Performance of Cognitive Radio-Based Wireless Mesh Networks

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Abstract—Cognitive radio presents a new approach to wireless spectrum utilization and management. In this work, the potential performance improvement gained by applying cognitive radio to wireless mesh networks is investigated. Specifically, the potential benefits in terms of QoS provided to users and the efficiency of resource utilization are quantified in a system consisting of a collection of one or more service provider wireless networks. To achieve this, we formulate the problem mathematically using integer linear programming. It is shown that the cognitive radio abilities provide an advantage over the classical network, either by improving QoS through increasing the probability of accepting connection requests, or by reducing the resources needed to fulfill the QoS requirements of users. This advantage is gained without impacting the service of primary clients. More importantly, we show that virtual wireless networks can be created, utilizing only the residual wasted bandwidth of the primary service providers. These virtual networks are able to support large volumes of users, while still ensuring that QoS reliability requirements, such as acceptance probability guarantees, are achieved.

Index Terms—Cognitive radio, wireless mesh networks, spectrum sharing, performance evaluation.

1 Introduction

Increasing demands for broadband wireless services with widespread coverage has made wireless mesh networks (WMNs) an attractive technology. Many WMNs have been deployed, delivering service to campuses, cities, and wide rural areas [1], [2], [3], [4], [5]. As most WMN nodes do not require a wired connection to the Internet, nodes can be installed quickly and inexpensively, with fewer constraints on their placement. They instead rely on wireless communication to interconnect individual access points, forwarding traffic over multiple hops to its destination.

However, the scarcity of wireless resources presents a challenge for WMNs. The WMN's multihop traffic must be transmitted over a limited amount of available spectrum. When combined with the openly shared nature of the medium, these factors limit the traffic capacity a WMN can support. It is, therefore, imperative that WMNs effectively utilize all the wireless resources available to them.

Cognitive radio (CR) is a new approach to intelligent managing wireless resources. Although the complete CR picture includes a wide-ranging vision of spectrum management combining perception, coordination, and intelligence, initial works are more limited, focusing on capitalizing on wasted spectrum. Under the current static spectrum allocation model, wireless channels are allocated to specific purposes or users. Primary users of a channel have exclusive rights to that channel. Even if the channel is idle and resources are being wasted, other wireless users are legally prevented from using the channel.

In view of this, despite the demand for and expense of the resource, overall utilization is actually quite low [6]. While some channels in some locations are heavily used, even congested, there are very often others that are essentially unused. The current system for resource allocation creates, therefore, many holes of unused spectrum due to static channel assignment and licensing, which prevents the spectrum bands from being used by anybody other than the primary user/licensee.

These spectrum holes are potential opportunities for making smarter use of wireless resources. Regulatory bodies have recognized this opportunity and acknowledged the need for a new system for spectrum management, one that is more flexible, dynamic, and efficient [7]. This impetus, combined with advances in radio technology and software-defined radio, has created the vision of Cognitive Radio. CRs are a new type of radio device, with the ability to detect and exploit residual bandwidth left idle by licensed users, under the condition that they do so without impacting on primary users.

For a WMN, CR represents a way to improve overall utilization of available spectrum and expand the spectrum available to individual networks. In this work, we study the benefits that can be gained using CR capabilities. A WMN controlled by one or more service providers, each with their own spectrum resources, is formulated as an Integer Linear Programming (ILP) problem. Using this ILP model, we show that enabling CR can offer improved QoS, the ability to support additional users, increased resource utilization, and QoS differentiation. Although we have intended this ILP formulation primarily as a method for showing the potential capacity, the runtime required to find the optimal configuration is short enough to be useful in moderately sized networks.

More importantly, we use this analysis to demonstrate the feasibility of creating a virtual wireless network (VWN)

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within the wireless mesh network. This virtual network can operate using only the residual wasted bandwidth of the primary service providers. Despite their lack of dedicated resources, the VWN can support a considerable traffic volume, while still satisfying probabilistic QoS guarantees.

The remainder of this paper is organized as follows: The next section presents a background of research related to this work. Section 3 describes the system model to be considered, describing first the classic network, then extending it to include CR capabilities. Following this, Section 4 formulates the system as an ILP problem, which is then used in Section 5 to study and characterize various aspects of the system's performance. Finally, Section 6 summarizes our conclusions.

2 Related Work

Using cognitive radio in WMNs was studied in [8], [9], and [10]. In [8], the authors investigated the problem of spectrum sharing, i.e., how to divide efficiently the available frequency bands into subbands and allocate them to the traffic demands of CR-enabled users. In their scenario, all of the users are equipped with CR devices. The problem is formulated mathematically as a mixed-integer nonlinear program (MINLP) with the objective of minimizing the radio spectrum resources required to serve a set of sessions, by efficiently dividing and allocating available spectrum.

In [9], the authors propose a new spectrum sensing method called COgnitive Mesh NETwork (COMNET) to identify primary user frequencies in the context of WMNs. This work focuses mainly on the assignment of channels between the users and their associated mesh routers. Multihop routing between mesh nodes is not considered since it is assumed to be achieved throughout of band communication on different channels.

Yang and Wang [10] focus on network planning, to determine where radios should be optimally placed within the network. The problem is formulated as a large-scale optimization problem, jointly considering data routing, resource allocation, and scheduling. However, it does not consider the notion of prioritized channel use.

Each of these works addresses particular aspects of enabling CR within a WMN. This paper considers and quantifies the potential gain to be achieved by taking such an approach, relative to a classic network without CR capabilities. By studying this capacity, a number of interesting characteristics are identified.

The term cognitive radio was first used to describe providing software radios with a self-awareness about their characteristics and requirements, so that they could determine the appropriate radio etiquette to use [11]. This self-awareness includes an awareness of its environment, through the monitoring, modeling, and prediction of the radio spectrum [12]. However, much of the recent work on CR has focused on the secondary use of spectrum assigned to primary licenses. For example, the IEEE 802.22 working group on Wireless Regional Area Networks is working toward communications that can coexist with TV broadcast service [13], and the IEEE Standards Coordinating Committee 41 on Dynamic Spectrum Access Networks (DySPANs) has also been established to specify terminology, study coexistence, and conformance issues, and create an architecture for making radio resource decisions [14].

The capacity of CR has been addressed in several works. In both [15] and [16], the authors address the capacity of CR from the information theory perspective. These works focus on the amount of information that is possible to encode on the wireless channel. This work takes a different approach, instead addressing CR from a network point of view, particularly the network's ability to support QoS while relying on CR. Other works have focused on the ability of CR to support opportunistic data traffic within identified spectrum holes. However, the characteristics and requirements of this additional traffic may be fundamentally different from the original traffic, therefore giving a distorted view of the true gains achieved by CR. In this work, users with different QoS-level requirements and various CR scenarios are directly compared to classic networks.

Of course, there have been numerous works on resource allocation in wireless mesh networks, ad hoc networks, as well as other types of networks. Both [17] and [18] consider joint channel assignment and routing in mesh and ad hoc networks. Many works on resource allocation in mesh or mesh-like networks have relied on linear-programming-based approaches for this optimization, including [17], [19]. In each of these works, the linear programming formulation is the tool used to investigate the specific problems considered in each work.

Finally, we have previously addressed the capacity gains of CR within single-hop systems of networks. In [20], we used a Markov-chain-based analysis, to evaluate the QoS gains achieved through enabling CR, as well as demonstrating the feasibility of a CR-based virtual wireless network. This work adopts the same basic approach in terms of comparing QoS experienced in classic and CR-enabled scenarios, however, focuses on multihop WMNs, and uses ILP to formulate the problem.

3 System Model

We represent a WMN by a directed graph $G(V,E)$, called a connectivity graph. Each node $i \in V = \{1, \dots, N\}$ represents an Access Point (AP), which is characterized by a circular transmission range $R_t(i)$ and an interference range $R_I(i)$ (also called hearing or carrier sensing range). During the transmission of a node i, all the nodes inside its interference range, denoted by $H(i)$, sense the channel to be busy and cannot access the medium. Hereafter, we denote by $H^+(i) = H(i) \cup \{i\}$ and by $H^-(i)$ the set of nodes that node i cannot hear, i.e., $H^-(i) = V \backslash H^+(i)$.

We denote by I the interference matrix of $G(V,E)$. I is a matrix with rows and columns labeled by the graph vertices V, with a 1 or 0 in position (i,j) according to whether j is within the interference range $R_I(i)$ of i (i.e., $j \in H^+(i)$) or not.

