Distributed and Coordinated Spectrum Access Methods for Heterogeneous Channel Bonding

Zaheer Khan, Janne Lehtomäki, *Member, IEEE*, Simon Scott, Zhu Han, *Fellow, IEEE*, Marwan Krunz, *Fellow, IEEE*, and Alan Marshall, *Senior Member, IEEE*

***Abstract*—Channel bonding (CB) is a technique that enables a wireless link to combine channels and achieve higher data rates. In this paper, competition for efficient spectrum access among autonomous users with heterogeneous CB capabilities is considered. Specifically, we propose distributed and coordinated channel/bonding selection methods under signal-to-interference-plus-noise ratio (SINR) and collision-protocol models. In our methods, users utilize only limited feedback to distributively arrive at CB selections that minimize their probability of conflict. The proposed method utilizes a novel *channel quality metric*, which is based on the ratio of noise power to the sum of interference and noise power. It is shown that CB can lead to higher data rates, and it is most beneficial when users have a high SINR. However, it is also shown that as the ratio of users to available channels increases, CB performance degrades. Our results show that under certain scenarios, the proposed coordinated and distributed channel/bonding selection schemes help users converge fast to conflict-free channel selections as compared to the other channel/bonding selection schemes. Moreover, the proposed schemes result in considerably superior performance to existing CB schemes in terms of network data rate.**

***Index Terms*—Channel bonding, distributed users, heterogeneous capabilities, collision-protocol model, SINR-protocol model, spectrum access system, opportunistic spectrum access.**

I. INTRODUCTION

THE USE of carrier aggregation (CA) in licensed cellular bands and channel bonding (CB) in unlicensed bands has been shown to increase network performance under certain conditions [1]–[3]. In CA, multiple contiguous and/or non-contiguous subcarriers are utilized for parallel data transmission to or from the same user. Wireless systems such as WiFi networks rely on CB techniques to combine multiple adjacent channels to form larger channels. Recent advances in spectrum aggregation technologies allow the cellular industry to extend CA/CB techniques to heterogeneous shared-spectrum bands, such as unlicensed spectrum in 2.4 and 5 GHz bands, and opportunistic spectrum access (OSA) bands [4]–[6].

In this paper, we consider CB scenarios for distributed cognitive radio networks where secondary users compete for opportunistic access in potentially available primary user (PU) channels. Techniques designed for conventional channel aggregation in the licensed bands, such as CA techniques in LTE-A networks [7], cannot be directly applied to perform CA/CB in unlicensed and OSA bands. Unlike the licensed bands, unlicensed and OSA bands exhibit high unpredictability in the interference environment due to uncoordinated competing users. Different users may have different CA/CB capabilities, and this heterogeneity needs to be taken into account while making CA/CB decisions. Moreover, recent works have shown that when multiple users with heterogeneous CB capabilities independently employ CB in unlicensed or OSA bands, the performance may actually degrade due to adjacent channel interference (ACI) [3].

In this paper, we design distributed and coordinated CB methods under both signal-to-interference-plus-noise ratio (SINR) and collision-protocol models. Under the SINR-protocol model, when two or more simultaneous transmissions occur on the same channel, additional interference will be experienced at the respective receivers, and loss of communication occurs when the sum of interference exceeds a certain threshold [8]. In the collision-protocol model, all users are in the same collision domain, and if two or more of these users transmit simultaneously on the same channel, a collision occurs and the data frame is assumed to be lost. In practice, the SINR at each receiver is a function of the transmission powers of interfering users, and the channel characteristics, such as path loss and fading. This makes the design problem of autonomous OSA schemes under the SINR model fundamentally different from and the analysis considerably more complex than the same problem under the collision-protocol model.

We particularly focus on CB-based spectrum access techniques for scenarios where users operate over wide swathes of spectrum and use a single-radio transceiver to combine multiple channels. We consider two possible bonding models: (1) users can combine only adjacent channels to use them as a single pipe, as in some WLANs [3]; and (2) users can combine both adjacent and non-adjacent channels to use them as a single pipe. Note that from a hardware standpoint, it is beneficial for autonomous users to bond multiple channels and use them as a single pipe for data transmission since this

Manuscript received January 21, 2017; revised May 9, 2017; accepted May 19, 2017. Date of publication May 29, 2017; date of current version October 6, 2017. The associate editor coordinating the review of this paper and approving it for publication was J. Huang. *(Corresponding author: Zaheer Khan.)*

Z. Khan was with the University of Oulu, 90120 Oulu, Finland. He is now with the University of Liverpool, Liverpool L69 7ZX, U.K. (e-mail: zaheer@ee.oulu.fi).

J. Lehtomäki and S. Scott are with the University of Oulu, 90120 Oulu, Finland.

Z. Han is with the University of Houston, Houston, TX 77004 USA.

M. Krunz is with the University of Arizona, Tucson, AZ 85721 USA.

A. Marshall is with the University of Liverpool, Liverpool L69 7ZX, U.K.

Digital Object Identifier 10.1109/TCCN.2017.2709753

approach requires only one RF unit. This is different from some non-contiguous CA techniques that require multiple RF units for operating over aggregated non-adjacent frequency channels [9].

One special yet practically significant scenario for the underlying problem is CB for downlink transmissions by small cell base stations/access points. These base stations/access points can be deployed by multiple, independent wireless operators for data offloading purposes. Although we consider opportunistic use scenarios, our proposed CB methods can be easily adapted to other spectrum sharing scenarios; for example, in scenarios where multiple users have equal rights to access the spectrum.

The main contributions and findings of this paper are as follows:

1) We study the problem of spectrum access among autonomous users with heterogeneous CB capabilities, under both the SINR and collision-protocol models. We propose a distributed CB method and also a coordinated CB method that allow wireless links to arrive at CB selections that minimize the likelihood of interference between users.
2) Under the SINR-protocol model, a CB selection method called π^{Aut}, where 'Aut' denotes autonomous, is proposed for scenarios where autonomous users (with heterogeneous CB capabilities) searching for spectrum opportunities can only utilize their own limited feedback information to arrive at CB selections that minimize the probability of conflict. By limited feedback information, we mean information about a successful transmission, loss of communication, or no transmission. The key idea behind the proposed π^{Aut} is that an autonomous user is either in a 'persist' state, in which it will select the same CB selection with a certain probability that is a function of the channel quality, or in an 'explore' state, where it will explore a new CB selection.
3) We compare the performance of π^{Aut} to a coordinated distributed method called π^{Sig}, where 'Sig' denotes a signal. π^{Sig} utilizes simple binary feedback from a spectrum access system (SAS) [10] to arrive at CB allocations that reduce the likelihood of conflict among users. Moreover, to provide a benchmark for the performance of the proposed methods, we also compare them against a centralized CB selection method.
4) To evaluate the proposed methods, we consider the following metrics: (1) convergence time to conflict-free CB selections; (2) blocking rate, defined as the ratio of users who are unable to communicate successfully to the total number of users; and (3) data rate of all users. We show that in some scenarios, such as under low user density, the π^{Sig} method converges faster to conflict-free CB selections and enjoys a lower blocking rate compared to the fully distributed π^{Aut} method. However, π^{Aut} always outperforms the π^{Sig} method in terms of data rate, and also in terms of blocking rate when user density is high. Our empirical results show that for all the proposed methods, the expected number of rounds to converge to CB selections that reduce conflict is no more than $O_{max}^2 I$, where O_{max} represents the maximum CB capability of a user (due to its hardware limitations), and I is the number of users.
5) We find that CB achieves higher data rates, and is most beneficial when users have a high SINR. However, we also find that when the ratio of users to available channels increases, and users suffer from low SINR, the performance of CB in terms of data rates is decreased.

The rest of the paper is organized as follows. Section II summarizes relevant literature on the problem of CB in OSA systems. Section III presents the system model. In Section IV we propose distributed CB methods and a centralized method to be used as a baseline when making performance comparisons. In Section V we evaluate the performance evaluation of various CB methods in terms of convergence properties, blocking rate, and data rate. The paper is concluded in Section VI.

II. Related Literature

To address the so-called 1000X capacity challenge, wireless providers across the globe are aggressively seeking extending their cellular operation to license-exempt and OSA bands using innovative deployment of small cells with channel aggregation/bonding capabilities [4], [11], [12]. Xu *et al.* [13] and Alcaraz *et al.* [14] considered adaptive OSA techniques under the collision-protocol model, where users have no CB capabilities. In [15], the SINR-protocol model was used to analyze the performance of autonomous OSA methods for capacity enhancement in multihop cognitive radio networks, again considering that users have no CB capabilities. The work in [16] considered the problem of channel selection in dynamic spectrum access scenarios under the collision-protocol model and multiple collision domains, with emphasis on spatial spectrum reuse. In that work, users are considered to have no CB capabilities.

Recently, Uyanik *et al.* [17] and Salameh *et al.* [18] considered guard-band-aware channel aggregation assignments in OSA systems. In contrast to [17] and [18], we consider the same problem for scenarios where channel selections are made autonomously and adaptively by each user. In our setup, there is no centralized entity that can perform optimize channel/bonding selections. Moreover, unlike [17] and [18] where only collision-protocol model was considered, in our work we also consider the SINR-protocol model. In [3], a measurement-based framework was presented to investigate CB in unlicensed channels. In [19], an analytical framework was proposed to investigate the average channel throughput at the medium access control (MAC) layer for OSA networks with CB. Unlike our work, the work in [19] considered the problem of CB under the collision-protocol model.

The work in [20] presented two distributed protocols to to support channel bonding: Static Bonding Channel Access Protocol (SBCA), which uses a fixed number of bonded basic channels and requires finding all these basic channels empty before starting a packet transmission; and Dynamic Bonding Channel Access scheme (DBCA), which dynamically adapts the channel width to the instantaneous spectrum availability.

