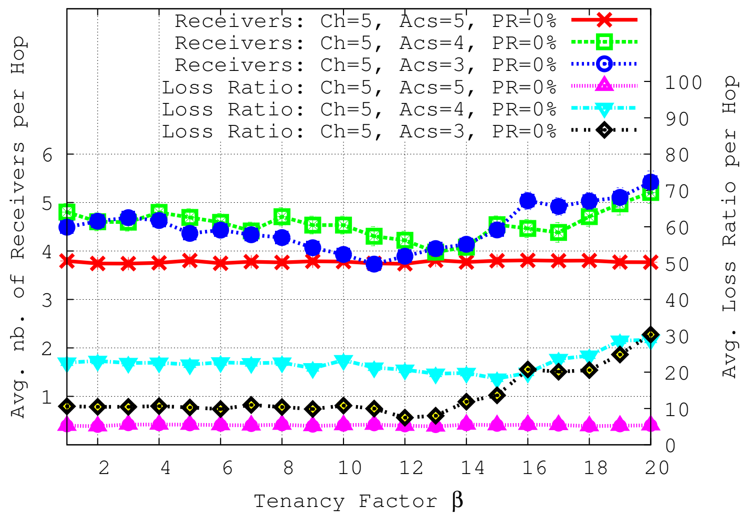


Figure 6: Tenancy factor β, average number of receivers per hop and average loss ratio per hop, in a CRN with 70 CR nodes for varying number of Acs and fixed PR occupancy, for channels=5.

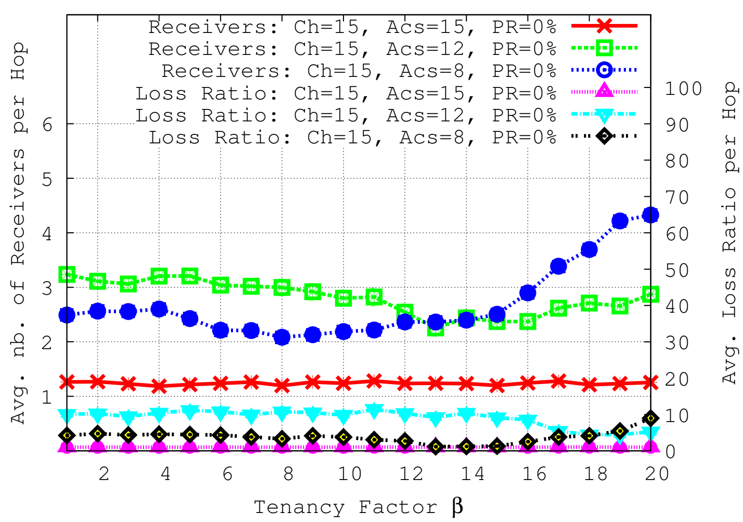


Figure 7: Tenancy factor β, average number of receivers per hop and average loss ratio per hop, in a CRN with 70 CR nodes for varying number of Acs and fixed PR occupancy, for channels=15.

It can be verified that when a node is accessible by its neighbors on all the channels, $Ch = Acs$ (i.e. all CRs can overhear all channels), β does not impact on the average number of receivers and loss ratio. This is due to the fact that all the channels will have the same computed weight $P_w^{(i)}$: the same PR occupancy (PR occupancy=0%) and number of CR neighbors $CR_n^{(i)}$ is perceived on all channels. Thus, CR nodes randomly select the channel for transmission and/or overhearing. Indeed, a random selection of a channel for transmitting and overhearing reduces the chances of message reception by neighboring CR. Moreover, this effect is even aggravated by the increase of the number of available channels for communication, note the decrease from 4 receivers to 1 for $Ch = 5$ and $Ch = 15$, respectively (cf. Fig. 6 and Fig. 7).