On the other hand, during the transmission of the node i, all the nodes residing in its transmission range, and thus, representing its neighborhood denoted by $N_e(i)$, receive the signal from i with a power strength such that correct decoding is possible with high probability. A unidirectional wireless link exists between i and every neighbor $j \in N_e(i)$ and is represented by the directed edge $(i,j) \in E$.

We represent the graph connectivity by a connectivity matrix T. The connectivity matrix T of $G(V, E)$ is a matrix with rows and columns labeled by the graph vertices V, with a 1 or 0 in position (i, j) according to whether i and j are directly connected or not.

We note that this model of pairwise interference has numerous criticisms [21]. Perhaps, most importantly, the model ignores the effects of multiple interference, where two or more transmissions can additively combine to disrupt a communication, despite each being beyond their singular interference range. Although this could be addressed by making the interference matrix I a nonbinary matrix and modifying our formulation, we have chosen to rely on this well-known model, rather than utilizing a wireless model that has not been validated.

The system under consideration is a WMN made up of one or more service provider networks. For this, we consider the scenario where all mesh APs combine to create a single infrastructure (graph), with different providers differentiated by spectrum resources alone. Each service provider has its own independent set of channels to be used within the mesh network. This makes the assumption that infrastructure from all service providers is colocated, which is, in fact, consistent with many cellular deployments where base stations share a common tower. The general case (where infrastructure is not colocated) raises a number of additional questions about the sharing both spectrum and physical resources. It is, therefore, left to future work.

This work will consider the capacity gains achieved by utilizing CR in the presence of such multiple primary networks. In order to illustrate and quantify the performance improvement gained by enabling CR capabilities, a simple classical network is first described. The cognitive network can then be created by extending the classic network with the additional requirements and capabilities of CR.

3.1 The Classic Network

Consider the network of service provider k $(k = 1, \ldots, K)$. The network possesses wireless resources in the form of M_k channels on each wireless link. Connection-based traffic is considered, where service requirements of each flow or connection l_k are continuous and constant. Each flow requires the capacity of one channel on each hop along the path between the source and destination nodes for the duration of its service in order to fulfill its requirements.

Flows arrive at the network and request service. If the network has available resources, it can accept the flow. If not, then the flow must be blocked—service is refused and the flow ends without being serviced. Once accepted, a flow must have continuous service for the duration of its service time. After the service time has elapsed, the flow is deemed to have been completed successfully. It is then terminated and the wireless channels along the path are released. The single (i.e., $K = 1$) classic two-node network (i.e., one hop) is depicted in Fig. 1.

The classical system consists of K classical networks. Each network has its own set of channels, with the total capacity of the system being $M = \sum_{k=1}^{K} M_k$. However, these networks are completely independent of each other, with clients arriving to network k only being serviced on network k.

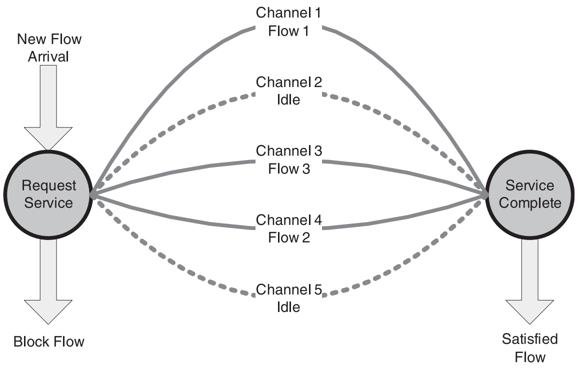

Fig. 1. A two-node WMN with five channels.

In this scenario, traffic only occupies channels on its home network, never utilizing channels of any other network. As a result, when a network reaches its capacity, it must start blocking flows, as it has no available channels. Therefore, flows may be blocked even if the overall utilization of the total system (the complete set of K networks) is relatively low.

3.2 The Cognitive Scenario

The above model for a system of classical networks represents the existing primary users of spectrum. The requirements and capabilities of cognitive radio devices are now considered.

With CR enabled, rather than simply blocking flows, the home network can search for another way to service the flow. Depending on the model used, the home network could request that another network (network k', $k' \neq k$) provides service to the user on one or multiple hops of the path. Alternatively, network k could borrow (lease) a channel from network k' in order to to service the flow. Note that although these two approaches require different system architectures, the result is essentially the same.

First, classical and cognitive traffic for network k are distinguished as $l_{CL}(k)$ and $l_{CR}(k)$, respectively. The behavior of classical traffic is the same as in the purely classical case—it can operate on its home network (network k) only. However, for cognitive traffic, if resources are not available on its home network in certain hops, the flow can switch to another network (operate on network k', $k' \neq k$) if that network has available channels.

As in the purely classic network, classic flows are still blocked if the home network is fully occupied by its own flows (classic or cognitive). Cognitive flows, however, are only blocked if the home network is fully occupied by its own flows and all other networks are also fully occupied.

3.3 Virtual Wireless Networks

Using the concept of a cognitive user, VWNs are a special case of this wireless network model. With no physical resources of its own, the VWN is a network k with $M_k = 0$. This means that a VWN does not service traffic on its own, instead relying on other (real) networks to provide service to its client flows.

Therefore, although a VWN has its own traffic, all of its flows must obviously be of cognitive type. Any classic flows would not be serviced, as there are never resources available

TABLE 1
Mathematical Notations

Notation	Description of the Notation
N	Number of APs
$R_t(i)$	The transmission range of node i
$R_I(i)$	The interference range of node i
T	The connectivity matrix
I	The interference matrix
K	The number of service provider networks
M_k	The number of channels provided by service provider k
Channel (k, m)	Channel m of the network k spectrum band
$x_{ij}^{(k,m)}$	A binary variable equal to 1 if node i transmits to node j on channel (k,m)
L	The list of connection requests between mesh nodes
$s(l)$ and $d(l)$	The source and destination nodes of connection $l \in L$
$h(l)$	The home network of connection l
$CR(l)$	A binary variable indicating whether connection l have CR capabilities (i.e., $CR(l) = 1$) or not
$y_{ij}^{(k,m)}(l)$	A binary variable equal to 1 if connection l uses on its route the channel (k, m) on link (i, j)
Success(l)	An output binary variable of the optimization problem that takes 1 if connection l is served and 0 otherwise
$S_{home}(l)$	A binary variable indicating whether connection l is served only using its home network resources or not
$S_{foreign}(l)$	A binary variable indicating whether connection l is served or not while using at least one foreign resource along its path
$P_A(k, CL)$	The probability of accepting arriving classic flows belonging to network k
$P_A(k, CR)$	The probability of accepting cognitive flows of network k
$P_A(k)$	The total acceptance probability for arriving flows to network k
U_k	The average occupancy of all channels on network k
SR_k	The spatial reuse of network k channels
H	The average number of hops per accepted connection

for them. Cognitive flows, however, can be handled in the same way as they are in the cognitive networks.

4 Problem Formulation

The notations used in this work are summarized in Table 1.

This work will consider the capacity gains achieved by utilizing cognitive radio in the presence of one or more existing primary networks. The problem can be expressed in the form of an ILP problem within a WMN as follows:

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- A physical topology represented by the graph $G(V, E)$, which is described by the connectivity and interference matrixes T and I, respectively. Each wireless link represents $M = \sum_{k=1}^{K} M_k$ channels. So, the physical topology is completely defined by:
  T, I: the connectivity and the interference matrixes, respectively;
  K: the number of service provider networks; and
  M_k: the number of channels (subbands) possessed by each service provider network $k (k = 1, \dots, K)$.
- A list L of connection requests between mesh nodes. We denote by $s(l)$ and $d(l)$ the source and destination nodes of connection $l \in L$, and $h(l) \in \{1, \dots, K\}$ the home network of connection l.

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- The optimal routing maximizing the total network throughput (i.e., minimizing the number of blocked connections).

According to our optimization problem, connections are established on the basis of maximizing the total network throughput. First, the problem will be treated in the light of classic networks. Afterward, it will be considered in the context of CR systems by extending the classic network with the additional requirements and capabilities of CR.

4.1 ILP Formulation for Classic WMNs

In this section, we provide an ILP formulation of the problem that consists of maximizing the throughput inside a WMN composed of independent classic networks (i.e., when CR capability is disabled). In this case, flows only occupy channels on their home networks, never utilizing channels of any other network. Using some of the notations from [8], we formulate the problem as follows:

4.1.1 Interference Constraints

Once a node i successfully accesses the shared medium, it blocks the transmission on that channel of all nodes inside its interference range (i.e., $H(i)$) during the service time of the connection l. The node i transmission may also prevent the nodes in $H(i)$ from receiving correctly from their neighbors that are hidden from i, according to the signal capture property.

