Distributed and Coordinated Spectrum Access Methods for Heterogeneous Channel Bonding

Zaheer Khan, Janne Lehtomäki, Simon Scott, Zhu Han, Marwan Krunz, and Alan Marshall

Abstract

Channel bonding (CB) is a technique that enables a wireless link to use wider channels to achieve higher data rates. In this paper, competition for efficient spectrum access among autonomous users with heterogeneous CB capabilities is considered. We propose distributed and coordinated channel/bonding selection methods under signal-to-interference-plus-noise ratio (SINR) and collision-channel models. In particular, we propose a distributed channel/bonding selection method in which users only utilize limited feedback to distributively arrive at CB selections that minimize their probability of conflict. The proposed method utilizes a novel *channel quality metric* 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 is increased then the performance of CB is decreased. Our results show that under certain scenarios, the proposed coordinated channel/bonding selection scheme helps users converge fast to reduced conflict channel selections. However, the proposed distributed scheme results always in considerably superior performance in terms of network data rates.

Index Terms

Channel bonding, distributed users, heterogeneous capabilities, collision-channel model, SINR-channel model, spectrum access system, opportunistic spectrum access.

I. Introduction

The use of carrier aggregation (CA) in licensed cellular bands and channel bonding (CB) techniques in unlicensed bands has been shown to increase network capacity under certain conditions [1]–[3]. In CA, multiple contiguous and non-contiguous carriers are combined and used as a single pipe. Wireless systems, such as WiFi networks rely on CB techniques to combine

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multiple channels to form larger transmission bandwidths. Recent advances in spectrum aggregation technologies allow the cellular industry to consider the adoption of CA/CB techniques not only in licensed bands but also across heterogeneous shared spectrum bands such as unlicensed, and opportunistic spectrum access (OSA) bands [4]–[6]. For instance, to provide cellular systems with additional spectral resources, the authors in [4]–[6] suggest combining channels not only in the licensed bands but also in the unlicensed and OSA bands.

In this paper, we consider CB scenarios for distributed cognitive radios (secondary users) which 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, this can severely limit the performance of the bonded channels in terms of adjacent channel interference (ACI) [3].

In this paper, we design distributed and coordinated spectrum access methods under both signal-to-interference-plus-noise ratio (SINR) and collision-channel models, and present a comparison according to several performance metrics and network scenarios. In the SINR-channel model, when two or more simultaneous transmissions occur on the same channel, the model considers that this can lead to additional interference at receivers, and a loss of communication only occurs when the sum of interference exceeds a certain threshold value [8]. In the collision-channel 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 lost. In practice, the SINR at each receiver is a function of the transmission powers of interfering users, and the communication 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 under the collision-channel 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 different models: (1) users can only combine 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 it is beneficial for autonomous users to bond multiple channels and use them as a single pipe for data transmission since it requires a single RF unit and hence simplifies a user's transmission hardware. This is different from some non-contiguous CA techniques which require multiple RF units for using aggregated channels over non-adjacent frequency channels [9].

One special yet practically significant scenario for our studied 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:

- We consider spectrum access among autonomous users with heterogeneous CB capabilities, under the SINR and collision-channel 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.
- Under the SINR channel 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 core idea of 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 a channel quality metric, or in an explore state, where it will explore a new CB selection.
- We compare the performance of π^{Aut} to a coordinated distributed method, π^{Sig}, where 'Sig' denotes a signal, that 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.
- 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 reduces the blocking rate, as compared to the fully distributed π^{Aut} method. However, the π^{Aut} method always outperforms the π^{Sig} method in terms of data rate, and also outperforms 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.

- We find that CB can lead to higher data rates, and that CB is most beneficial when users have a high SINR. However, we also find that when the ratio of users to available channels is increased, and users suffer from low SINR, then 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 for a baseline when making performance comparisons. In Section V, we present a performance evaluation of the CB methods in terms of convergence properties, blocking rate, and data rate, as well as details of our simulation setup. The paper is concluded in Section VI.

II. Related literature

To address the so-called 1000X capacity challenge, network operators across the globe mobile now share the perception that expansion of cellular spectrum in license-exempt and OSA bands using innovative deployment of small cells with channel aggregation/bonding capabilities can solve many capacity problems [4], [11], [12]. In [13], [14], the authors consider adaptive OSA techniques under the collision-channel model, where users have no CB capabilities. In [15], the SINR model has been 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] considers the problem of channel selection in dynamic spectrum access scenarios under the collision-channel model with multiple collision domains, with an emphasis on spatial spectrum reuse. In this work users are considered to have no CB capabilities.