The decrease of the Acs set's size to 4 and 3 for $Ch = 5$ and to 12 and 8 for $Ch = 15$, imposes some diversity at the number of neighbors per channel, resulting in different weights $P_w^{(i)}$ being assigned to channels. In particular, the average density of CR nodes per channel is: 12 for $Acs = 4$ and for $Acs = 12$ and 8 for $Acs = 3$ and for $Acs = 8$. That neighborhood diversity implies different levels of contention per channel, which consequently, makes the use of β impacting the average number of receivers and loss ratio, since channels will be assigned to varying weight values. It can be seen from Fig. 6 and Fig. 7 that for lower values of β (i.e. when $CR_n^{(i)} \geq \beta$), CR nodes try to select those channels that have number of neighbors close to β. In this case, the average number of receivers and the average loss ratio is lower due to less contending nodes for same channel resource. Whereas with the increase of β to values higher than $CR_n^{(i)}$ (i.e. higher than 12 for $Acs = 4$ and $Acs = 12$ or 8 for $Acs = 3$ and $Acs = 8$), we notice an increase in the average number of receivers as well as the average loss ratio. As previously mentioned, this happens due to the fact that message retransmission is not implemented in our simulations. Thus, the contention increase caused by the increase of β does not significantly affects the average number of receivers.

5.4 Choosing the correct value of Tenancy Factor β

In real environments, channels can be available in some parts of the network and occupied in others. Thus, to incorporate this notion, we consider varying PR occupancy and limited available channels. We then set PR occupancy to the range of [20%-80%] for each PR node over each channel and Acs size to 3 and 8 for $Ch = 5$ and $Ch = 15$, respectively. Here, we investigate how SURF adapts under this dynamic environment with varying PR occupancy and limited Acs sets. We perform experiments in order to determine appropriate value of β to be used in SURF performance analysis presented in the next section.

In Fig. 8 and Fig. 9, we investigate the impact of β on average number of neighbors, number of receivers, and loss ratio per hop. Clearly, the best value of β is the one that provides a good tradeoff between number of receivers and loss ratio. In this case, for $Ch = 5$, the best value of β is $\beta = 10$ (cf. Fig. 9). For $Ch = 15$, the low average number of 5 neighbors on channels (cf. Fig. 8) is not enough to cause high contention and consequently, to decrease the receiver number when high values of β are used, as shown in Fig. 9. Therefore, it is better to use the channels with higher number of neighbors, and thus, a higher value of beta. For this reason, we select $\beta = 18$ for $Ch = 15$, as it provides a good tradeoff between receivers and loss ratio.

Note that, in our simulations, we consider that the same number of PRs is spread over the available channels. Thus, using more channels reduces the number of PRs over

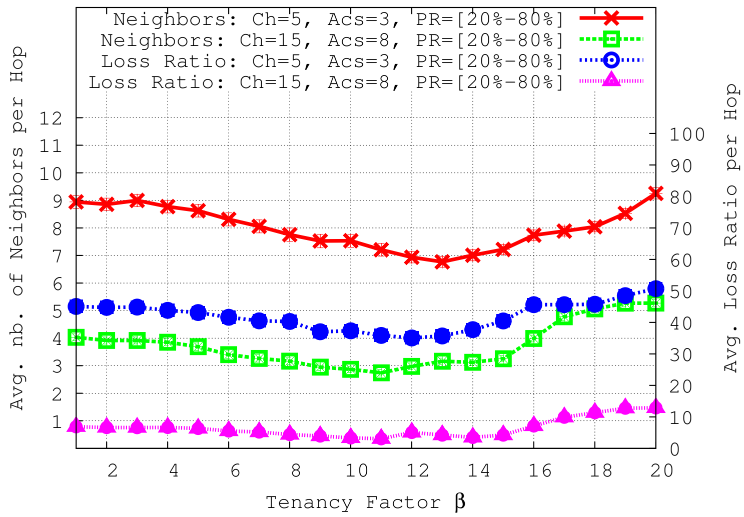


Figure 8: Tenancy factor β, average number of neighbors per hop, and average loss ratio per hop, in a CRN with 70 CR nodes for varying PR occupancy in the range [20%-80%] by PR nodes.