In view of this, successfully carrying connection l across hop (i, j) on channel (k, m) (i.e., channel m of the network k spectrum band) requires both nodes i and j to be neither already transmitting nor receiving data on that channel. Consequently, the sender node i must not be within the interference range of any node p transmitting on channel (k, m). With regards to the receiver node j, a successful transmission from i to j requires all the hidden nodes from i (i.e., $H^{-}(i) \cap H(j)$) to be silent during the service time of connection l.

Specifically, successfully carrying a connection across hop (i, j) on the wireless channel (k, m) needs that channel to be idle on each wireless link (p, q) (i.e., $d(p, q) \le R_t(p)$) verifying the following condition:

$$\begin{cases} d(p,i) \leq R_I(p), \\ \text{or } d(p,j) \leq R_I(p), \end{cases} \tag{1}$$

where $d(p,q)$ denotes the distance between nodes p and q. If the link (p,q) verifies the condition (1), it is referred to as interferer link to the link (i,j). Note that in (1), we have not considered the signal capture property.

Let consider the variable $x_{ij}^{(k,m)}$ representing the state of the channel (k,m) on the link (i,j) and defined as follows:

$$x_{ij}^{(k,m)} = \begin{cases} 1, & \text{if node } i \text{ transmits to node } j \text{ on channel} \\ & (k,m), \\ 0, & \text{otherwise,} \end{cases}$$

where channel (k,m) is the channel $m \in \{1,\dots,M_k\}$ of the network k spectrum band. $x_{ij}^{(k,m)}$ verifies, therefore,

$$x_{ij}^{(k,m)} \leq T_{(i,j)}. \tag{2}$$

According to (1), node i cannot connect to node j if this latter is already occupied due to a transmission of a node $p \neq i$ that node j is within its interference range (including the node j itself, i.e., $p = j$), which gives:

$$x_{ij}^{(k,m)} + \sum_{q \in V} I_{(p,j)} T_{(p,q)} x_{pq}^{(k,m)} \leq 1. \tag{3}$$

Moreover, node i cannot transmit to neighbor j on the channel (k,m), while node i is already occupied in reception on that channel due to a transmission of a node $p \neq i$ that node i is within its interference range (i.e., node i cannot transmit on a sensed busy channel), which yields to

$$x_{ij}^{(k,m)} + \sum_{q \in V} I_{(p,i)} T_{(p,q)} x_{pq}^{(k,m)} \leq 1. \tag{4}$$

Node i also cannot transmit to multiple neighbors using the same channel. Hence, given a channel (k,m), we have

$$\sum_{q \in N_e(i)} x_{iq}^{(k,m)} \leq 1. \tag{5}$$

Note that in [8], node i is allowed to transmit on a busy channel (k,m) (i.e., while node i is already hearing another node transmission on that same channel) given that the sensed signal is not intended to i. In other words, the following constraint is used instead of (4):

$$x_{ij}^{(k,m)} + \sum_{q \in V} T_{(q,i)} x_{qi}^{(k,m)} \leq 1. \tag{6}$$

According to (6), node i cannot use the same frequency for transmission and reception due to self-interference at the physical layer. But node i is allowed to transmit on that frequency if the detected signal is not intended to i, even if in reality, protocol constraints often prevent node i from transmitting on a channel that is sensed busy.

To illustrate the difference between constraints (4) and (6), let consider the simple five-node WMN in Fig. 2. Each wireless link is supposed to have only one channel. Two connection requests are to be served between the pair of nodes $(2,1)$ and $(4,5)$. Considering constraint (6) instead of (4), both connections can be served. However, in reality, protocol constraints often prevent node 4 from transmitting while hearing the transmission of node 2 as dictated by constraint (4). Satisfying both connections is indeed not usually possible in the wireless environment.

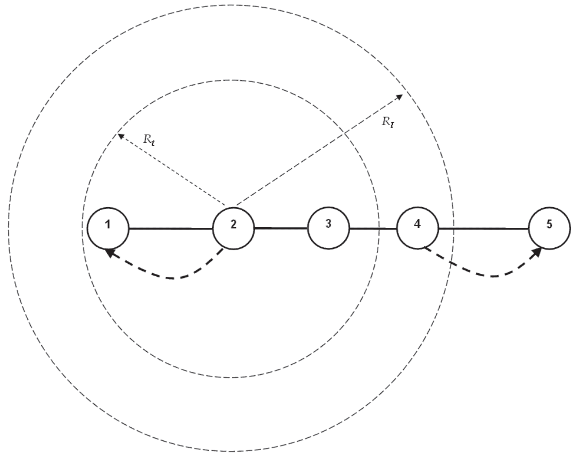


Fig. 2. A five-node WMN: Interference constraint illustration.

4.1.2 Routing Constraints

Routing a connection l in a multihop wireless network needs using different channels on the interfering hops along the path. Let consider the binary variable $y_{ij}^{(k,m)}(l)$ defined as follows:

$$y_{ij}^{(k,m)}(l) = \begin{cases} 1, & \text{if connection } l \text{ uses on its route the} \\ & \text{channel } (k,m) \text{ on link } (i,j), \\ 0, & \text{otherwise.} \end{cases}$$

As such, $y_{ij}^{(k,m)}(l)$ verifies:

$$y_{ij}^{(k,m)}(l) \leq T_{(i,j)}. \tag{7}$$

Clearly, the source node of connection l (i.e., $s(l)$) cannot receive the traffic of l. Hence, we have

$$\sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{i \in V} T_{(i,s(l))} y_{is(l)}^{(k,m)}(l) = 0. \tag{8}$$

In the same way, the destination node $d(l)$ cannot transmit data for connection l:

$$\sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{j \in V} T_{(d(l),j)} y_{d(l)j}^{(k,m)}(l) = 0. \tag{9}$$

In other words, constraints (8) and (9) avoid the traffic coming in its source node or going out its destination node.

Moreover, for an intermediate node q, i.e., $q \neq s(l)$ and $q \neq d(l)$, we have

$$\sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{i \in V} T_{(i,q)} y_{iq}^{(k,m)}(l) = \sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{j \in V} T_{(q,j)} y_{qj}^{(k,m)}(l). \tag{10}$$

This constraint, called flow continuity constraint, ensures the path to be continuous (i.e., connected).

Considering classic networks, a flow only occupies channels on its home network $h(l)$, never utilizing channels of any other network. Hence,

$$y_{ij}^{(k,m)}(l) = 0 \text{ if } k \neq h(l), \quad \forall m \in \{1, \ldots, M_k\}. \tag{11}$$

The following constraint (12) stipulates that a connection is successfully served to its destination only if it is carried by one of the channels that terminates at that destination:

$$\text{Success}(l) = \sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{i \in V} T_{(i,d(l))} y_{id(l)}^{(k,m)}(l), \tag{12}$$

where $\text{Success}(l)$ is an output binary variable of the optimization problem that takes 1 if connection l is served and 0 otherwise.

In the same way, a connection l is successfully served to its destination only if it is carried by one of the channels that originates at the source node $s(l)$. Hence,

$$\text{Success}(l) = \sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{j \in V} T_{(s(l),j)} y_{s(l)j}^{(k,m)}(l). \tag{13}$$

It can be easily verified that constraints (12) and (13) are equivalent given the constraints (8), (9), and (10). Hence, it is sufficient to list only one of them in the formulation.

Finally, constraint (14) relates the physical topology variable $x_{ij}^{(k,m)}$ to the routing variable $y_{ij}^{(k,m)}(l)$ as follows:

$$T_{(i,j)} x_{ij}^{(k,m)} = \sum_{l \in L} T_{(i,j)} y_{ij}^{(k,m)}(l). \tag{14}$$

Constraint (14) limits the number of connections routed through the channel (k, m) on link (i, j) to at most 1.

Based on the above formulation, maximizing the number of accepted connections turns out in maximizing the following objective function:

$$\text{Maximize} \sum_{l \in L} \text{Success}(l). \tag{15}$$

We now introduce optional constraints that do not impact the final result provided by the objective function (15), but necessary to derive correctly the output variable $y_{ij}^{(k,m)}(l)$, which can be used to calculate other performance metrics such as the network resource utilization or spatial reuse.

First, to avoid the construction of a path in the form of a loop for a rejected connection l, we need to introduce the following constraint:

$$T_{(i,j)} y_{ij}^{(k,m)}(l) \leq \text{Success}(l). \tag{16}$$

In the same way, the following constraint is required to avoid the formation of loops on the path of an accepted connection l:

$$\sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{q \in V} T_{(i,q)} y_{iq}^{(k,m)}(l) \leq 1. \tag{17}$$

4.2 ILP Formulation for CR-Enabled WMNs

In this case, the requirements and capabilities of cognitive radio devices are considered. We have two types of connections for each network k, classical and cognitive flows according to whether the customer is contracted to the cognitive radio service or not. The behavior of classical flows is the same as in the purely classical case—it can operate on its home network (network k) only. However, for a cognitive flow, if resources are not available on its home network, the flow can use another network resources.