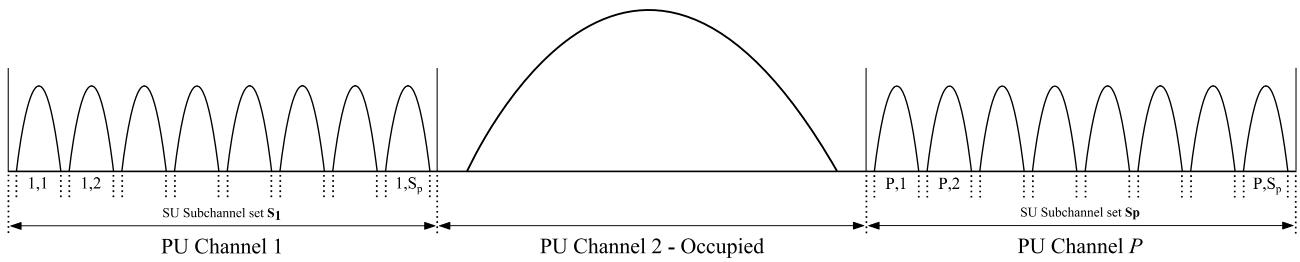


Fig. 1. PU channels and SU subchannels.

In Section V, we compare the performance of our proposed distributed CB scheme with SBCA and DBCA.

III. System Model

A. Network Model

We consider a set of I autonomous users (transmitter/receiver wireless links) with fixed transmission powers. Users exhibit different CB capabilities. They compete in a set $\mathcal{P}$ of potentially available PU channels, where $\mathcal{P} = \{1, 2, \ldots, P\}$ represent the indices of these channels. Each PU channel $p \in \mathcal{P}$ is divided into a set of secondary user (SU) channels, which we refer to as subchannels $\mathcal{S}_p = \{1, 2, \ldots, S_p\}, p \in \mathcal{P}$ (see Fig. 1). Let O_k, $k = 1, 2, \ldots$, represent the CB selection for a given user. O_1 means no CB is implemented for the given user, and a user utilizes a single subchannel. O_2 means two subchannels are bonded, and so on. Each user i can bond up to a maximum of $O_{max,i}$ subchannels. Note that $O_{max,i} = 1$ means user i has no CB capability and $O_{max,i} = S_p$ means user i can bond all S_p subchannels. In our model, we consider both heterogeneous and homogeneous CB capabilities. Under homogeneous CB, $O_{max,i}$ is the same for all users, whereas, in heterogeneous scenarios $O_{max,i}$ can be different for different users. Moreover, our model also considers both contiguous and non-contiguous CB capabilities.

In sensing-based multiuser OSA, PUs with time-slotted access have generated much interest (see [21], [22] and references therein). In such a model, the PU network operates with a fixed time slot period T_{slot}, where for each time slot the channel is either free or occupied by the PU for the duration of the time slot. To protect a PU from harmful interference, SUs are required to perform periodic spectrum sensing so that when a PU becomes active, the SUs can vacate that channel. An SU determines whether the channel is free or occupied by the PU at the beginning of every time slot by sensing the channel for a period T_{sense}. The SU may utilize the channel only if it is determined to be free, and may subsequently transmit for the remainder of the time slot $T_{data} = T_{slot} - T_{sense}$.

Broadly speaking, two approaches can be taken to effectively utilize available subchannels. One is the multi-channel technique in which multiple frequency channels are used for communications. The other is CB, in which multiple frequency channels are bonded into a single channel [23]. CB techniques are widely used in shared channels, such as the 5 GHz unlicensed band [24]. In our work, we focus on the second approach. When a user finds two or more (contiguous or non-contiguous) subchannels free for communications, it bonds these subchannels into a single channel and transmits a larger packet.

In our model, SUs are assumed to be synchronized. This can be done using one of several available techniques. For example, synchronization beacons can be provided by a spectrum manager, such as the spectrum access system (SAS) suggested by FCC [25]. Another possibility is to utilize a primary systems' beacon transmissions for synchronization. Several wireless systems periodically broadcast beacons to their users, and as SUs sense PU activity, they can overhear these beacons and use them to synchronize.

B. SINR and Collision-Protocol Models

Under the SINR model, if the received SINR is greater than a threshold γ_0, a transmission is considered to be successful. The value of γ_0 varies from one wireless system to another. It depends on various parameters such as the transmit power, coding and modulation scheme, and bandwidth utilized, etc. In practice, γ_0 should be selected to achieve reasonable communication performance between users. For the SINR model, we consider an additive white gaussian noise (AWGN) channel where the received signal strength at a receiver i from transmitter j is [26]:

$$P_{r,ij} = P_{0,ij}\left(\frac{d_{ij}}{d_{0,ij}}\right)^{-\alpha} \tag{1}$$

where $d_{ij} \geq d_{0,ij}$ is the distance of receiver i from transmitter j. The reference received power level $P_{0,ij}$ at the close-in distance $d_{0,ij} = \max\{\frac{2D_i^2}{\lambda_i}, D_i, \lambda_i\}$ of receiver i from transmitter j is given by [26]:

$$P_{0,ij} = \frac{P_{t,j}G_{t,j}G_{r,i}\lambda_i^2}{\left(4\pi d_{0,ij}\right)^2} \tag{2}$$

where D_i is the length of the receiver antenna, λ_i is the wavelength of the center frequency, $P_{t,j}$ and $G_{t,j}$ are the transmit power and transmit antenna gain, respectively, for transmitter j, and $G_{r,i}$ is the receive antenna gain. The SINR at the receiver of user i is calculated as follows:

$$\gamma_i = \frac{P_{r,ij}}{\left(\sum_{k=1,k\neq j}^{I} P_{r,ik}\right) + N_0 W_i} \tag{3}$$

where $P_{r,ik}$ is the interference power from transmitter k at receiver i (depends on overlap of subchannel selection), N_0 is noise power spectral density, and W_i is the bandwidth of the subchannel utilized by user i. Loss of communication only occurs when $\gamma_i < \gamma_0$. In Eq. (3), the interference power from transmitter k to receiver i is obtained as follow. We calculate the fraction of the interferer's subchannels that the receiver is receiving on, either directly or through adjacent subchannels. For example, consider the situation at a receiver that is affected by only one interferer. Suppose that the interferer is transmitting on subchannels 1 and 2 and the receiver is receiving on subchannels 2, 3, and 4. Assume that the interferer divides its transmit power equally over subchannels 1 and 2 then the receiver is directly impacted by 50% of the interferer's transmit power. Moreover, the receiver may also get adjacent channel interference (ACI) from interferer's subchannel 1, corresponding to 50% of the interferer's transmit power scaled down by the ACI factor (ACI factor will be 0 if ACI effect is not modeled). For example, if the ACI factor is 0.05 (-13 dB), the receiver for the above mentioned scenario is impacted by $50\% + 50\% * 0.05 = 52.5\%$ of the interferer's power. If the receiver is tuned to subchannel 3 only, it would only receive ACI from subchannel 2 corresponding to 50%*0.05 = 2.5% of the interferer's power.

We also consider a collision-protocol model when evaluating the performance of our proposed CB methods. In this model all I users are assumed to be close to one another, and they all can interfere with each other. When multiple transmitters transmit over the same channel or subchannel, a collision occurs, i.e., the data frames are lost for all colliding users. In contrast to the SINR-protocol model, the collision-protocol model does not take into account the SINR values in determining packet losses.

C. Contiguous and Non-Contiguous CB Selection Models

In our work, we consider two possible CB models: (1) users select subchannels for CB such that selections are limited to adjacent subchannels, as in some WLANs [3]. Moreover, they are non-overlapping CB selections with respect to the same *CB order*, where CB order represents the number of subchannels bonded by a SU, and *maximum CB order* represents the maximum number of subchannels that a SU can bond; and 2) users can bond both adjacent/non-adjacent subchannels, and the selections can be also made out of overlapping subchannels with respect to the same CB order.

For the first model, the number of possible CB selections for a given CB order O_k is $\lfloor \frac{S_p}{O_k} \rfloor$. Let the set of all possible CB selections in a given channel p for $O_{k=1}$ to $O_{k=max}$ be defined as:

$$\Sigma^{(p)} = \left\{ \begin{array}{l} \overbrace{\{\{1\},\{2\},\ldots,\{S_p\}\}}^{\text{Set of } O_1 \text{ selections}}, \overbrace{\{\{1,2\},\{3,4\},\ldots..\}}^{\text{Set of } O_2 \text{ selections}} \\ ,\ldots\ldots\ldots\ldots\ldots\ldots, \\ \overbrace{\{\{1,2,\ldots,O_{max}\},\{O_{max}+1,O_{max}+2,\ldots,2O_{max}\},\ldots\ldots.\}}^{\text{Set of } O_{max} \text{ selections}} \end{array} \right\} \quad (4)$$

For example, if any overlapping/non-overlapping combination of adjacent subchannels were allowed for a given CB order $O_{k=2}$, a user who bonds two out of four available subchannels could also select the pair (2, 3) in addition to the non-overlapping pairs (1, 2), and (3, 4). However, (2, 3) partially overlaps with both (1, 2) and (3, 4). Hence, for total available four subchannels and for $O_{k=2}$, only pairs (1, 2), and (3, 4) are allowed under the first model. Under this model, by limiting the CB selections to adjacent and non-overlapping subchannels, the complexity of the CB selection search is reduced. However, the number of available CB selections is also reduced.

The restrictions of the first model are relaxed in the second model, as users can now bond adjacent and non-adjacent subchannels and also overlapping ones. For the second CB model, the number of possible CB selections for a given CB order O_k is therefore $\binom{S_p}{O_k}$, and the number of all possible CB selections in a given channel p for any CB order (from $O_{k=1}$ to $O_{k=max}$) is $\sum_{k=1}^{max} \binom{S_p}{O_k}$. Furthermore, the set $\Sigma^{(p)}$ of all possible CB selections in a given channel p for $O_{k=1}$ to $O_{k=max}$ is simply the set of all combinations of size $k = 1, 2, \ldots, k_{max}$.