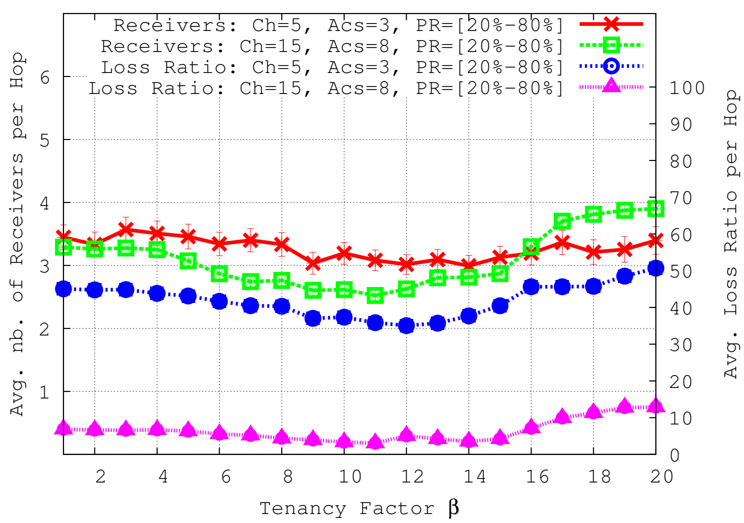


Figure 9: Tenancy factor β, average number of receivers per hop and average loss ratio per hop, in a CRN with 70 CR nodes for varying PR occupancy in the range [20%-80%] by PR nodes.

each channel and consequently reduces the PR occupancy, resulting in higher available space for CR nodes for communicating. Therefore, the average loss ratio per hop for $Ch = 15$ is much lower than $Ch = 5$. This is due to the fact that CR nodes find more space and hence, causes less contention for the same channel resource. On the other hand, the increase of the number of channels increases the probability of having two or more channels assigned to the same $P_w^{(i)}$ value, increasing consequently the probability of having a random selection of channels.

6 Performance Evaluation

6.1 Simulation Environment

In order to evaluate the performance of SURF, we compare it with an intuitive random strategy (RD) and the two variants of selective broadcasting protocol [7], i.e. selective broadcasting strategy (SB) [7] without any centralized authority, and selective broadcasting with centralized authority (CA).

In RD strategy, channels are randomly selected to be used by CR nodes for transmission and/or overhearing, i.e. without any consideration to the ongoing PR and CR activity over these channels. In selective broadcasting SB, each CR node selects a minimum set of channels i.e. Essential Channel Set (ECS) for transmission, that covers all its geographic neighbors, without considering the PR occupancy. In our simulations, we consider an implementation of SB with a single transceiver. Thus, transmissions over multiple channels in the presence of single transceiver is done sequentially with incurred delay, i.e with a round robin process over the channels of the ECS. Regarding message reception, each neighbor sequentially overhears on the channels present in the ECS list. Clearly, selecting channels from the ECS one after the other for overhearing reduces the probability of reception on each of them. Selective broadcasting with centralized authority CA, i.e. the third algorithm we compare SURF with, works on the same principle for transmission as SB, except that each neighbor node simultaneously overhears on all the channels present in the ECS list.

It is worth noting that selective broadcasting with centralized authority (CA) can be used as a theoretical upper bound in message dissemination comparison; since it maximizes the number of receptions by performing overhearing over multiple channels, simultaneously. The main difference between SB, CA, RD, and SURF is the number of transmissions generated by the first two strategies: 2.5 times more than RD and SURF. Additionally, multiple transmissions of the same message over multiple channels may cause multiple receptions of the same message at neighbor nodes, decreasing the transmission opportunity perceived by CRs. Otherwise, in SURF, nodes switch to a single channel based on its occupancy and receivers availability, being no multiple transmissions performed which results in less message overhead. Therefore, SURF has an added advantage in this case, as there is no need for *a central entity* or any other control message to switch overhearing nodes to the same channel on which the neighboring node is transmitting.

We assume that the spectrum opportunity map of PR is available for cognitive radios. We further consider in our simulations that PR nodes over every channel switch evenly between ON/OFF states with probability in range [20%-80%]. At each CR transmission, the PR occupancy per channel i, ($PR_o^{(i)}$), is calculated according to the number of PR nodes provided by the opportunity map. Additionally, each CR node locally computes the CR occupancy ($CR_o^{(i)}$) and the availability level ($P_w^{(i)}$) of each channel i. The channel with the highest weight is then selected for transmission and/or overhearing (cf. Section 4). The message dissemination phase then starts, in which a randomly selected CR node disseminates the message on the selected channel by setting the *TTL*. CR neighbor nodes that are on the same selected channel will overhear the message, decrease *TTL*, redo the spectrum sensing, select the best available channel, and disseminate the message to the next-hop neighbors until *TTL=0*.

6.2 Blocking Ratio

We say that a message is blocked if it is lost because no CR is overhearing over the same channel (while the TTL value is still >0). The *Blocking Ratio* is then defined as the number of blocked messages over the total number of sent packets.