We introduce the binary variable $CR(l)$ to indicate whether connection l has CR capabilities (i.e., $CR(l) = 1$) or not. To allow the CR-enabled connections be served by foreign networks, we modify constraint (11) as follows:

$$y_{ij}^{(k,m)}(l) = 0 \quad \text{if } \big(k \neq h(l) \text{ and } CR(l) = 0\big), \quad \forall m \in \{1, \ldots, M_k\}. \tag{18}$$

We recall that home (primary) connections have a preemptive priority over foreign CR-enabled connections. The above ILP formulation does not stipulate such priority among different types of connections. Primary (i.e., home) and foreign connections are considered as equally important when contending for the use of the network resources.

One way to introduce priority among different connections is carrying them into two steps:

- First step: Carry all the connections (classic or CR-enabled) only through their home networks with the objective maximizing the network throughput. This turns out in serving the connections without considering the CR-capabilities.
- Second step: Carry the remaining nonserved CR-enabled connections using the still available resources on both home and foreign networks with the objective maximizing the network throughput.

It is worth noting that running steps 1 and 2 successively and independently does not allow necessarily the global problem optimization.

To achieve this, the preemptive priority among classic and CR-enabled foreign connections can be expressed simply by modifying the objective function as follows:

$$\text{Maximize} \sum_{l \in L} A \times S_{home}(l) + S_{foreign}(l), \tag{19}$$

where A is a constant that is greater than $|L|$, $S_{home}(l)$ is a binary variable indicating whether connection l is served only using its home network resources or not, and $S_{foreign}(l)$ is a binary variable indicating whether connection l is served or not while using at least one foreign resource along its path.

The objective function (19) simply implies that satisfying a connection through its home network is better than blocking such connection in order to serve A CR-enabled connections by using foreign resources. This is achieved by giving a greater weight for the service of primary connections over foreign connections in the objective function. Therefore, putting $A \geq |L|$ gives a preemptive priority to connections routed on their home networks over foreign CR-enabled connections.

We now introduce the following constraints to take into account the new variables $S_{home}(l)$ and $S_{foreign}(l)$:

$$S_{home}(l) = \text{Success}(l) \quad \text{if } CR(l) = 0, \quad \forall l, \tag{20}$$

$$S_{foreign}(l) \geq T_{(i,j)} y_{ij}^{(k,m)}(l) \quad \text{if } \big(h(l) \neq k \text{ and } CR(l) = 1\big), \quad \forall i, j, k, m, l, \tag{21}$$

$$S_{home}(l) + S_{foreign}(l) = \text{Success}(l), \quad \forall l. \tag{22}$$

4.3 Generic ILP Formulation

To summarize, we are given a list of $|L|$ connections to be served between different pairs of mesh nodes. Each connection l is identified by the tuple $\{s(l), d(l), h(l), CR(l)\}$. Each service provider network has a set of wireless channels that can be used to route connection requests. We aim at maximizing the number of accepted connections subject to the physical constraints considering both classic and CR-enabled systems. The optimization problem can be formulated mathematically as follows:

$$\text{Maximize} \sum_{l \in L} |L| \times S_{home}(l) + S_{foreign}(l).$$

Subject to:

$$
\begin{aligned}
& x_{ij}^{(k,m)} \leq T_{(i,j)}, \quad \forall i, j, k, m, \\
& x_{ij}^{(k,m)} + \sum_{q \in V} I_{(p,j)} T_{(p,q)} x_{pq}^{(k,m)} \leq 1, \quad \forall i, j, p \neq i, k, m, \\
& x_{ij}^{(k,m)} + \sum_{q \in V} I_{(p,i)} T_{(p,q)} x_{pq}^{(k,m)} \leq 1, \quad \forall i, j, p \neq i, k, m, \\
& \sum_{q \in N_e(i)} x_{iq}^{(k,m)} \leq 1, \quad \forall i, k, m, \\
& y_{ij}^{(k,m)}(l) \leq T_{(i,j)}, \quad \forall i, j, k, m, l, \\
& \sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{i \in V} T_{(i,s(l))} y_{is(l)}^{(k,m)}(l) = 0, \quad \forall l, \\
& \sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{j \in V} T_{(d(l),j)} y_{d(l)j}^{(k,m)}(l) = 0, \quad \forall l, \\
& \sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{i \in V} T_{(i,q)} y_{iq}^{(k,m)}(l) = \sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{j \in V} T_{(q,j)} y_{qj}^{(k,m)}(l), \\
& \forall l, q \text{ with } q \neq s(l) \text{ and } q \neq d(l) \\
& y_{ij}^{(k,m)}(l) = 0 \quad \text{if } \big(k \neq h(l) \text{ and } CR(l) = 0\big), \\
& \qquad \forall i, j, k, m, l \\
& \text{Success}(l) = \sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{i \in V} T_{(i,d(l))} y_{id(l)}^{(k,m)}(l), \quad \forall l, \\
& T_{(i,j)} x_{ij}^{(k,m)} = \sum_{l \in L} T_{(i,j)} y_{ij}^{(k,m)}(l), \quad \forall i, j, k, m, \\
& T_{(i,j)} y_{ij}^{(k,m)}(l) \leq \text{ Success}(l), \quad \forall i, j, k, m, l, \\
& \sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{q \in V} T_{(i,q)} y_{iq}^{(k,m)}(l) \leq 1, \quad \forall i, l, \\
& S_{home}(l) = \text{Success}(l) \quad \text{if } CR(l) = 0, \quad \forall l, \\
& S_{foreign}(l) \geq T_{(i,j)} y_{ij}^{(k,m)}(l) \quad \text{if } \big(h(l) \neq k \text{ and } CR(l) = 1\big), \\
& \qquad \forall i, j, k, m, l \\
& S_{home}(l) + S_{foreign}(l) = \text{Success}(l), \quad \forall l,
\end{aligned}
$$

where $T, I, l, s(l), d(l), h(l)$, and $CR(l)$ are input parameters, while $x_{ij}^{(k,m)}, y_{ij}^{(k,m)}(l), S_{home}(l)$, $S_{foreign}(l)$, and Success(l) are output optimization variables.

Note that putting the $CR(l) = 0$ for all connection $l \in L$, we get the ILP formulation in the context of classic WMNs.

4.4 Performance Metrics

Building on the output results of the above ILP problem resolution, the performance of the different classes of flows can now be evaluated. Three QoS metrics are considered: probability of accepted connections, network resource utilization, or spatial reuse as well as the average number of hops per accepted connection.

4.4.1 Acceptance Probability

$P_A(k, CL)$ is the probability of accepting arriving classic flows belonging to network k and can be expressed as follows:

$$P_A(k, CL) = \frac{\sum_{l \in L} 1_{\{h(l)=k\}} 1_{\{CR(l)=0\}} \text{Success}(l)}{\max\Big(1, \sum_{l \in L} 1_{\{h(l)=k\}} 1_{\{CR(l)=0\}}\Big)}, \tag{23}$$

where $1_{\mathcal{A}}$ is the indicator function of the condition $\mathcal{A}$, i.e., it is equal to 1 if the condition $\mathcal{A}$ is true and 0 otherwise.

$P_A(k, CR)$ is the probability of accepting cognitive flows of network k. It is given by

$$P_A(k, CR) = \frac{\sum_{l \in L} 1_{\{h(l)=k\}} 1_{\{CR(l)=1\}} \text{Success}(l)}{\max\Big(1, \sum_{l \in L} 1_{\{h(l)=k\}} 1_{\{CR(l)=1\}}\Big)}. \tag{24}$$

The total acceptance probability $P_A(k)$ for arriving flows to network k (both classic and CR-enabled connections) is given by

$$P_A(k) = \frac{\sum_{l \in L} 1_{\{h(l)=k\}} \text{Success}(l)}{\max\Big(1, \sum_{l \in L} 1_{\{h(l)=k\}}\Big)}. \tag{25}$$

Note that as each flow requires the full capacity of one channel over each hop, the probability of accepted connections is equivalent to the network (end-to-end) throughput. In Appendices A and B, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TMC.2010.149, we show how our formulation can be easily extended to include the general case where connections with different rates use different channel capacities.