IV. Channel Bonding Methods

When designing an efficient CB technique, one must consider how interference from other users impacts data reception at a given user. In this section, we first consider the SINR-protocol model in the design of efficient distributed CB techniques among users with heterogeneous CB capabilities. Later on, we consider the collision-protocol model in designing such techniques. Finally, for comparison purposes, we present a centralized method where a centralized entity makes CB decisions.

A. π^{Aut} Method

In the proposed π^{Aut}, while searching for spectrum opportunities, users utilize only limited feedback, specifically, indication of a successful transmission, collision, or no transmission, to autonomously arrive at CB selections that minimize the likelihood of harmful interference with one another. The flow diagram for π^{Aut} is presented in Fig. 2. To account for traffic dynamics, the CB algorithm can be executed periodically or when triggered by changes in traffic. Existing CB selections can be used to initialize the algorithm so that at re-execution time, the currently used subchannels will be a subset of the highest CB order.

We now explain the main steps in π^{Aut} method and the motivation behind the parameters used:

- Upon becoming active, SU i sets its current CB order to $O_{max,i}$, i.e., it first considers, its maximum CB capability, and it initializes its subchannel selection probabilities for a channel p as:

$$\mathrm{P}_{ini}^{(p)} = \frac{\left(1-\theta_p\right)}{\left(\sum_{p=1}^{P}\theta_p\right)} \left(\left[\frac{1}{\left|\sigma_{k=max}^{(p)}\right|}, \frac{1}{\left|\sigma_{k=max}^{(p)}\right|}, \ldots . \right] \right) \forall p \in \mathcal{P} \quad (5)$$

where θ_p is the average PU occupancy in channel p and $\sigma_k^{(p)}$ is the set of order k subchannel sets of PU channel p. In practice, θ_p can be provided by a spectrum manager, such as a spectrum access system (SAS) as

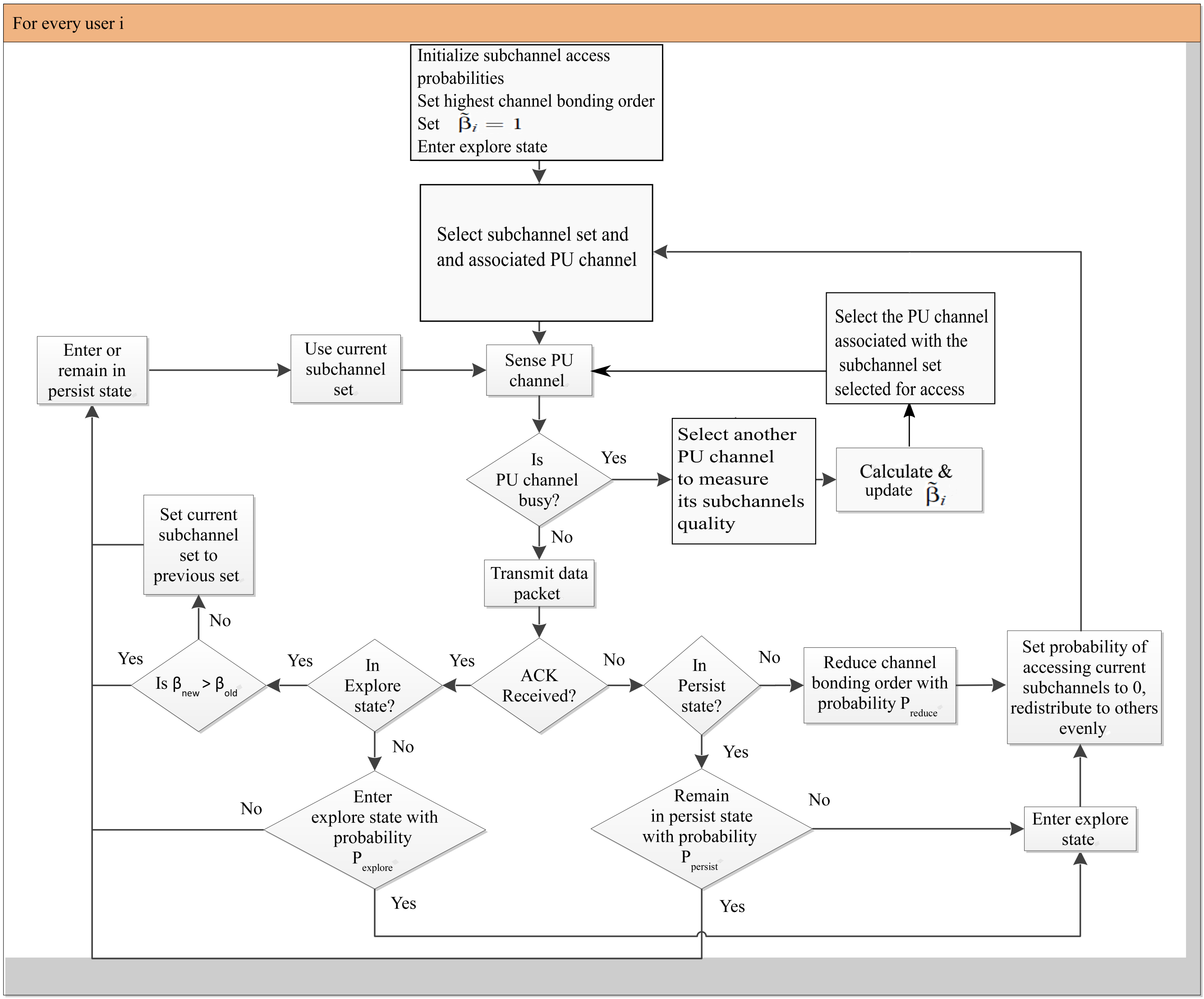


Fig. 2. π^{Aut} Method.

proposed by the FCC. For example, recently the FCC has suggested the use of environment sensing capability (ESC) devices in the vicinity of PUs [27]. These devices measure the channel occupancy of PUs as well as the aggregate received power from SU transmissions to avoid any potential interference from SUs onto PUs. However, in the absence of knowledge of θ_p, an SU can initialize subchannel selection randomly with uniform distribution. After initialization the SU enters the 'explore' state and sets $\tilde{\beta}_i = 1$, where $\tilde{\beta}_i$ refers to the statistical (long term) average of β_i. β_i is the ratio of noise power at receiver *i* to the sum of interference from all transmitters (excluding its own transmitter *j*) and noise power at receiver *i*:

$$\beta_i = \frac{N_i}{N_i + \sum_{k=1,k\neq j}^{I} P_{r,ik}} \tag{6}$$

$\tilde{\beta}_i$ is measured by taking mean of the β_i values sampled across subchannels that have been visited by a user. As the data rate is directly proportional to the SINR, it would be logical for the channel quality metric to be a function thereof; however, the SINR of the current subchannel tells us nothing about the state of other subchannels. Furthermore, a low SINR could be caused by a low signal to interference ratio (SIR), by a low SNR, or by a combination of both. For example, a low SINR could be caused by the distance between transmitter and receiver (low SNR). If the user is experiencing low SNR as a result of this, then it is unlikely that switching subchannels will result in any improvement in the data rate, and will instead lead to increased system overhead through excessive signalling. However, in the case of a low SIR caused by high levels of interference, switching subchannels could improve the data rate, provided that another subchannel with a lower interference level is available. A low SIR can also be related to a specific CB selection, as it is possible that the SU made a poor CB selection due to several other interfering users selecting all or some of the channels in the CB selection. In this case, making other CB selections can help improve the performance. The proposed β_i takes into account such SINR-related factors. In some scenarios, low SNR could also be the result of significant frequency-selective fading over the current subchannel(s). Possible mobility of users (or changes in the environment) will over time average out the fading effect. In these cases, the SNR could be measured over several time slots to average out fading, so that SNR depends mainly on the transmitter-receiver distance for all subchannels. Also, if the coherence bandwidth is much less than the subchannel bandwidth, then averaging out of fading will occur in the frequency domain (different subchannels will likely exhibit similar SNR values for given distance) and no time-domain averaging is required. To obtain β_i, we need to measure the noise level N_i. One way is to use receivers that can switch the input chain to use internal termination, which greatly reduces the incoming signals and provides mostly a signal-free estimate of the noise level. Another way is to use signal processing techniques to locate signal-free samples and use them for noise-floor estimation. One such technique is Minimum Value Processing (MVP), in which one obtains a running average of the square of the received signal, obtains a large number of samples of it, and selects their minimum value. The key in avoiding a negative bias is to use a sufficiently large averaging window. The obtained minimum value is the estimated noise floor. Other noise-floor estimation techniques include the forward consecutive mean excision (FCME) algorithm [28], which has been used in many measurement studies [29]. Note that in the first time slot when a user becomes active, it has no knowledge of $\tilde{\beta}_i$ for different subchannels. In this case, user i can either start with a pessimistic value, e.g., $\tilde{\beta}_i = 0$, or an optimistic value, e.g., $\tilde{\beta}_i = 1$. In our work, we consider the optimistic value. Note that immediately after becoming active, the user measures β_i for different subchannels over next time slots and update its estimate.

- In subsequent time slots, user i can be either in the ‘explore’ or ‘persist’ state. When user i is in the explore state, it randomly selects a subchannel CB set. When user i is in persist state, it utilizes the previously used subchannel set. The user then senses the associated PU channel of the selected subchannel set over the period T_{sense}. One of two possibilities can occur: (1) The PU channel is found to be occupied; or (2) The PU channel is found to be free.
- If the PU channel is found to be occupied, user i remains quiet and utilizes the remaining time period of the frame to measure the β_i (see Eq. 6) over another PU channel that is randomly selected from the remaining channels.
- If the PU channel is found to be free, data is transmitted for the duration T_{data}. One of two possibilities occur: 1) Successful transmission; or 2) Unsuccessful transmission.
- If the SINR at the intended receiver is greater than a threshold value γ_0, then the transmission is successful and an acknowledgement (ACK) will be sent to the user. In this case there are two possibilities: (1) the user is currently in the explore state and will enter persist state; and (2) the user is currently in the persist state and will enter the explore state with probability $\mathrm{P}_{explore}$. It is important to note that due to the relatively smaller size of the ACK packets, it is less likely that the ACK packets could also experience packet losses. Also, to reduce further ACK packet loses they may be transmitted with more robust coding/modulation/control rate techniques. For example, Maadani *et al.* [30] have suggested the use of low rate ACK transmission where packet ACK are sent with lower control rate of 1Mbps. Lower rate for ACK can lead to lower requirement for SINR tolerance.

$$\mathrm{P}_{explore} = \sqrt{\frac{1}{C_\beta}\tilde{\beta}_i(1-\beta_i)^\zeta} \tag{7}$$

where $\zeta > 0$ is a constant, and C_β represents a counter which counts the number of time slots since $\beta_{i,new} \not> \beta_{i,old}$.