For effective data dissemination, not only the sender should select the best channel but also the receiver should be tuned to the right channel (selected by the sender) in order to receive the sent information. Thus, a good channel selection strategy is the one that tunes both the sender and the receiver to the right channel in the multi-hop context. Fig. 10 shows, for example, that if receivers nodes are not tuned to the right channel, the dissemination will be stopped before reaching the highest distant nodes in the network.

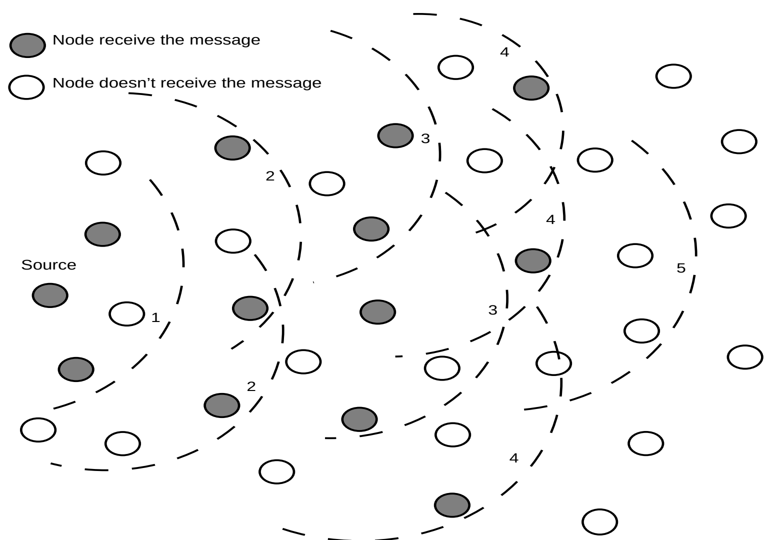


Figure 10: Message blocked after $TTL = 4$ in a multi-hop CRN.

In Fig. 11, we compare the blocking ratio obtained with the four strategies detailed above for multi-hop CRN. Over 1000 sent packets, we compute the blocking ratio caused by receiver not overhearing the appropriate channel.

In a network where 15 channels are available for CR use ($Ch = 15$), RD and SB strategies have higher blocking ratio than SURF and CA. Such results are highly predictable due to (1) the naive selection approach of the random strategy and (2) the availability of single transceiver and the lack of any central entity of the SB strategy.

In particular, in SB, the probability of a node overhearing the same channel used for transmission is $\frac{1}{|ECS|}$.

In fact, in both cases when $Ch = 5$ and $Ch = 15$, the blocking probability of SB is higher than RD. Practically, the round robin process used at the transmitter *and* at the receiver, requires that both of them are tuned to the same frequency in the same time to correctly receive sent messages. This strict synchronization process is hard to achieve first because the sender/receiver do not necessarily have the same set of ECS on which they sequentially transmit/receive, and second, a light dephasing on the transmitter or the receiver side may yield to errors in messages reception. Additionally, since SB try to use channels with higher number of neighbors, there is also a chance of having higher contention and consequently, higher loss ratio than in a random selected channel. The same happens for CA, where the higher number of CR neighbors increases the contention in each channel, increasing then the number of blocked messages.

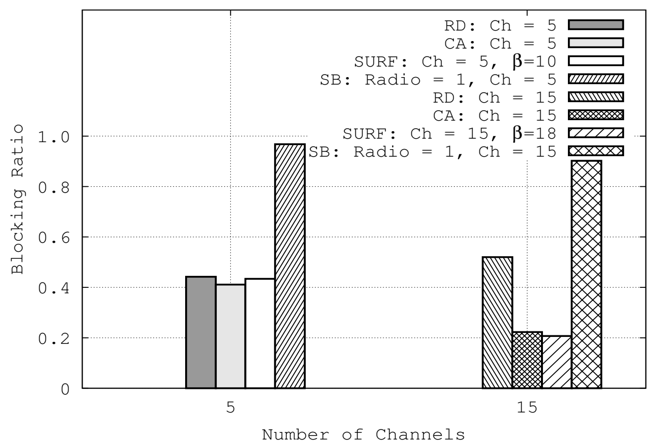


Figure 11: Blocking Ratio in a CRN with 70 CR nodes, for varying number of channels.