4.4.2 Utilization or Spatial Reuse

The utilization U_k is the average occupancy of all channels on network k. Therefore, it is the average number of channels that are in use, divided by the total number of channels of network k. The total number of channels is counted as the sum of wireless channels on each link (i.e., between each pair of neighbor nodes) regardless of the interference between different wireless links. Hence, U_k can be expressed as follows:

$$U_k = \frac{\sum_{m=1}^{M_k} \sum_{i,j \in V} \sum_{l \in L} T_{(i,j)} y_{ij}^{(k,m)}(l)}{M_k \sum_{i,j \in V} T_{(i,j)}}. \tag{26}$$

The utilization U of the total system of networks is then

$$U = \sum_{k=1}^{K} U_k \frac{M_k}{M}. \tag{27}$$

The meaning of utilization values is not always clear in a multihop network. Therefore, an alternative metric to

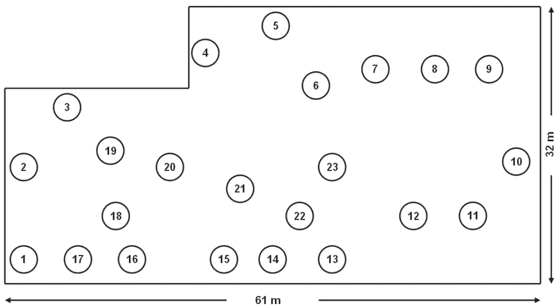


Fig. 3. A 23-node wireless mesh network.

consider is the spatial reuse of network k channels. The spatial reuse of channel (k, m) is defined as the average number of transmissions on that channel over the whole network. The spatial reuse of network k channels can be then given by

$$SR_k = U_k \sum_{i,j \in V} T_{(i,j)}. \tag{28}$$

The spatial reuse of any channel in the total system is then

$$SR = U \sum_{i,j \in V} T_{(i,j)}. \tag{29}$$

For a given network, utilization and spatial reuse are proportional. However, we feel that spatial reuse gives a clearer meaning in the context of WMNs.

4.4.3 Average Number of Hops

The average number of hops per accepted connection is given by

$$H = \frac{\sum_{k=1}^{K} \sum_{m=1}^{M_k} \sum_{i,j \in V} \sum_{l \in L} T_{(i,j)} y_{ij}^{(k,m)}(l)}{\max\left(1, \sum_{l \in L} \text{Success}(l)\right)}. \tag{30}$$

5 Performance Evaluation

In this section, we evaluate the gain enabled by using CR capabilities in WMNs. We first compare the CR-enabled systems to the classic networks and assess the introduced gain in terms either of resource savings or the QoS levels provided to users. We also show the performance of virtual wireless networks that can be created utilizing only the residual wasted bandwidth of the primary service providers. Then, we study the cognitive abilities to differentiate QoS for different user types on the same network. We show how this feature can also enable further resource savings while fulfilling the different user classes' requirements.

Most of this analysis is achieved using the 23-node WMN in Fig. 3 [3], [4]. Random network deployments of varying size have also been considered in Section 5.4. These results were obtained using a commercial ILP solver, "CPLEX" [22], taking into consideration the different network resource and topology parameters and various traffic scenarios. The reported results for each experience are averaged over 100 traffic demand sets (i.e., L). For each traffic set, the source/destination pairs of the connection requests are randomly generated.

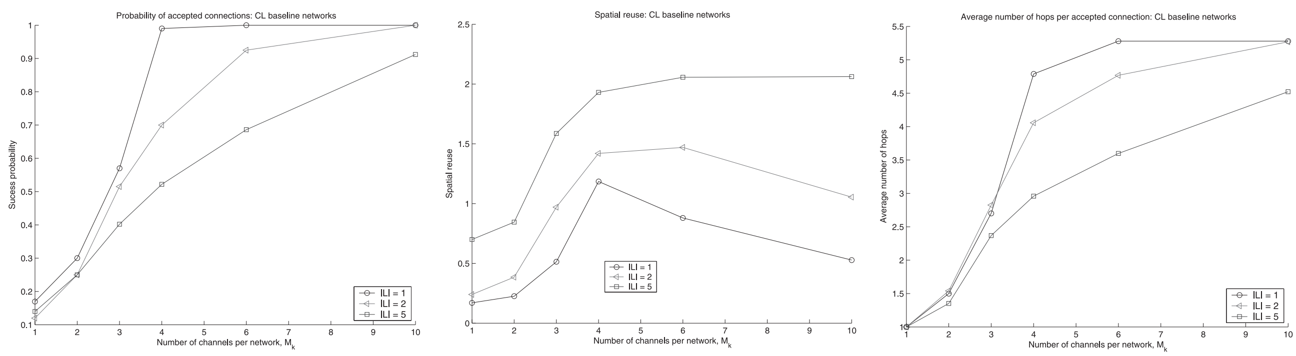
The ILP problem is NP-complete. The resolution of the ILP formulation is computationally intensive. While the 23-node network can be resolved in a relatively short period of time, the time required to evaluate larger networks quickly stretches to hours or days and beyond.

5.1 Classic Network Baseline

The case of a single classic network was used to develop a baseline to which CR improvements could be compared. Results from the single network case can easily be extended to multiple networks as the networks are, by definition, independent of each other. Obviously, for a single network, only classic traffic must be considered.

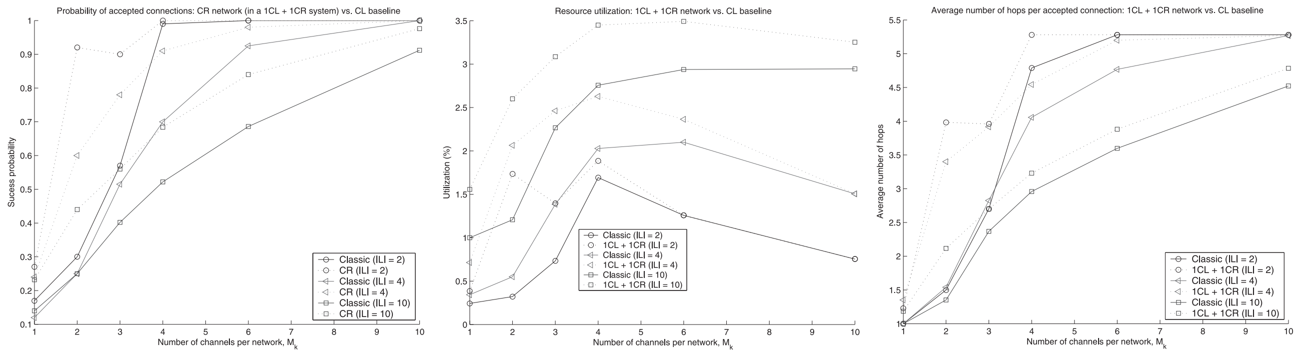
It is assumed that the network service provider must deliver a certain level of QoS, based on the probability of accepted connections. Fig. 4a shows the probability of accepted connections for various traffic intensities (i.e., various numbers of connection requests arriving to the classic network): $|L| = 1$, $|L| = 2$, and $|L| = 5$. Results for networks with between 1 and 10 channels are shown. Two main observations can be identified. First, the acceptance probability increases with the increase of the number of channels, as more resources are available. Moreover, increasing the network load (i.e., $|L|$) increases the number of blocked connections.

Fig. 4b shows the spatial reuse of the network. At small numbers of channels, the reuse is very low, meaning that a large number of channels are not exploited to the full extent possible. Many links are unoccupied much of the time, as



(a) (b) (c)

Fig. 4. Classic baseline network. (a) Probability of accepted connections. (b) Spectrum reuse. (c) Average number of hops per accepted connection.



(a) (b) (c)

Fig. 5. One classic + one cognitive network system. (a) Probability of accepted connections. (b) Spectrum reuse. (c) Average number of hops per accepted connection.

there are not enough frequencies (i.e., channels) to avoid interhop interference when serving the multihop connections. For example, if the network has only one channel, all the connections requiring more than one-hop path would have to be rejected. Only connections between neighboring nodes can, in this case, be served. Therefore, the number of accepted connections is very low, resulting in a very low utilization of the network channels.

Increasing the number of channels increases the spectrum reuse as the number of accepted connections increases. However, once all the connection requests are already accepted, further increasing the number of channels results in resource underutilization and wastage. This explains the convex shape of the curves.

Fig. 4c shows the average number of hops H used by an accepted connection. This increases as the number of channels increases. The rational behind this can be explained as follows: if the number of channels is small, particularly if it is 1, then only one-hop connections between neighboring nodes can be served. Increasing the number of channels gives the network more flexibility to meet the interference constraints, allowing it to serve connections requiring longer paths.