Motivation for the use of the channel quality metric: β_i *and* $P_{explore}$. After making a successful CB selection, the user may later be able to identify better CB selection than the current one. To take into account this, a user after successful transmission enters the explore state with probability $P_{explore}$. It is important to note that to avoid constant exploration (and hence constant subchannel switching), $P_{explore}$ must be decreased after making a successful CB selection. The probability $\mathrm{P}_{explore}$ takes into account the data rate on the current subchannel and the likelihood of discovering a better subchannel. This is achieved by utilizing the proposed channel quality metric β_i. In the presence of no interference β_i equals to 1, while as interference increases $\beta_i \to 0$. As the value of β_i decreases, the likelihood of achieving a higher data rate by changing subchannel assignment increases. Therefore, β_i reflects how beneficial changing subchannel assignment can be, while being strictly between the values of 0 and 1. The constant $\zeta > 0$ is a weighting factor. When $\zeta = 1$, the parameter has no impact on the $P_{explore}$. However, when $\zeta > 1$, $P_{explore}$ starts decreasing. A careful choice of ζ is required: if it is set to a very high value, then we may not be able to achieve convergence to a state where users experiences the highest value β_i; on the other hand, if it is set a too low value, then it encourages more exploration and hence subchannel switching more often among the users. $\tilde{\beta}_i$ reflects the state of the channels visited by a user over period of time and $\tilde{\beta}_i \to 0$ means that the channels are of poor quality. In this case further exploration can incur only overhead costs in terms of subchannel switching. Hence, in Eq. 7 $\mathrm{P}_{explore} \to 0$ also as $\tilde{\beta}_i \to 0$. Moreover, $\mathrm{P}_{explore}$ should also take into account the fact that if a user after finding subchannel selections for utilization is not able to find new subchannel selections offering an improvement then the user should explore less often as exploration incurs cost in terms of subchannel switching.

- If the SINR at the intended receiver is less than the threshold value γ_0 then the transmission is unsuccessful and no ACK will be received by the user. In this case there are two possibilities: (1) The user has been successful in a previous transmission using the subchannel selection and is currently in persist state, it will persist after failure with the probability $P_{persist}$ in the next slot. $P_{persist}$ for such cases is given by:

$$P_{persist} = 1 - \left(\frac{1}{\left(T_{SCS} - (T_{fail} - 1)\right)} - \frac{1}{T_{SCS}} \right) \quad (8)$$

where T_{SCS} is the number of time slots the user has been utilizing the current subchannel selection (SCS) set. Note that T_{SCS} after first failure is always greater than one. T_{fail} is the number of time slots the user has had failed transmission on the current subchannel. Note that $P_{persist} = 1$ in the first time slot after a failed transmission, and decreases with each further failed transmission.

Motivation for the use of $P_{persist}$: Being in the persist state means the user has been previously successful on its current subchannel set. When the user experiences a failed transmission in the current time slot it can be that at least one interfering user has attempted to utilize at least one subchannel in the current set. There are two outcomes in this case: 1) that all interfering users experienced a failed transmission and were unsuccessful, or 2) at least one of the interfering users had a successful transmission and has entered persist state. In the first case, all the interfering users will continue in explore state and attempt to utilize different subchannel sets in the next time slot. This will likely lead to a successful transmission as interfering users will not select the same subchannel selection and the user can get improved SINR. In the second case where at least one of the interfering users is successful on the subchannel set and enters persist state, the current user of the subchannel set may or may not continue to have failed transmissions as aggregate interference levels may change depending on the subchannel selections of other interfering users. As the number of sequential failed transmissions increases, the more likely it is to be caused by at least one persisting user in the current subchannel set, and not users exploring the subchannel set. In this case, it is desirable to enter explore state and find another set of subchannels to utilize. We therefore base the probability $P_{persist}$ as a function of T_{SCS} and T_{fail}. 2) The second possibility is that the user is in explore state and was unsuccessful on this subchannel. If the user has CB selection O_k, where $k > 1$ it will reduce its CB order by 1 with probability P_{reduce}, it then sets the probability of accessing the current subchannel set in the next time slot to 0. P_{reduce} (the probability of reducing CB order by 1) is given by:

$$P_{reduce} = \frac{\beta_i + T_{lim}\left(1 - \tilde{\beta}_i\right)}{2} \quad (9)$$

where T_{lim} is defined as:

$$T_{lim} = \min\left\{1, \frac{T_{active}}{\delta}\right\} \quad (10)$$

where T_{active} is the number of time slots the user has been active and $\delta > 0$ is a parameter set sufficiently high that the estimate $\tilde{\beta}_i$ accurately reflects the state of the channels in use. For example, $\delta = 1$ means that even when the user has been recently active in the network (active only a few time slots), $\tilde{\beta}_i$ will still have high influence on reducing the CB order when a user gets unsuccessful in transmissions. However, $\tilde{\beta}_i$ is statistical average and it would be good for a user to collect more samples of β_i to have better long term average value. Hence, a higher value for δ allows a user to take decision of reducing CB order based on better estimates of $\tilde{\beta}_i$.

Motivation for the use of P_{reduce}: Even in the presence of no interference it is possible that channel quality between a transmitter and its receiver is degraded due to bad signal-to-noise (SNR) ratio. For example, it could be caused by the distance between a transmitter and its intended receiver (low SNR). In such scenarios it can be less efficient to communicate with a higher CB selection, as lower CB selection can improve the coverage. Reducing the CB order in such scenarios may be desirable as a transmitter may spend the same amount of power in a smaller bandwidth and hence may improve its SNR. The probability P_{reduce} ensures that when transmissions are failed the probability of reducing CB order is high where β_i is high, in which case a low SNR is likely the cause of the failed transmission. In the case of lower values of β_i where interference may be the cause of failed transmission, the probability of reducing CB order increases with failed transmissions. This is due to the reason that as a user explores channels it mostly measures low values of β_i which in turn decreases the estimate $\tilde{\beta}_i$. Low values of $\tilde{\beta}_i$ means most of the subchannel are poor quality and by reducing CB order a user may increase its SINR.

- If a user enters explore state after a previously successful transmission and finds a subchannel set on which it can communicate successfully, it will persist with the new subchannel set if β_i of the new set is greater than β_i of the previously utilized set. Otherwise it will persist with the previous subchannel set.

B. The π^{Sig} Method With SAS Coordination

To protect the PUs from interference and to facilitate the users seeking to utilize the spectrum for secondary usage, recent approaches to spectrum sharing have suggested the use of a spectrum manager entity, such as SAS [10]. In SAS based systems multiple independent users may be required to register their information (which can include CB capabilities, location information, etc) and also to inform their subchannel selection decisions to a SAS [10]. In our work, we ask the following question. In the presence of a SAS system, which has such user information available; can it be utilized for efficient CB selections? We particularly focus on the scenarios where the information can be made available with minimum overhead.

Under the collision-protocol model, where only a single user can utilize a given channel when in interference range, a SAS entity with knowledge of user channel and subchannel selections can help users to converge quickly to subchannel selections that minimize the probability of collisions. This can be achieved with *low overhead information exchange*; for example, a SAS can inform users with a single bit if they should utilize a given subchannel. A user can inform the SAS of it's channel and subchannel selections only when it changes it's selection. This information exchange between the SAS system and the users can be achieved using the concept of anchoring the control channel which is recently proposed in [4]. In this approach, through aggregation, the connectivity on the opportunistic access spectrum always comes with the connectivity on the more reliable spectrum. The control signaling always happens on the reliable channel such as a licensed or an unlicensed channel with no incumbent. Note that the proposed method does not allow for any information exchange between users. Also, in the proposed method, we consider interference range to be twice the transmission range of a user. This is a typical assumption in standard literature when considering interference ranges.

It is important to note that unlike the collision-protocol model, under the SINR-protocol model, a SAS entity using the above low overhead information exchange to obtain the knowledge of all users' SCS selections at a given time instant can be of little help to users to converge quickly to those selections that minimize the probability of interference. This is due to the reason that different users can have different sets of interferers that can cause loss of communication, and hence the universal knowledge of SCS selections obtained by the SAS entity (as explained above) may not lead to efficient SCS selections.

SAS information exchange: Using knowledge of user locations, the SAS determines the users that are within interfering range of a particular user. Based on this, and the subchannel selections of the users that are within interfering range of a user; the SAS generates a subchannel status bit-map for each user. Each element of the bit-map corresponds to a subchannel, where a value of 1 indicates that the subchannel is singleton, i.e., occupied by only a single user, that is within the interference range of the user. A value of 0 indicates that the subchannel is either free, or utilized by 2 or more users within the interfering range of the user.

The important steps involved in the proposed π^{Sig} method are explained in detail in Pseudocode 1.