Moreover, the blocking ratio of RD increases with the increase in the total number of channels. This is because less nodes overhear on the same channel selected by the transmitting node, since CRs are spread over different channels. On the contrary, an increase in the number of channels has a minor effect on SB. This is because the increase of total number of channels results in lower sizes of ECS, composed by channels that can potentially reach more neighbors. Therefore, more nodes have the probability to overhear over the same channel.

SURF has lower blocking probability because our decentralized channel selection makes more nodes overhear over the same channel. In fact, this happens since during channel selection SURF considers both the PR occupancy and number of CR neighbor receivers. More surprisingly, SURF has a decrease in blocking ratio as the number of channels increases. This is mainly due to the fact of having nodes selecting best channels for transmission and reception.

6.3 Reliability in Data Dissemination

To assess the performance of SURF with RD, SB, and CA in term of reliable data dissemination, two performance metrics are evaluated with different total number of channels: (i) the average delivery ratio, which is the ratio of packet received by a particular CR node over total packets sent in the network and (ii) the average number of accumulative CR receivers at each transmission, until TTL=0. Recall that higher number of channels yields to lower PR occupancy. In addition, it is worth mentioning here that even the centralized approach CA could not get a 100% of data dissemination because of the performed randomly assignment of Acs set to CR nodes. This may generate topology disconnections caused by physical close nodes being assigned to disjoint channels. In this way, as previously stated, we consider the CA approach gets the theoretical upper bound results in terms of message dissemination.

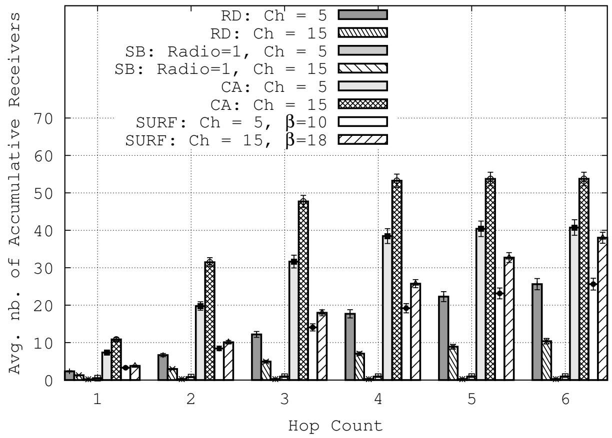
Fig. 12(a) compares the number of accumulative CR receivers at each hop of communication until TTL=0, for the four strategies. When $Ch = 15$, SURF allows the message dissemination to 55% of nodes in the network (i.e. 38 out of 70 CR nodes), while CA allows 78% (i.e. 54 over 70 CR nodes). Additionally, due to its central control and multiple transmissions, the CA strategy reaches this upper bound of receivers percentage at the TTL=4. It can be clearly seen that SURF outperforms RD and SB and compared to CA, only provides a decrease of 25% in performance. The gain achieved with CA is at the price of more transmissions, more energy consumption, and more expensive and sophisticated devices.

Fig. 12(b) compares delivery ratio of RD, SB, CA and SURF, as a function of the CR nodes' ID. SURF outperforms RD and SB in terms of delivery ratio, when number of channels are high. Compared to the CA strategy, SURF has only 20% of performance reduction. In particular, for *Ch=5* and *Ch=15*, SURF guarantees the delivery of approximately 60% of messages (with a single transmission), contrarily to less than 20% for the RD and SB strategies (with single and multiple transmissions, respectively) and 80% for the CA strategy (with multiple transmissions).

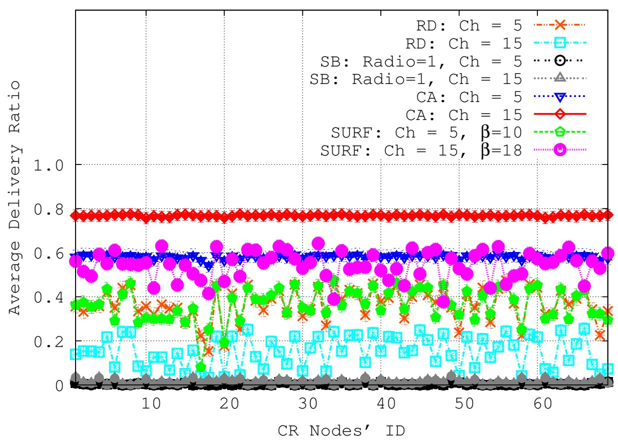
7 Advantages of SURF

SURF, by exploiting information regarding PR and CR occupancy, brings several advantages. Some of them are highlighted below:

- Less interference with PR nodes: Through our channel selection strategy, CR nodes are bound to select those channels which are less utilized by PR nodes. Therefore they cause less interference to PR nodes thus, satisfying the major constraint of CRN.
- Autonomy and decentralization: CR nodes make local and distributed decision for channel selection. Therefore SURF makes CR nodes autonomous in their channel selection decision.
- No control messages exchange: Implementing the same strategy at the sender and receiver helps both of them tune to the appropriate channel for undergoing transmissions or reception without the need of any prior information exchange or synchronization.



(a) Accumulative receivers



(b) Delivery ratio

Figure 12: Average number of accumulative receivers per hop and average delivery ratio in a 70-node CRN, for random (RD), selective broadcasting (SB), centralized approach (CA), and our strategy (SURF).

- Less overhead: As SURF is based on single transmission, it generates less overhead compared to channel selection strategies based on multiple transmissions (e.g. [7]).
- Practical feasibility and low cost: A key characteristic of our channel selection strategy is that it assumes the availability of single transceiver, which is used for both transmission and/or overhearing. It reduces thus, the operational cost of the network. Besides reducing transmissions overhead, transmitting over a single channel cuts down energy consumption and increases the battery lifetime of CRs.

- Information relaying: Another key advantage of our multi-hop channel selection strategy is that the same strategy can be reused and reconfigured to relay information from one or more users to others receiving users located in various locations in the network.
- Network coverage improvement: Improved network performance in terms of CR network' perspective is achieved by making CR nodes to switch to highly reliable channels, which as a consequence, increase network coverage.

8 Related Work

Recently, a lot of work has been carried out for dynamic channel management in cognitive radio networks [13,16,9,10]. However, all these approaches focuses on single-hop cognitive radio networks and either requires the presence of any central entity or coordination with primary radio nodes in their channel selection decision. For instance, [13] proposed an efficient spectrum allocation architecture that adapts to dynamic traffic demands but they considered a single-hop scenario of Access Points (APs) in Wi-Fi networks. [11] proposed a channel selection strategy based on the primary user's occupancy but specifically designed for single-hop architecture.

In this paper, we focus on channel selection in the context of multi-hop cognitive radio ad hoc networks, where no cooperation or feedback is expected from primary nodes and the network operates in the absence of any centralized authority. In addition, an adaptive channel selection strategy is required at both the sender and receiver node, so that the receiver node tuned to the right channel to receive sent information. Moreover, the holding time and the granularity of wireless spectrum bands also affects on multi-hop CR communications [6]. All these factors makes channel selection in these networks extremely challenging, having very few works been done so far [7,12]. In [12], the authors proposed a dynamic resource management scheme for multi-hop cognitive radio networks. But their approach is based on periodic control information exchange among nodes, which is not the case in SURF.

In selective broadcasting (SB) [7], each cognitive node selects a minimum set of channels (ECS) covering all of its geographic neighbors to disseminate data in multi-hop cognitive radio networks. There are however, several challenges in the practicality of SB. Indeed, from the communication perspective, simultaneous transmission over a ECS requires more than one transceiver, which means having bigger and more complex devices, as it is done for military applications [14].

9 Conclusion and Future Work

In this paper we have proposed SURF, a channel selection strategy for reliable contention-aware data dissemination in multi-hop cognitive radio network. SURF selects a single channel for every message transmission allowing the best opportunities for CR-to-CR communications due to (1) low primary radio nodes activities, and (2) limited contention of cognitive radio nodes acceding that channel. The result is a connected network with limited contention, where reliable communication can take place. SURF strategy is simple, completely decentralized, and is based on practical assumptions. Thus, it can be applied today to many possible cognitive radio networks deployments to deliver emergency alerts and advertisement messages. We have demonstrated through simulations the performance of our channel selection strategy when compared with three other related approaches. Simulation results confirmed that our approach is effective in selecting the best channels for efficient and reliable multi-hop data dissemination.

As plan of our future work, we intend to investigate the time needed to disseminate messages in the network. This delay will surely depend on the size of the network and on the number of available channels at CR nodes. Besides, empowering SURF with channel history components that assist the channel selection process and mainly that tie-breaks when two or more channels have the same weight is also a future research direction.

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