5.2 Cognitive Radio Network Scenarios

With the basic classic network case established, cognitive radio networks can now be explored. This exploration begins with the simplest cases involving only two networks, then continues with larger systems. Additionally, this section discusses only systems where all networks have the same number of channels (with the exception of virtual networks).

Three cases are possible: in the first, only one of the networks has clients with cognitive abilities, while the other network is entirely a classic network; in the second, both networks utilize cognitive radios; in the third case, the system consists of one or multiple classic networks and one VWN.

5.2.1 One Classic + One Cognitive Network

In the first scenario, consider two nearly identical networks—both networks have the same number of channels, and the same traffic intensities (exactly half of the connection requests, i.e., $|L|/2$, arrive to each network). However, while network 1 is a classic network, network 2's clients are equipped with cognitive radios, enabling them to operate on either network.

Using the same set of traffic demands of the baseline case, Fig. 5a shows the acceptance probability $P_A(k)$ for each of the two networks' connections. While the classic network's $P_A(1)$ has remained the same as expected, network 2's $P_A(2)$ has been dramatically increased. A CR-enhanced connection of network 2 can indeed mix between home resources and network 1 resources along the different hops of its path in order to be served.

More significantly, however, Fig. 5a shows that fulfilling a given QoS level required by clients needs deploying less resources by a service provider enhancing its users by the CR capabilities. For instance, for a classic network in the above system with load $|L| = 10$, maintaining a $P_A \geq 0.8$, needs a set of nine channels. Instead, the cognitive network needs only six channels to achieve the same target.

Clearly, the cognitive abilities provide an advantage over the classical network, either by improving QoS through increasing the acceptance probability, or by achieving great savings on resources needed to fulfill the QoS requirements of users, all without impacting clients on network 1.

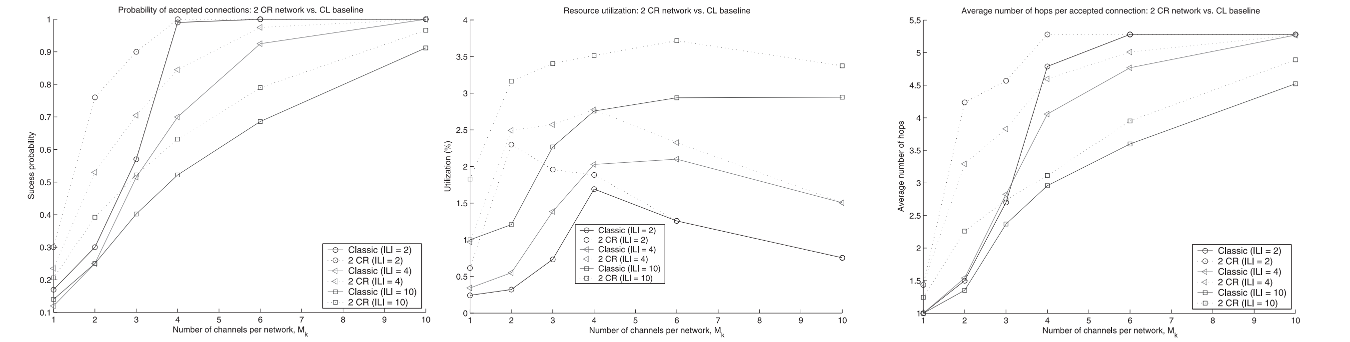
As more CR-enhanced connections are accepted, the spectrum reuse of the total system of networks increases compared to a system of classic networks, as shown in Fig. 5b. The cognitive capabilities allow also more flexibility for the cognitive network to serve distant connections as it profits from the available channels on the classic network. In view of this, the average number of hops per accepted connection in the system increases compared to the case where only classic networks are considered, as shown in Fig. 5c.

5.2.2 Two Cognitive Networks

The same evaluation has been performed for the two network scenario, with both networks supporting CR-enhanced clients.

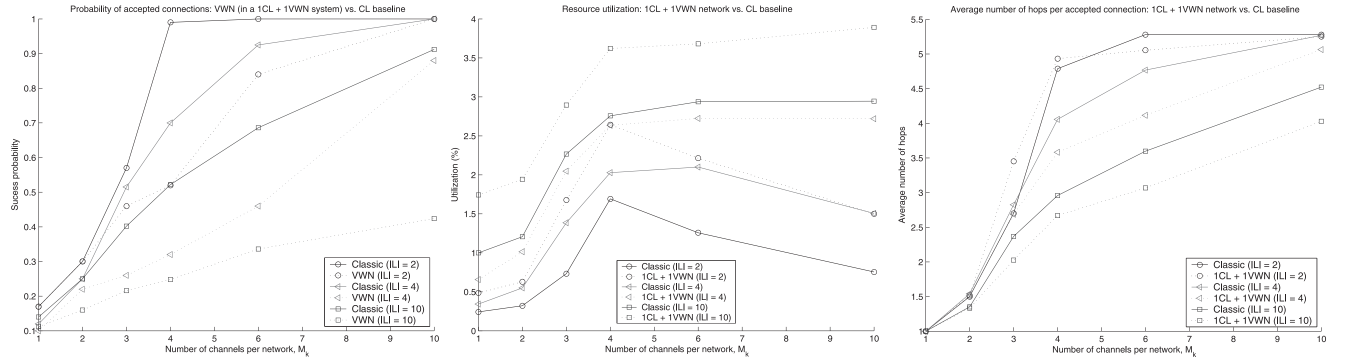
Considering the same traffic pattern, the resulting acceptance probability as depicted in Fig. 6a is very similar to the cognitive network in the previous two-network scenario (see Fig. 5a). Enhancing the classic network with cognitive capabilities improves, however, the spectrum reuse in the system, as shown in Fig. 6b. Additional connections are indeed accepted for network 1.

Fig. 6c shows that enabling CR capabilities on both networks also improves the probability of accepting distant



(a) (b) (c)

Fig. 6. Two cognitive network system. (a) Probability of accepted connections. (b) Spectrum reuse. (c) Average number of hops per accepted connection.



(a) (b) (c)

Fig. 7. One classic + one virtual wireless network system. (a) Probability of accepted connections. (b) Spectrum reuse. (c) Average number of hops per accepted connection.

connections. The average number of hops per accepted connections increases compared to the previous scenarios. This indicates that the network has more capabilities to carry a connection through a relatively long path (i.e., not necessarily using the shortest path) in order to profit from the spatial reuse of the spectrum. This feature is more pronounced when CR is enabled. Clearly, the cognitive systems are a major improvement over the classic networks.

5.2.3 *One Classic + One Virtual Wireless Network*

To take advantage of some of this remaining unutilized bandwidth, virtual networks are now introduced to the scenario. The simplest scenario involving a virtual network is the system consisting of one classic network and a virtual network. Both networks have the same traffic intensities (exactly half of the connection requests, i.e., $|L|/2$, arrive to each network). If the classic network traffic intensity is already high, then obviously, the virtual network cannot make the same QoS guarantee. One possibility is to simply support additional traffic, without any QoS guarantees—this is often the approach suggested in CR.

Fig. 7a shows the acceptance probabilities if the VWN network has to serve the same number of connection requests as the classic network. The QoS performance of the additional virtual network connections is lower than that of the classic network. To achieve comparable QoS performance, the VWN has to deal with lower traffic intensity. In other words, it has to maintain fewer subscriber contracts. For instance, the 10-channel classic network ensures 90 percent of the connections to be accepted among the $|L|/2 = 5$ simultaneous client demands. To achieve the same performance, the VWN has to limit the number of concurrent connections to 2.

In view of this, virtual service providers could take different approaches: either service a small number of clients with high QoS requirements, or accept large number of virtual-aware clients without any QoS guarantees on the provided service. In the latter case, connections may experience low QoS performance, however, as shown in Fig. 7b, this traffic does increase the utilization of resources (i.e., spectrum reuse) compared to classic networks, similarly to the previous CR scenarios.

Fig. 7c shows, however, that the average number of hops per accepted connection for the VWN is lower than that of the baseline classic network case. Unlike the previous scenarios, enabling CR reduces the resulting H in the total system for this scenario. This is because the VWN does not service traffic on its own, instead it relies on other (real) networks to provide service to its client flows. In other words, it profits from the remaining available spectrum on real networks. However, the spectrum of a real network is utilized by its primary clients in such a way that the remaining free spectrum on each hop is not sufficient to carry easily multihop connections due to the interference constraints. In this regard, short connections are more likely to be served successfully by VWNs.