Pseudocode 1 π^{Sig} Method

a) Each user i Module

Initialize $O_{k=max}$, and each element of the local binary subchannel status bitmap to 0
Update binary subchannel status bitmap if new bit map received from SAS
Select uniformly at random O_k non-singleton subchannels associated with a PU channel p
Inform Inform SAS of the subchannel selection
Sense the PU channel associated with the selected subchannels
if PU is present **then**
    Enter State = persist, Return to **Sense** and wait for the next time slot
else
    Transmit data
    if Successful communication **then**
        Enter State = persist, Return to **Sense** and wait for the next time slot
    else
        Enter State = explore
        Check for the availability of at least one other non-singleton subchannel set of order O_k
        Reduce $O_k \rightarrow O_{k-1}$ when $k \geq 2$ and no non-singleton subchannel set of order O_k is available.
        Return to **Update**
    end if
end if

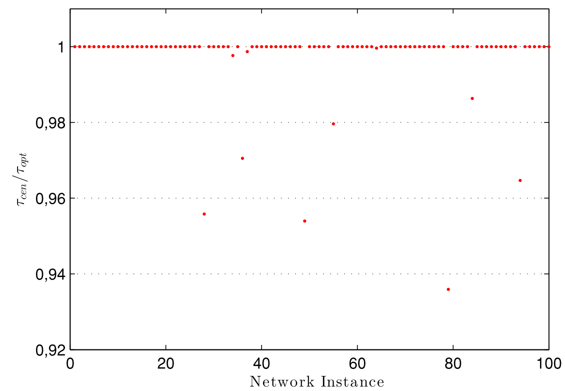
b) SAS Module

Collect subchannel selections of every user i
Generate bit-map of subchannel status, non-singleton channel subchannels = 0, singleton channels = 1
Communicate bitmap to users
Update subchannel selections when received from a user and *Return* to **Generate**

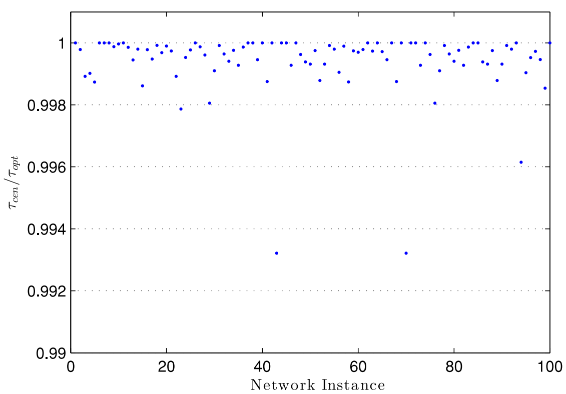
C. π^{Cen} Centralized Method for Subchannel Selection

To establish a baseline for comparing the results obtained from the proposed π^{Aut} and π^{Sig} methods, we consider a π^{Cen} centralized method to the CB selection problem. A centralized CB and subchannel allocation solution that performs an exhaustive search over a set of all possible subchannel sets for I users with different distances, subchannel and interference conditions is computationally intensive and becomes numerically untractable beyond a certain number of users. The π^{Cen} method finds a subchannel assignment for all users in the network that maximizes the data rate of the network such that each user is able to successfully communicate. The steps involved in the π^{Cen} method are explained in detail as follows:

1) *Step 1:* The method works by first assigning a different O_1 subchannel set to each of the I users. When no unused subchannels remain, the centralized method goes through all subchannels one-by-one and assigns a subchannel that maximizes data rate.
2) *Step 2:* The method then attempts to increase O_k by trying one by one different CB orders O_k for a user i. For instance, if the user i has $O_{max,i} = 3$ then the method first tries all subchannel sets of O_2 for the user i and then all subchannel sets of O_3. While trying each subchannel set, if there are any interferers on this new subchannel set, it attempts to relocate the interferers by trying all possible subchannel sets (of their current O_j) assignments for the interferers. The method calculates data rate for each round of increase in O_k. However, the subchannel assignments are only updated if the total data rate has increased. The assignment that maximizes the data rate is utilized. The above step of attempts to



(a) 1 channel / 4 SUs



(b) 2 channels / 8 SUs

Fig. 3. Ratio of time average data rate of the π^{Cen} subchannel assignment to the optimal assignment.

increase O_k is repeated one by one for all the users in the network.

3) *Step 3:* Once step 2 is performed for all I users, the method checks whether at least one user has a different subchannel assignment after the current iteration. If this is true then an improved subchannel assignment has been found in the current iteration for at least 1 user, and the method proceeds to the next iteration in which step 2 is repeated again. If this is false then no improved subchannel assignments were found for any user in the current iteration, and the method ends.

In Fig. 3 we show that the utilized π^{Cen} method performs close to an exhaustive search, and hence can be utilized as a benchmark for performance comparisons. Fig. 3 presents the ratio of time average data rate obtained using the π^{Cen} to the optimal solution, where the optimal solution is found by an exhaustive search of subchannel assignments. For 100 random network instances, we perform an exhaustive search over all possible subchannel allocations in the scenario that $|\mathcal{S}_p| = I$. Because of the computational complexity of the exhaustive search, which increases exponentially with the number of PU channels, we consider the cases of only 1 and 2 potentially available PU channels for comparison. It can be seen that numerically the mean decrease in data rate for the π^{Cen} method over the optimal solutions are found to be 0.0026%, and 0.0006% in the 1 and 2 channel cases respectively.

V. Performance Analysis of CB Methods

A. Convergence Evaluation of π^{Aut} and π^{Sig} Methods

In this subsection, we first show that the proposed π^{Sig} method allows the network to arrive at a conflict free channel allocation within a finite time period. The proposed method converges for the scenarios where the number of usable subchannels within the same collision domain is $|\mathcal{S}_p| \geq I$ users. We also provide the expected number of time slots required to arrive at a conflict-free allocation using the π^{Sig} method. For analytical convergence analysis, we consider a difficult scenario where all I users are within the same collision domain, and $|\mathcal{S}_p| = I$.

Let $E[T(n)]$ denote the expected number of time slots required for a network of I users to arrive at a conflict-free CB allocation, starting from the initial state n. When I users operate in the network then using the π^{Sig} method, the stochastic subchannel selection process in this case can be modeled as a finite-state Markov chain with a finite set $\mathcal{S}$. Let

$$\mathcal{S} = \{n, n-1, n-2, \ldots, 1\} \tag{11}$$

where each element of $\mathcal{S}$ is a state representing the number of users randomly selecting a subchannel in a time slot. Set $\mathcal{S}$ forms the state space of the subchannel selection process. For instance, when $I = 4$ users operate in the network, there are 4 states in the Markov chain, $\mathcal{S} = \{4, 3, 2, 1\}$, a state $(n = 4)$ means that all 4 users randomly perform a selection in a time slot, a state $(n = 3)$ means that 3 users randomly select while 1 user does not perform random selection in a time slot, a state $(n = 2)$ means that 2 users randomly select while 2 users do not perform random selection in a time slot, and state $(n = 1)$ is the state in which no user performs random selection.

Definition 1: A state i in a Markov chain is called absorbing if the chain must stay in state i with probability 1 once it has visited that state. The states that aren't absorbing are called transient.

Definition 2: A Markov chain is called absorbing if every state i has a path of successors $i \longrightarrow i' \longrightarrow i'' \longrightarrow \ldots$ that eventually leads to an absorbing state.

The above Definitions 1 and 2 are given in [31]. The initial state of the stochastic CB selection process is $n = I$, in which all I users randomly perform a selection in a time slot. If the Markov chain is currently in state i it moves to state j at the next step with a transition probability denoted by P_{ij}. We say that in a given time instant, the process moves forward when the number of users performing random selection changes due to one or more users selecting singleton subchannel. It stays in the same state if the number of users performing random selection remains the same. For example, when $I = 4$ users, the process starts in state $n = 4$. In the next time slot, it will remain in state $n = 4$ if no user selects a singleton subchannel, it will move to state $n = 3$, if one user selects a singleton subchannel, and so on. When all users have selected a singleton subchannel then they settle down in terms of subchannel selections. Hence, in the next time instants the network remains in that state. Hence, the considered Markov chain is absorbing in which state 1 is absorbing and all other states are transient.

Proposition 1: For an absorbing Markov chain, the probability that the chain eventually enters an absorbing state (and stays there forever) is 1.

The state $n = 1$ is called absorbing as transition probability from state 1 to 1 is one. In other words, once the system hits state 1, it stays there forever not being able to escape. This is due to the reason that when all users have selected a singleton subchannel, i.e., a subchannel occupied by only a single user, they settle down in terms of subchannel selections in this conflict-free state. Hence, in the next time instants the network remains in that state. Hence, the considered Markov chain is absorbing in which state 1 is absorbing.

Proposition 2: For an absorbing Markov chain, the time that it takes for the chain to arrive at a certain absorbing state (a random variable) has finite expected value.

The transition probability from any state i to j, given $i \neq 1$, is greater than zero, and also the transition probability from the state $i = 2$ to $i = 1$ is greater than zero. Hence, it takes finite time to reach the absorbing state, i.e., the state $n = 1$.

The above propositions 1 and 2 are proved in [31].