Recently, in [17], [18], the authors considered guard-band-aware channel aggregation assignments in OSA systems. Different from the works in [17], [18], we consider the same problem for scenarios where channel selections are made autonomously and adaptively by each user. In our set up, there is no centralized entity that can perform optimization of channel selection decisions. Moreover, unlike [17], [18] where only collision-channel model is considered, in our work we also consider the SINR-channel model. In [3], a measurement-based framework is presented to investigate CB in unlicensed channels. In [19], an analytical framework is 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] considers the problem of CB under the collision-channel model.

The work in [20] has considered two distributed protocols to support channel bonding: 1) the Static Bonding Channel Access Protocol (SBCA), which uses a fixed number of bonded basic channels and requires finding all those basic channels empty before starting a packet transmission; and the Dynamic Bonding Channel Access scheme (DBCA), which is able to dynamically adapt the channel width to the instantaneous spectrum availability. In Section V, we compare the performance of the proposed distributed bonding selection scheme with the SBCA and the DBCA methods.

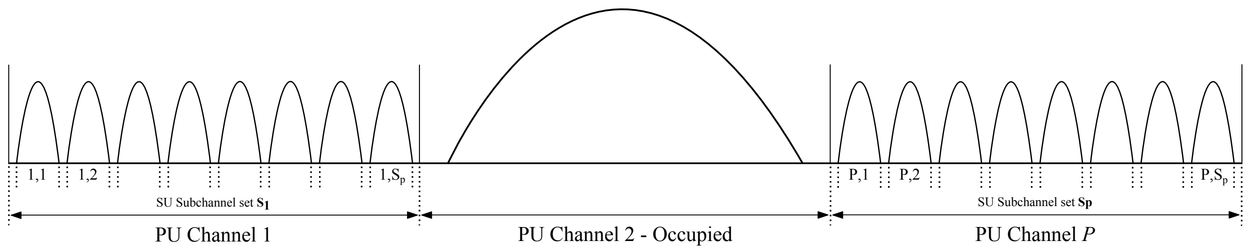


Fig. 1: PU channels and SU subchannels

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 $\mathcal{P} = \{1,2,...,P\}$. Each PU channel is divided into a set $\mathcal{S}_p$ of secondary user (SU) channels, which we refer to as subchannels, where $\mathcal{S}_p = \{1,2,...,S_p\}, p \in \mathcal{P}$ (see Fig. 1). Let O_k, where $k = 1,2,....$, 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 a user has no CB capability and $O_{max,i} = S_p$ means a user 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 users can have different maximum CB capabilities, i.e., $O_{max,i}$ 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. A SU determines whether the channel is free or occupied by the PU at the beginning of every time slot by sensing the channel over the period T_{sense}. A 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 in 5 GHz unlicensed channels [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 entity, such as a spectrum access system (SAS) as proposed by FCC [25]. Another possibility is to utilize a primary systems' beacon transmissions for synchronization. Several wireless system periodically broadcast beacons for their own users, and as SUs sense the PUs. They can receive the beacons without causing any interference to the PUs.

B. SINR and Collision-channel 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 can vary from one wireless system to another. It depends on various parameters such as the transmit power, bandwidth utilized, etc. In practice,

γ_0 should be selected to achieve reasonable communication performance between users. 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 [26]:

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

where D_i is the receiver antenna length, λ_i is the wavelength of the center frequency of the channel, $P_{t,j}$ and $G_{t,j}$ are the transmit power and transmitter antenna gains, respectively, of transmitter j, and $G_{r,i}$ is the receiver antenna gain. We consider a fixed transmission power for all users. 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 $\gamma_i < \gamma_0$. We calculate the interference power from transmitter k to receiver i (given in Eqn. 3) as follows: The interference power is found by calculating 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 one interferer. Suppose that the interferer is transmitting on subchannels 1 and 2 and the receiver is receiving on 2, 3, and 4. Assume that the interferer divides its transmit power equally over subchannels 1 and 2, the receiver can directly get interference impact from 50% of the interferer's transmit power. 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 in the cases where ACI is not modeled). For example, if the ACI factor is 0.05 (-13 dB), the receiver for the above mentioned scenario can get interference impact from 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. If ACI is not modeled, receiver on subchannel 3 only would not get any power from the interferer on subchannels 1 and 2.

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

C. Contiguous and non-contiguous CB Selection Models

In our work, we consider two different CB models: 1) Users select subchannels for CB such that selections are limited to adjacent subchannels, as in some WLANs [3], and they are non-overlapping 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 adjacent/non-adjacent subchannels and also non-overlapping.