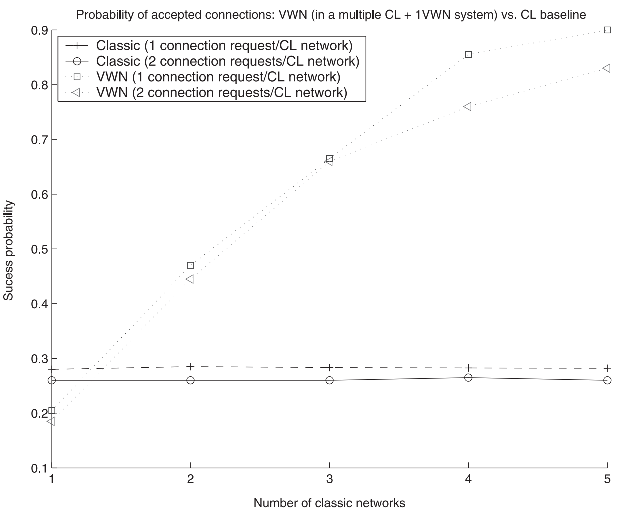


Fig. 8. QoS levels provided by VWN when varying the number of classic networks.

5.2.4 *Multiple Classic + One Virtual Wireless Network*

In the two-network scenario, the only way to improve the VWN QoS performance is to reduce the number of contracted clients. The more interesting scenario occurs as more classic networks are introduced.

Consider the scenario where there are K networks: one VWN and $K-1$ independent classic networks. Each classic network $k (k = 1, \ldots, K-1)$ possesses $M_k = 2$ channels. For the traffic intensity, we consider two cases: in the first case, each classic network receives only one connection request; in the second case, two connection requests arrive to each classic network. In both cases, the VWN receives four connection requests, which is four and two times the intensity of a classic network in the first and second case, respectively. While any additional classic traffic would deteriorate the QoS performance, if an additional virtual network is added using CR-techniques, it can make use of unused capacity on any of the existing networks, without affecting the acceptance probability of the classic networks. Fig. 8 shows the resulting QoS for a VWN in a system containing $K-1$ classic networks.

As can be seen in the figure, the resulting performance depends on both the number of networks and the number of connection requests. Fig. 8 shows two important properties. First, as the number of classic networks increases, $P_A(\text{VWN})$ increases, as there is an increased probability that one of the networks has available resources. Second, increases in $|L|$ (number of connection requests per classic network) result in a decrease in the $P_A(\text{VWN})$. This is due to the fact that fewer resources remain available on the classic network when the demand for connections increases. This leaves a lower probability of having resources available for cognitive use.

Again, we note that each classic network continues to maintain the same QoS performance for its clients regardless of the number of classic networks in the system. However, as the number of classic networks increases, the QoS performance of the virtual service provider improves. More importantly, the QoS performance of VWN clients outperforms that of classic networks. Considering a system with five classic networks, each operating with a traffic intensity equal to 2, the VWN actually allows 83 percent of the arriving connections to be accepted. This is equivalent to the performance of a classic network with six channels instead of two (see Fig. 4a). This is a tremendous improvement over multiple classical networks.

5.3 Impact of the Network Connectivity Degree

In the scenarios so far, the connectivity degree δ of the WMN was 3, i.e., each node has, on average, three nodes within its transmission range R_t. R_t was set equal to 12 m, while the interference range is set equal to $1.5 \times R_t$. Increasing the transmission range of each node increases the degree of network connectivity (and hence, the number of links in the network). This essentially reduces the average number of hops between any pair of nodes. Fewer channels are then required to connect any pair of nodes. From this perspective, increasing the connectivity degree can improve the QoS performance of the network. However, increasing R_t consequently increases R_I. The increased interference among nodes may reduce the real capacity of the network to carry connections.

Clearly, there is a trade-off between the above opposite trends to maximize the network throughput. This is illustrated in Fig. 9a, where the acceptance probability of the total system of networks is plotted as a function of the connectivity degree δ. Each system of networks receives a traffic intensity with $|L| = 10$ (i.e., $|L|/2 = 5$ connection requests for each network). Two cases are considered: each service provider network possesses $M_k = 1$ or 2 channels.

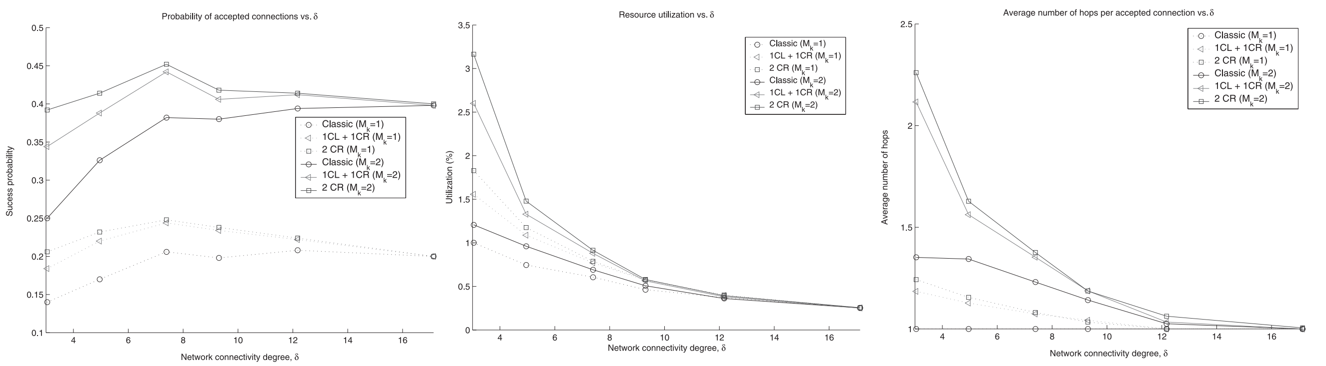
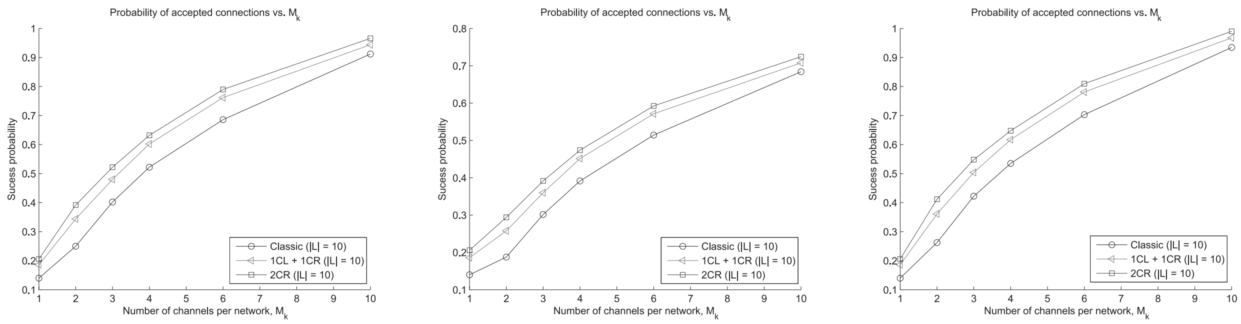


Fig. 9. Impact of the WMN connectivity degree δ. (a) Probability of accepted connections. (b) Spectrum reuse. (c) Average number of hops per accepted connection.



(a) (b) (c)

Fig. 10. Probability of accepted connections. (a) 20-node WMN. (b) 40-node WMN. (c) 60-node WMN.

According to the results in Fig. 9a, we can draw two main observations:

- In all cases, the capacity of the network to accept connections is a convex function of δ. This is representative of the aforementioned trade-off. On the one hand, small values of δ (i.e., R_t) result in extremely long multihop paths between nodes, which increases the number of channels required to carry a connection. On the other hand, high values of δ increase the interference among nodes. This reduces the real capacity of the network. Therefore, there is an optimal value of δ that maximizes the network capacity. In our experiments, $\delta = 7.4$ corresponding to $R_t = 19$ m represents the optimal setting. We can see that correctly adjusting the transmission ranges of nodes can increase the network capacity without requiring new channels.
- Enhancing the system with CR (either for one or both networks) practically doubles the capacity, most notably for small to moderate values of δ. This result confirms that CR creates significant gains. However, for high values of δ, all the nodes are at one hop from each other. Hence, enabling CR has very little effect on the overall acceptance probability.

Fig. 9b shows that the system's spectrum reuse decreases drastically with δ. This is for two reasons. First, increasing δ increases the interference range so that each transmission forces a greater number of other links to remain inactive. Second, increasing δ decreases the average number of hops needed to connect nodes, as shown in Fig. 7c. As a result, fewer resources are required, reducing the overall utilization.