To calculate transition probability from state i to j for the considered stochastic subchannel selection process, we need to consider the probability that when in a state, n users select uniformly at random randomly out of n subchannels, exactly r of these users will select singleton selections, i.e., a subchannel occupied by only a single user. This probability is given by [32]:

$$p(n,r) = \sum_{s=r}^{n} \left(\frac{n!}{(n-s)!}\right)^2 \frac{1}{(s-r)!r!} \frac{(n-s)^{n-s}}{n^n} (-1)^{s-r}, \quad 0 \leq r \leq n. \tag{12}$$

Let $\mathbf{P}$ represent the state transition probability matrix of an absorbing Markov chain in canonical form:

$$\mathbf{P} = \begin{pmatrix} \mathbf{Q} & \mathbf{R} \\ \mathbf{O} & \mathbf{I} \end{pmatrix},$$

where $\mathbf{I}$ is an identity matrix, $\mathbf{O}$ is a matrix with all zero entries, $\mathbf{R}$ is the matrix of transition probabilities from transient to absorbing states and $\mathbf{Q}$ is the matrix of transition probabilities between the transient states. The transition probability matrix $\mathbf{P}$ for the absorbing Markov chain of subchannel selection process can be constructed using Eq. 12. For example, for $I = 4$, $\mathbf{P}$ can be calculated using Eq. 12 as follows:

$$\mathbf{P} = \begin{array}{c} \\ \text{state 4} \\ \text{state 3} \\ \text{state 2} \\ \text{state 1} \end{array} \left(\begin{array}{ccc|c} \text{state 4} & \text{state 3} & \text{state 2} & \text{state 1} \\ P_{44} = p(4,0) & P_{43} = p(4,1) & P_{42} = p(4,2) & P_{41} = p(4,4) \\ P_{34} = 0 & P_{33} = p(3,0) & P_{32} = p(3,1) & P_{31} = p(3,3) \\ P_{24} = 0 & P_{23} = 0 & P_{22} = p(2,0) & P_{21} = p(2,2) \\ \hline P_{14} = 0 & P_{13} = 0 & P_{12} = 0 & P_{11} = 1 \end{array} \right)$$

(upper blocks: $\mathbf{Q}$, $\mathbf{R}$; lower blocks: $\mathbf{O}$, $\mathbf{I}$)

Using the standard theory of absorbing Markov chains (presented in [31]), one can calculate $E[T(n)]$ for the subchannel selection process starting from the initial state n as follows. Let $\mathbf{N}$ be fundamental matrix which is given by $\mathbf{N} = (\mathbf{I}-\mathbf{Q})^{-1}$, where $\mathbf{I}$ is an identity matrix and $\mathbf{Q}$ is the matrix of transition probabilities between the transient states. In [31], it has been shown that the *ij*-entry of the matrix $\mathbf{N}$ gives the expected number of times the Markov chain is in state j, given that it starts in state i. Hence, using the π^{Sig} method, when the network starts from the initial state $n = N$, $E[T(n = N)]$ until convergence to a conflict-free allocation for the network is given by $E[T(n = N)] = \sum_{j=1}^{N} N_{1,j} C_j$, where $N_{1,j}$ is the *jth* entry of the first row of matrix $\mathbf{N}$, and C_j is the jth entry of vector $\mathbf{C}$. All entries of $\mathbf{C}$ are 1.

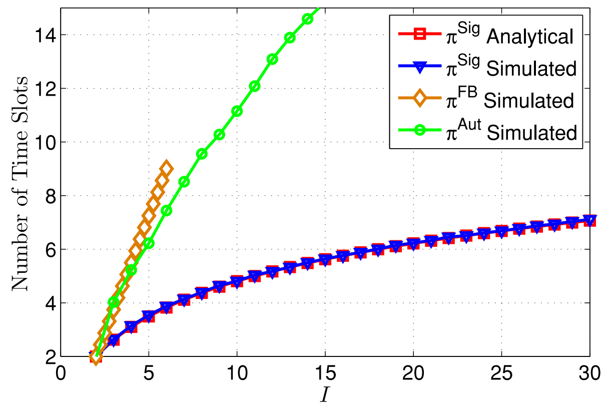


Fig. 4. Expected time to converge to conflict free subchannel selections of the π^{Sig} and π^{FB} methods as a function of I users, under collision-protocol model. The number of available subchannels $|\mathcal{S}_p| = I$, and $O_{max,i} = 1 \forall i$.

In Fig. 4, we compare the results given by the analytical expected time to convergence we derived in Section V-A and the calculated expected time to convergence from a Monte Carlo simulation. Observe that the values calculated from Monte-Carlo simulations agree perfectly with those obtained from the presented analytical model.

In Fig. 4 we also evaluate and compare the expected time to converge (E[TTC]) to conflict free subchannel selections (in terms of time slots), of the π^{Sig} method both analytically and simulated, with a method proposed in [21], as a function of I increasing users. Moreover, we consider a difficult scenario under collision-protocol model where the number of available subchannels $|\mathcal{S}_p|$ is equal to the number of users I. The method proposed in [21], which we will refer to as π^{FB}, considers autonomous selection of channels for users which utilize only their own feedback information from their previous subchannel selections, and have no CB capabilities. It can be seen from Fig. 4 that the π^{Sig} method allows the users to quickly converge to conflict-free selections, as compared to the π^{FB} method and π^{Aut} method. The reason for this is as follows: In the π^{Sig} method, users have additional binary feedback via an SAS system, which allows them to determine which channels are currently free, whereas the π^{FB} and π^{Aut} methods may utilize only their limited feedback from previous subchannel selections. For the distributed π^{Aut} method, we only numerically evaluate its convergence. Please note that providing closed form expressions or upper bounds for convergence times are difficult for the π^{Aut} as the complexity of the problem makes the analysis intractable.

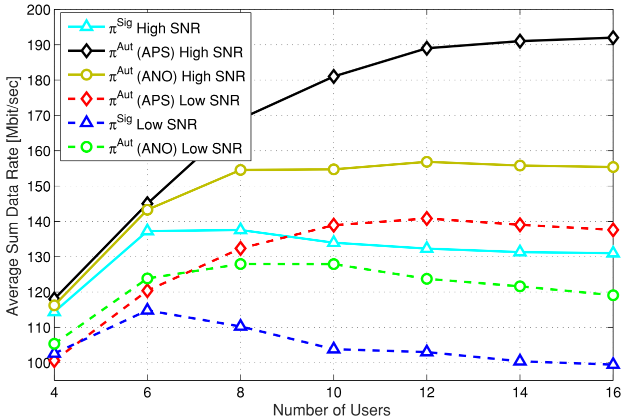


Fig. 5. Average sum data rate achieved by the π^{Aut} and π^{Sig} methods vs. number of users, with $|\mathcal{S}_p| = 8$, $N_R = 50meters$, and users with heterogeneous CB capabilities, i.e., maximum CB capabilities are uniformly selected from $O_{max,i} = 1$ to $O_{max,i} = |\mathcal{S}_p|$.

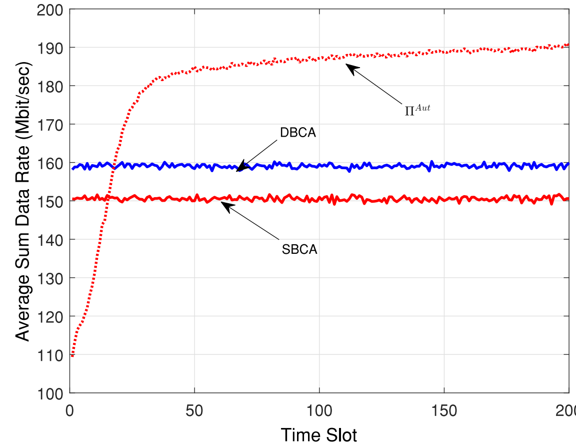


Fig. 6. Average sum data rate vs. time for the proposed π^{Aut} method, SBCA and DBCA, where $|\mathcal{S}_p| = 8$, $N_R = 50m$, and $I = 8$ users, with maximum CB capability of bonding 3 subchannels.

B. Numerical Analysis Model and Results

Using numerical analysis, we evaluate and compare the distributed and coordinated methods in terms of data rate of all the users, user blocking rate, average CB selection utilized. We also compare the methods in terms of data rate to the centralized π^{Cen} method which serves as a benchmark in terms of the proposed methods performance. In Table I we present the main simulation parameters.

1) Data Rate: In order to calculate data rate for each network iteration, we consider the subchannel selections of all users after 1000 simulated time slots. Based on these final subchannel selections, we calculate data rate based on the Shannon capacity formula:

$$\tau_{sum} = \sum_{i=1}^{I} \left(1 - \theta_{p,i}\right) \frac{O_{k,i} W_{p,i}}{\left|\mathcal{S}_{p,i}\right|} log_2(1 + \gamma_i), \tag{13}$$

where $\theta_{p,i}$ is the average occupancy of PU channel p, $O_{k,i}$ is the CB order of user i, $W_{p,i}$ is the bandwidth of PU channel p used by user i, $|\mathcal{S}_{p,i}|$ is the number of subchannels in PU channel p used by user i, and γ_i is the SINR of user i on it's current subchannel set σ_i. The total data rate result is plotted based on Monte Carlo simulations. In each simulation run, calculations are done using Eq. 13.

Average data rate comparison under high and low SNR scenarios: In Fig. 5 we present a comparison of average data rate achieved using the π^{Aut} and π^{Sig} methods as a function of Number of users I for a fixed number of subchannels $|\mathcal{S}_p| = 8$. We consider the π^{Aut} method under two different scenarios: 1) users can only bond k adjacent non-overlapping subchannels, which we call π^{Aut} (ANO); and 2) users can bond any combination of k subchannels, which we call π^{Aut} (APS), where APS means all possible selections. It can be seen from the figure that of the two CB methods, the π^{Aut} method achieves the highest sum data rate for the network under the both ANO and APS scenarios. The reason for this is as follows; the π^{Sig} method does not allow users that are within interference range of one another to select the same subchannels, whereas in the π^{Aut} method a user does not select a subchannel only when the SINR it experiences is below the threshold γ_0, causing a collision. As a consequence, under the π^{Sig} method users do not bond channels in circumstances where it may be beneficial in terms of data rate. It can be also seen that the π^{Aut} (APS) due to its freedom to use both contiguous and non-contiguous CB selections outperforms the π^{Aut} (ANO).

Moreover, in Fig. 5 we also evaluate the impact of SNR on the proposed methods. This is important, as even in the presence of little to no interference it is possible that channel quality between a transmitter and its receiver is degraded due to low SNR. One factor that can impact the SNR is the distance between the users. We consider two scenarios, where the minimum distance of receivers from their transmitters is no less than 8 m, and 16 m, respectively, and in both cases a maximum distance is no more than 40 m (between a transmitter and its intended receiver). The maximum distance is selected so that at this maximum distance a user without CB can successfully communicate given that there is no interference (based on the other parameters such as path loss exponent). It is possible that a receiver may be located closer to interfering transmitters than the 8 m / 16 m minimum distance. Increasing the minimum distance from 8 m to 16 m reduces mean SNR. We will refer to the case of 8 m minimum distance as the high SNR scenario, and 16 m case as the low SNR scenario from here on. It can been seen in Fig. 5 that under high SNR the π^{Aut} (APS) achieves the highest gain in sum data rate for the network.

In Fig. 6 we depict the achieved total data rate of all users vs. time under π^{Aut}, SBCA and DBCA methods. It can be seen from the figure that of the three distributed CB methods, π^{Aut} method achieves the highest rate. The reason for this is as follows. The SBCA and the DBCA methods do not utilize any adaptation in their CB selections, whereas the proposed π^{Aut} method utilizes adaptive CB, such adaptation takes into account the channel quality metric β_i. π^{Aut} method enables users to select CB selections that increase the likelihood of achieving higher data rates.

Average data rate under adjacent channel interference (ACI): In Fig. 7 we evaluate the impact of Adjacent Channel interference (ACI) on performance of the

TABLE I
SIMULATION PARAMETERS

Site radius N_R	50 and 100 m
Minimum distance between transmitter and receiver	8 m (High SNR) and 16 m (Low SNR)
Maximum distance between transmitter and receiver	40 m
Center frequency	2.4 GHz
PU channel bandwidth	20 MHz
Number of subchannels per PU channel	8
Maximum transmission power	30 mW
Transmitter and receiver antenna gain	1 dBi
Transmitter and receiver antenna length	5 cm
PU channel occupancy rate	30%
PU channel occupancy model	independently and identically distributed
Path-loss exponent α	3
SINR threshold γ_0	5 dB
Explore parameter ζ	5
Reduce parameter δ	30
Simulation iterations	1000
Time slots per iteration	1000

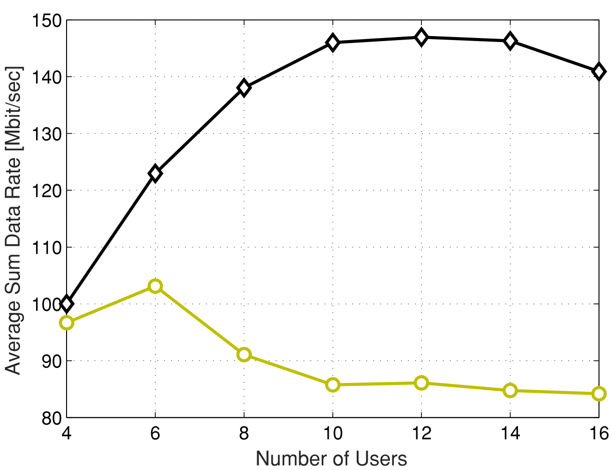


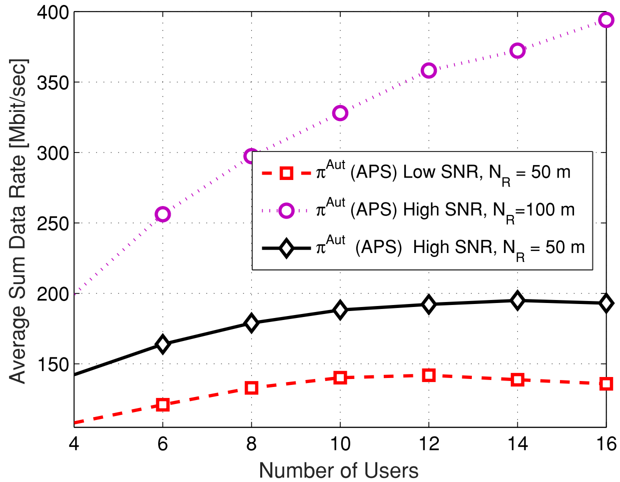
Fig. 7. Average sum data rate achieved by the π^{Aut} under the APS and ANO CB selections as a function of Number of users I, where $|\mathcal{S}_p| = 8$, and ACI= 5%. Users are with heterogeneous CB capabilities, i.e., maximum CB capabilities are uniformly selected from $O_{max,i} = 1$ to $O_{max,i} = |\mathcal{S}_p|$.

π^{Aut} method under the APS and ANO CB selections. ACI is set to 5% which means 5% of a user's transmit power is leaked to its adjacent subchannels. We consider high SNR scenario (with the same parameters as used in Fig. 5. Comparing Fig. 5 and Fig. 7 for the π^{Aut} method , it can be seen that ACI degrades its performance. However, π^{Aut} APS outperforms π^{Aut} ANO.

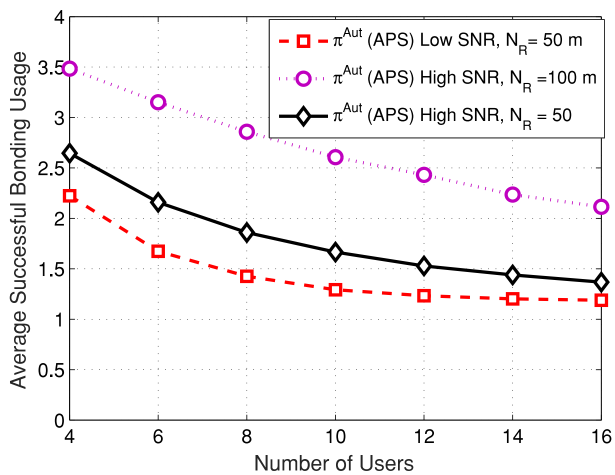
Average sum data rate under maximum CB capabilities: Fig. 8a shows that allowing maximum CB capability for all the users results in higher sum data rate for the network only when the network site radius N_R is twice as considered before. N_R is the radius of network circle in which users are randomly deployed. When compared with the sum data rate achieved by the π^{Aut} (APS) method under high SNR and the same network radius of $N_R = 50m$ in Fig. 5. It can be seen that when there are few number of users the sum data rate is increased when all the user have maximum CB capability as compared to when they have heterogeneous capabilities as in Fig. 5. However, as the number of users in the network increases it can be seen that the heterogeneous CB capabilities scenario in Fig. 5 and the homogeneous maximum CB capabilities scenario in Fig. 8a obtain the same sum data rate for the network.

Average CB Usage under maximum CB capabilities: Fig. 8b present average successful CB usage for a user under the π^{Aut} method for the scenarios where all the users have maximum CB capabilities. It can be seen from the figure that for network site radius $N_R = 100m$, and high SNR, allowing maximum CB capability for all the users results in average successful usage between 3.5 bonded subchannels to 2 bonded subchannels when the number of users is varied from 4 to 16. When network site radius is reduced to $N_R = 50m$ while keeping the other parameters same, then the average successful CB usage varies from 2.7 to 1.4 bonded subchannels under high SNR, and it varies from to 2.3 to 1.3 for low SNR. The results in Fig. 8 show that for the π^{Aut} method, the average successful bonding order usage is greater than one for all studied cases. However, it is also true that as the users to available subchannels ratio (UCR) increases, the average bonding order that a user can successfully utilize goes down. As the UCR increases, ultimately there comes a point where CB becomes of no benefit to a user due to high user density, i.e., the user can successfully utilize only one subchannel for access. This means that the proposed distributed CB method gives either better performance or equal performance, compared to the scenarios when no bonding is applied. It is important to note that this degradation in CB performance due to the increased UCR is common to all channel bonding/selection techniques [3].

Average sum data rate Comparison with benchmark Centralized method π^{Cen}: In Fig. 9 we present a comparison of the data rate achieved by the distributed π^{Aut} and π^{Sig} methods to the data rate achieved using the close to optimal centralized π^{Cen} method. The results show that of all the CB methods presented, the π^{Aut} performs the closest to the π^{Cen} solution. With 4 users and 4 subchannels, when $O_{max,i} = 3\forall i$, the average data rate achieved is approximately 123 Mb/s with the π^{Cen} method and 107 Mb/s with the π^{Aut} method. In other



(a)



(b)

Fig. 8. a) Average sum data rate achieved and b) Average successful CB utilized under the π^{Aut} with APS CB selections for $|\mathcal{S}_p| = 8$. Each user is with the same maximum CB capability which means that each user has the ability to bond all the subchannels.

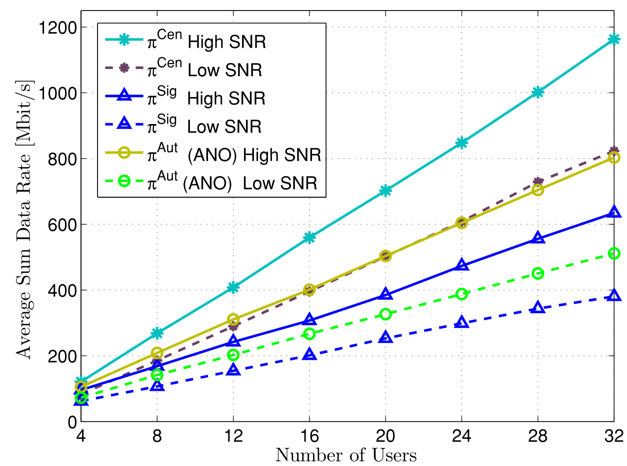


Fig. 9. Average sum data rate vs. number of users I for the π^{Aut}, π^{Sig} and the π^{Cen} methods. Number of subchannels is increased with the number of users, i.e., $|\mathcal{S}_p| = I$.

words with 4 users, the π^{Aut} achieves average data rate of 87% of that achieved by close to optimal π^{Cen} method. The gap in performance between the π^{Aut} and π^{Cen} methods does however increase with the number of users. For double the number of users, the performance of the π^{Aut} decreases to approximately 77% of the π^{Cen} method, reducing further to 69% with 32 users.