5.4 Randomly Generated WMNs

In addition to the 23-node WMN sample, results have been produced for three randomly generated WMNs, consisting of 20, 40, and 60 nodes, respectively. This covers a range of network sizes, although we are obviously limited by the ILP technique being used. Although some works and deployments have considered much larger networks, the typical approach has been to rely on network partitioning based on the clustering/association to individual gateways. Currently, WMNs clusters are typically less than 20 nodes per gateway, due to severe performance limitations.

Fig. 10 shows the acceptance probability as a function of the number of channels M_k per network k. Again, two classic networks, one classic + one cognitive network, and two cognitive networks are compared. Each system of WMNs receives a traffic intensity of $|L| = 10$. As in the previous results, enhancing the system with CR significantly improves the network capacity. Capacity to accept clients practically doubles in several cases. It is also worth noting that there is an advantage to be gained by having both networks CR-enabled compared rather than only one.

Moreover, we can see that the gain introduced by enabling CR is more pronounced with the small 20-node WMN compared to the 40-node WMN. This is because for the same traffic load and number of channels per network, connections within relatively larger WMNs are carried using longer paths, thus requiring more resources. Although large networks offer more disjoint routes to carry additional connections while avoiding the interferences issues, the 40-node WMN capacity to accept flows decreases compared to the 20-node network case. However, when the effect of increased spatial reuse dominates the effect of longer path lengths, the capacity of large networks to accept connections outperforms that of smaller networks, as seen in the 60-node sample network case (Fig. 10c).

5.5 Mixed User Types and QoS

In Section 5.2.1, it was shown that with the same traffic intensities, a cognitive network could greatly increase its acceptance capacity relative to a classic network. In this section, it is shown that cognitive abilities can also differentiate QoS for different user types on the same network.

Consider the following scenario. Each system has two networks, where the number of connection requests for each network is 5 (i.e., a total set of $|L| = 10$ connection requests arrives to the system). Three different cases are considered for the traffic: 1) all the connections are classic connections, 2) all the connections are CR-enabled, and 3) 60 percent of the connections are classic and the remaining 40 percent are cognitive.

Fig. 11 shows the acceptance probabilities, as the number of channels per network in the system is varied between 1 and 10. As previously illustrated, networks carrying all cognitive traffic see an increase in acceptance probability compared to the purely classic system.

The system of networks with mixed traffic shows that the QoS delivered to classic and cognitive users is also differentiated. The classic users see the same acceptance probability, as each classic user has a preemptive priority over

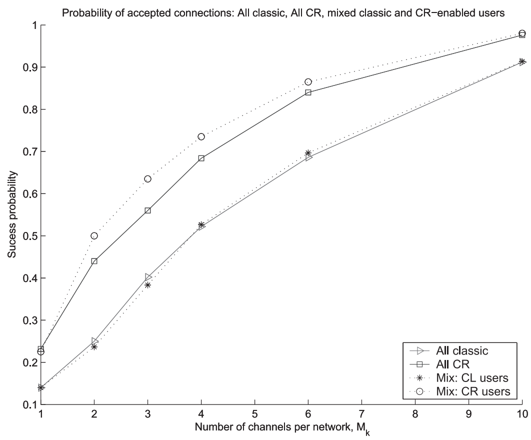


Fig. 11. QoS differentiation by using CR capabilities.

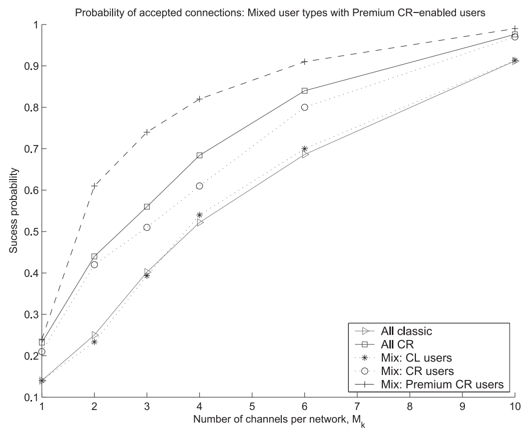


Fig. 12. Introducing the class of Premium CR-enabled users: QoS differentiation by using CR capabilities.

CR-enabled foreign connections. However, the acceptance probability of the cognitive users rapidly increases, beyond even the probability of the all cognitive user system. Most importantly, the overall acceptance probability for the entire mixed system also improves relative to the all classic case.

These results can be interpreted from a QoS-level perspective as follows: A gold client may request an acceptance probability of 90 percent, a silver client requires an acceptance probability of 80 percent, whereas a bronze client needs a 70 percent guarantee on its service. In our mixed traffic system, the gold and the silver classes can be mapped together as CR-enabled connections, whereas the bronze class can be mapped as classic connections. In order to achieve the above QoS requirements, each network must be equipped with eight channels, as shown in Fig. 11. In this case, we can see that silver clients receive a better service (90 percent of acceptance probability) than required since they are mapped into the same class as the gold clients. This is, however, not desirable from the service provider perspective, as it is synonym to resource wastage.

Mapping each class of service to its own class of connections can save resources while achieving the different QoS requirements. To do so, we define a new class of clients called "Premium CR-enabled clients." In addition to their CR capabilities, this class of clients has the same priority to use resources on foreign networks as the home clients. In other words, a Premium CR-enabled client acts as a home (primary) user on all the visited networks.

To take into account such class of clients in our ILP formulation of Section 4, we attribute $h(l) = 0$ as home network value for each premium CR-enabled connection l. Moreover, we modify the constraints (20) and (21) as follows:

$$S_{home}(l) = \text{Success}(l) \quad \text{if } (CR(l) = 0 \text{ and } h(l) = 0), \quad \forall l, \quad (31)$$

$$S_{foreign}(l) \geq T_{(i,j)} y_{ij}^{(k,m)}(l)$$
$$\text{if}\big(h(l) \neq k \text{ and } CR(l) = 1 \text{ and } h(l) \neq 0\big), \quad \forall i, j, k, m, l. \quad (32)$$

Fig. 12 shows the results when considering the new class of Premium CR-enabled clients. The same system of networks is considered as before, with the same traffic intensity. Again, three different cases are considered for the traffic: 1) all the connections are classic connections, 2) all the connections are CR-enabled, and 3) 60 percent of the connections are classic, 20 percent are CR-enabled, and 20 percent are premium CR-enabled.

Fig. 12 shows that the requirements of different clients can be fulfilled by mapping gold clients onto the Premium CR-enabled class, silver clients to the basic CR-enabled class, and bronze clients to the classic class. In doing so, different clients are satisfied while equipping each network with only six channels instead of the eight that were previously needed.

6 CONCLUSION

Cognitive radio is a potential solution to the tight resource constraints experienced by wireless mesh networks. By allowing the reuse of spectrum allocated to primary users, CR can be used to recapture wasted resources and utilize them in other ways, without affecting primary user service.

In this work, we have studied the improvements that can be gained from using CR in a WMN. From a classic system where primary service providers have assigned channel resources and all users belong to a home network (and must receive their service on their service provider's channels), we added CR-capabilities. CR-enabled nodes can operate on any channel, as required. After formulating the problem using integer linear programming, several metrics were studied, including the probability of accepting flows, spatial reuse of spectrum, and the path lengths of serviced flows.

Using an ILP-solver, the system was studied, comparing classic and CR-enabled networks, as well as purely virtual wireless networks. It was demonstrated that CR capabilities provide several benefits to a WMN. First, CR improves the QoS that can be provided to network flows. Alternatively, more flows can be supported by a service provider, or fewer channel resources can be used. Second, CR increases utilization by allowing the network more flexibility to service flows, particularly longer (more hops) flows. Third, CR provides a mechanism for QoS differentiation, where a CR-enabled achieves a higher level of service from the network, while still maintaining minimum service constraints for classic users.

Solving an ILP is computationally expensive; however, our evaluation has shown that moderately sized networks could be handled within a reasonable time. For these networks, the ILP, therefore, provides a potential method for obtaining an optimal resource management solution. However, for larger networks, the ILP approach becomes too cumbersome to be used in an online manner. To handle these situations, further investigations are required to develop an effective heuristic.

Additionally, we intend to continue to extend the formulation to create a more general model for resource sharing. The removal of the colocation assumption made in this paper will allow both spectrum and infrastructure sharing to be considered. Variable channel characteristics and traffic demands are also required to more accurately reflect the real wireless environment. We believe that all of these are natural extensions to the model described in this paper, although each will require considerable study.

For virtual wireless networks, despite having no dedicated spectrum resources, the feasibility of supporting QoS has been demonstrated. These VWNs benefit from having multiple primary networks from which they can borrow resources. The VWN supports additional users and considerably increases the utilization of channel resources. The successful operation of the VWN shows that the previously wasted spectrum resources of the primary networks have significant value.

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