2) User Blocking Rate: It is logical that as the number of users increases while the number of subchannels is constant, users will experience higher levels of interference, and some users will be left unable to communicate on any subchannels with $\gamma_i > \gamma_0$. We consider blocking rate to be the ratio of the mean number of blocked users per iteration to the total number of users:

$$R_{blocking} = \frac{\bar{I}_{blocked}}{I} \tag{14}$$

In Fig. 10 we present a comparison of the blocking rate observed using the π^{Aut} under the APS and ANO selections, and also π^{Sig} as a function of I users with $O_{max,i} = 3$, again considering both high and low SNR scenarios. The number of subchannels is fixed $|\mathcal{S}_p| = 8$. As previously mentioned, users in the π^{Aut} method do not select subchannels only when SINR is below the threshold γ_0. In the scenarios where a user is causing interference to others, but not experiencing high interference levels, the user may utilize a higher CB order and deprive other users of successful subchannel selections. As a consequence, the blocking rate of the π^{Aut} method as compared to the π^{Sig} method is greater for such scenarios.

The results in Fig. 10 show that the blocking rate of the π^{Sig} method is lower than the π^{Aut} with ANO selections method, when the number of users is less than 16 in the high SNR case, and 10 in the low SNR case. However, its blocking rate is higher than the π^{Aut} with APS selections method. For an increased number of users, i.e., as the ratio of users to subchannels increases, the blocking rate of the π^{Aut} method under both ANO and APS selections is lower than the π^{Sig} method. This shows that the information provided by the SAS (under the assumption of collision domain model) to users in the π^{Sig} method is useful for reducing conflict between users when the ratio of users to useable subchannels is suitably low. When the ratio of users to subchannels increases, it becomes increasingly likely that all subchannels are determined by the SAS to be in a state of conflict (i.e., state 0), therefore the subchannel status bit-maps no longer contain any useful information. In reality two or more users within interference range of one another may select the same subchannel, with interference levels low enough not to cause a collision. It is for this reason that the limited feedback information utilized in the π^{Aut} method proves to be more beneficial as the ratio of users to subchannels grows large.

VI. Conclusion

In our work we consider both the collision, and SINR-protocol models to analyze the problem of CB. We present a fully autonomous CB method designed under the SINR-protocol model, π^{Aut}, in which users utilize only their limited

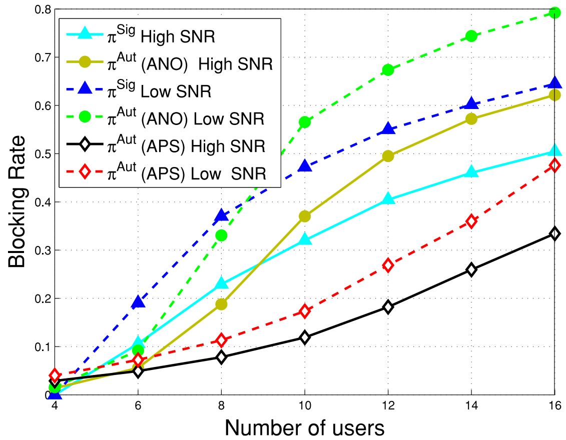


Fig. 10. User blocking rate of the π^{Aut} and π^{Sig} methods as a function of Number of users I.

feedback on previous transmissions, and measurements made while unable to transmit. We compare the performance of the π^{Aut}, with a method we design under the collision-protocol model; the π^{Sig} method, and a close to optimal centralized solution; the π^{Cen} method. The two distributed methods differ in terms of information available to users. In the π^{Sig} method, users inform a SAS of their subchannel selections, which in turn informs users of the state of each subchannel through a binary bit-map. We have shown that the scenarios where the number of subchannels is at least as great at the number of users, the π^{Sig} scheme which is designed under the collision-protocol model can help users converge fast to reduced conflict channel selections, and also reduce their blocking rates. One reason for this is due to the simplicity of the collision-protocol model, where only a single user can utilize a given channel when in interference range. We find, however, that when users have the ability to bond channels and/or when the number of available subchannels is less than the number of users, the π^{Sig} scheme can result in conservative spectrum reuse due to users attempting to avoid using the same subchannel selections as other users. We show that the π^{Aut} scheme which is designed under the SINR-protocol model considerably outperforms the π^{Sig} in such scenarios. Moreover, we also show that under all scenarios the π^{Aut} scheme outperforms the π^{Sig} scheme in terms of data rate of all users.

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Zaheer Khan received the M.Sc. degree in electrical engineering from University College Boras, Sweden, in 2007, and the Dr.Sc. degree in electrical engineering from the University of Oulu, Finland, in 2011. He has Currently a Tenure Track Lecturer position with the University of Liverpool, U.K. He was a Research Fellow/Principal Investigator with the University of Oulu from 2011 to 2016. His research interests include application of game theory to model distributed wireless networks, prototyping access protocols for wireless networks, IoT location tracking systems, cognitive and cooperative communications, and wireless signal design. He was a recipient of the Marie Curie Fellowship for 2007–2008.

Janne Lehtomäki (S'03–M'06) received the Doctorate degree from the University of Oulu, Finland, in 2005. He is currently an Adjunct Professor with the University of Oulu, Centre for Wireless Communications. He spent 2013 semester with the Georgia Tech, Atlanta, USA, as a Visiting Scholar. He is currently focusing on spectrum measurements and terahertz band wireless communication. He has served as a Guest Associate Editor for the *IEICE Transactions on Communications* Special Section (2014 and 2017) and as a Managing Guest Editor for *Nano Communication Networks* Special Issue (2016). He was the General Co-Chair of the IEEE WCNC 2017 International Workshop on Smart Spectrum, the TPC Co-Chair for IEEE WCNC 2015 and the 2016 International Workshop on Smart Spectrum, the Publicity/Publications Co-Chair for ACM NANOCOM 2015, 2016, and 2017. He was a recipient of the Best Paper Award in IEEE WCNC 2012 as a co-author. He is an Editorial Board Member of *Physical Communication*.

Simon Scott received the B.Eng. (Hons.) degree in electronic and communication engineering from the University of Northumbria at Newcastle, U.K., in 2008. He is currently pursuing the M.Sc. degree in wireless communication engineering with the University of Oulu, Finland.

Zhu Han (S'01–M'04–SM'09–F'14) received the B.S. degree in electronic engineering from Tsinghua University, in 1997, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Maryland, College Park, in 1999 and 2003, respectively.

From 2000 to 2002, he was an Research and Development Engineer with JDSU, Germantown, MD, USA. From 2003 to 2006, he was a Research Associate with the University of Maryland. From 2006 to 2008, he was an Assistant Professor with Boise State University, Idaho. He is currently a Professor with the Electrical and Computer Engineering Department as well as in the Computer Science Department, University of Houston, TX, USA. His research interests include wireless resource allocation and management, wireless communications and networking, game theory, big data analysis, security, and smart grid. He was a recipient of the NSF Career Award in 2010, the Fred W. Ellersick Prize of the IEEE Communication Society in 2011, the EURASIP Best Paper Award for the Journal on Advances in Signal Processing in 2015, the IEEE Leonard G. Abraham Prize in the field of Communications Systems (Best Paper Award in IEEE JSAC) in 2016, and several best paper awards in IEEE conferences. He is currently an IEEE Communications Society Distinguished Lecturer.

Marwan Krunz (F'10) is the Kenneth VonBehren Endowed Professor with the Department of ECE, University of Arizona. He also holds a joint appointment as a Professor of computer science. He co-directs the Broadband Wireless Access and Applications Center, a multiuniversity industry-focused NSF center that includes over 16 affiliates from industry and government laboratory. He previously served as the UA Site Director for Connection One, an NSF IUCRC that focuses on wireless communication circuits and systems. In 2010, he was a Visiting Chair of Excellence with the University of Carlos III de Madrid. He previously held various visiting research positions with University Technology Sydney, INRIA-Sophia Antipolis, HP Labs, the University of Paris VI, the University of Paris V, the University of Jordan, and U.S. West Advanced Technologies. His research interests lie in the areas of wireless communications and networking, with emphasis on resource management, adaptive protocols, and security issues. He has published over 250 journal articles and peer-reviewed conference papers, and is a Co-Inventor on several U.S. patents. He is an Arizona Engineering Faculty Fellow from 2011 to 2014 and an IEEE Communications Society Distinguished Lecturer from 2013 to 2014. He was a recipient of the 2012 IEEE TCCC Outstanding Service Award and the NSF CAREER Award in 1998. He currently serves as the Editor-in-Chief for the IEEE TRANSACTIONS ON MOBILE COMPUTING. He also serves on the editorial board for the IEEE TRANSACTIONS ON COGNITIVE COMMUNICATIONS AND NETWORKS. He served on the editorial boards for the IEEE/ACM TRANSACTIONS ON NETWORKING, the IEEE TRANSACTIONS ON MOBILE COMPUTING, the IEEE TRANSACTIONS ON NETWORK AND SERVICE MANAGEMENT, the *Computer Communications Journal*, and the *IEEE Communications Interactive Magazine*. He was the General Vice-Chair for WiOpt 2016 and the General Co-Chair for WiSec'12. He was the TPC Chair for WCNC 2016 (Networking Track), INFOCOM'04, SECON'05, WoWMoM'06, and Hot Interconnects 9. He has served and continues to serve on the steering and advisory committees of numerous conferences and on the panels of several funding agencies. He was a Keynote Speaker, an Invited Panelist, and a Tutorial Presenter at numerous international conferences.

Alan Marshall (M'88–SM'00) holds the Chair in Communications Networks with the University of Liverpool where he is the Director of the Advanced Networks Group and the Head of Department. He is a fellow of the Institution of Engineering and Technology. He has spent over 24 years working in the telecommunications and defense industries. He has been a Visiting Professor in network security with the University of Nice/CNRS, France and an Adjunct Professor for Research with Sunway University Malaysia. He has published over 200 scientific papers and holds a number of joint patents in the areas of communications and network security. He has formed a successful spin-out company Traffic Observation and Management Ltd. specializing in intrusion detection and prevention for wireless networks. His research interests include network architectures and protocols, mobile and wireless networks, network security, high-speed packet switching, QoS/QoE architectures, and multisensory communications including haptics and olfaction. He is currently a Section Editor (Section B: Computer and Communications Networks and Systems) of the Computer Journal of the British Computer Society and a member of the Editorial Board of the *Journal of Networks*. He is also on the program committees of a number of IEEE conferences.