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

$$\begin{aligned}\Sigma^{(p)} = \Bigg\{ & \overbrace{\{\{1\},\{2\},...,\{S_p\}\}}^{\text{Set of } O_1 \text{ selections}}, \overbrace{\{\{1,2\},\{3,4\},.....\}}^{\text{Set of } O_2 \text{ selections}} \\ & ,..................., \\ & \overbrace{\{\{1,2,...,O_{max}\},\{O_{max}+1,O_{max}+2,...,2O_{max}\},.......\}}^{\text{Set of } O_{max} \text{ selections}} \Bigg\}.\end{aligned} \tag{4}$$

For example, if any overlapping/non-overlapping combination of adjacent subchannels were allowed for a given CB order $O_{k=2}$, a user bonding two subchannels out of total four available subchannels could bond the pair of subchannels 2 and 3, and 4 and 5 in addition to the combinations 1 and 2, 3 and 4. However, 2 and 3 partially overlaps with 1 and 2, and 4 and 5 partially overlaps with 3 and 4. Hence, for total four subchannels and $O_{k=2}$ only combinations 1 and 2, 3 and 4 are allowed under the first model. Under this model, by limiting the CB selections to adjacent and non-overlapping subchannels, the size of a CB selection search (which can be computationally intensive) is reduced. However, it also reduces the the number of available CB selections.

The CB limitations in the first model are addressed in the second model in which users can bond adjacent/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 $\sum_{k=1}^{max}\binom{S_p}{O_k}$. For the second model, 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 $k=1$ to $k=max$.

IV. Channel Bonding Methods

When designing an efficient CB technique, one must consider how interference from other users impacts the reception of a data frame at a given user. In this section, we first consider the SINR-channel model for the design of efficient distributed CB techniques among users with heterogeneous CB capabilities. In the next subsection, we consider the collision-channel model in the design of distributed CB techniques. Finally, we present a centralized method where a centralized entity makes CB decisions, which provides a baseline for comparison of our proposed CB methods.

A. π^{Aut} Method

In the proposed π^{Aut}, while searching for spectrum opportunities, users utilize only their own limited feedback, i.e., information 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. Changes in traffic load can be handled by executing the CB algorithm periodically or when triggered by changes in traffic. Current CB selections can be used as basis for the restarted algorithm so that the currently used subchannels will be subset of the highest CB order where the algorithm restarts.

We now explain the important steps involved in the proposed method and motivation behind the parameters used in detail:

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

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

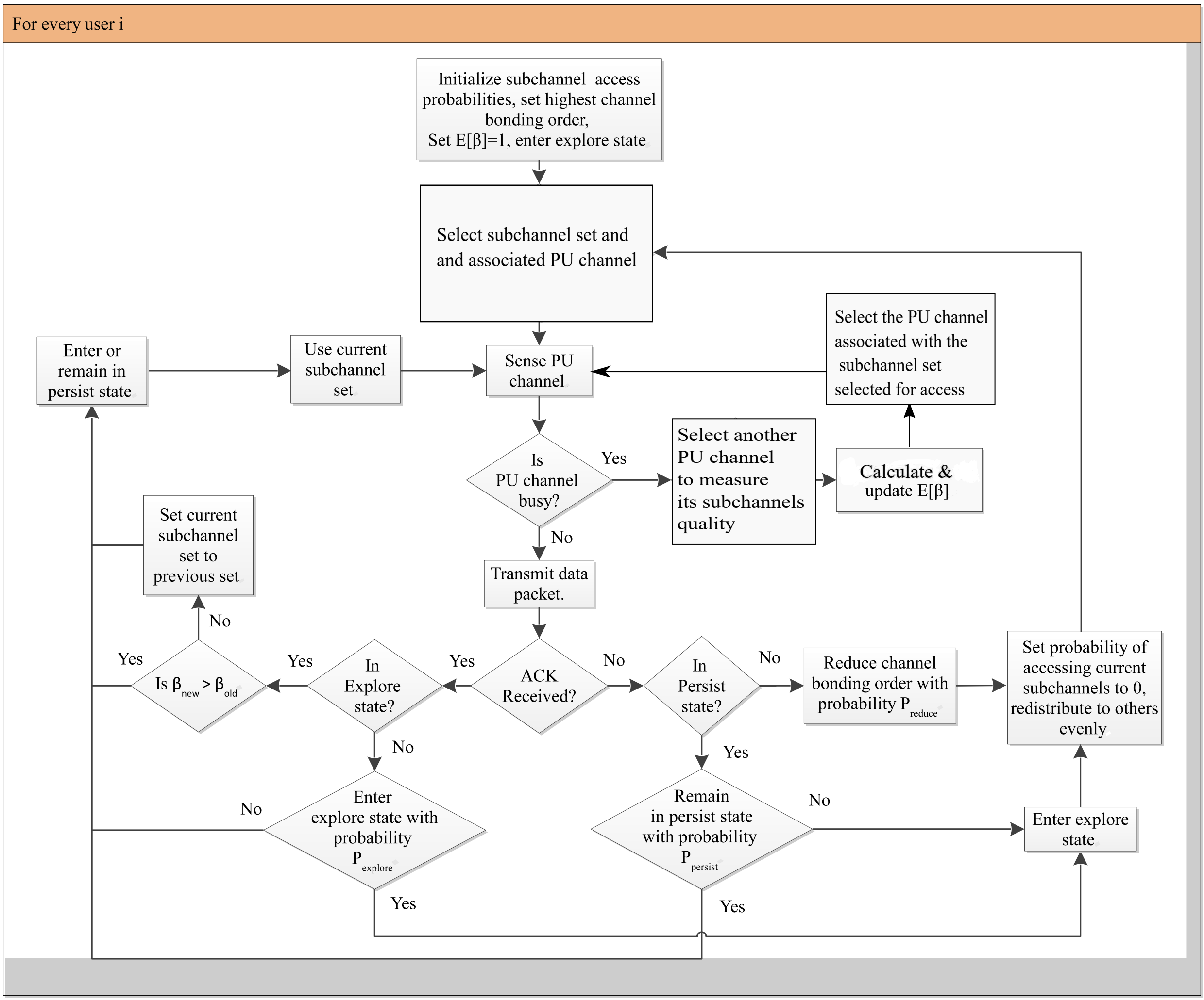


Fig. 2: π^{Aut} Method

where θ_p is the average PU occupancy of its channel p and $\sigma_k^{(p)}$ is the set of subchannel sets in PU channel p of order k. In practice, θ_p can be provided by a spectrum manager entity, such as a SAS which as 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 the SUs to the PU. However, in the absence of knowledge of θ_p, a SU can initialize subchannels selection randomly with uniform distribution. After initialization a user enters the ‘explore’ state and sets $E[\beta] = 1$, where $E[\beta]$ refers to the sample mean of the β values. β 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:

$$\beta = \frac{N_i}{N_i + \sum_{k=1,k\neq j}^{I} P_{r,ik}}, \; 0 \leq \beta \leq 1. \tag{6}$$

$E[\beta]$ is measured by taking mean of the β values sampled across subchannels which 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 in the system. Furthermore, a low SINR could be caused by high interference, i.e low signal to interference ratio (SIR), by the subchannel between transmitter and receiver (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 given there is some other subchannel with a lower interference level. As low SIR can be due to specific CB selection as it is possible that the CB selection by a user is crowded due to several other interfering users selecting the all or some of the channels in the CB selection. In this case, selecting some other CB selection can help improve the user performance. The proposed β takes into account such SINR-related factors. In some scenarios, low SNR could also be the result of high level of frequency selective fading in the current subchannel(s) (instead of long communication distance). 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 distance for all subchannels. Also, if coherence bandwidth is much less than the subchannel bandwidth, then averaging out of fading will occur in the frequency domain (and different subchannels likely lead to similar SNR values for given distance) and no time domain averaging is required.

To obtain β, 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 received squared signal, obtains a large number of samples of it, and selects the minimum value out of them. The key in avoiding negative bias is a sufficiently large averaging window for the running average. 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 cannot have any knowledge of the expected value of β for different subchannels. In this case a user can either start with a pessimistic value which will be $E[\beta] = 0$ or an optimistic value of $E[\beta] = 1$. In our work, we consider the optimistic value. Note that immediately after becoming active the user measures β for different subchannels over next time slots and update to the real estimate.

- After initialization, in later time slots, a user can be either in the explore or persist state. When the user is in the explore state, the user selects a subchannel CB set randomly. When the 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, the user remains quiet and utilizes the remaining time period of the frame to measure the β (see Eqn. 6) over another PU channel that is randomly selected out of the remaining channels.
- If the PU channel is found to be free, data is transmitted over the period 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) is received by 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 explore state with probability $P_{explore}$. 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, in [30] the authors 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.

$$\mathrm{P}_{explore} = \sqrt{\frac{1}{C_\beta}E[\beta](1-\beta)^{\zeta}}, \tag{7}$$

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

Motivation for the use of channel quality metric* β *and* $\mathbf{P_{explore}}$*:
When a user finds successful CB selection for usage it is possible there is some other CB selection that is better than the current one. To take into account this, a user after successful transmission can enter the explore state with probability $P_{explore}$. It is important to note that to avoid constant exploration (and hence constant subchannel switching), $P_{explore}$ decays with time after a user is able to find a CB selection for successful subchannel utilization. The probability $\mathrm{P}_{explore}$ takes into account the data rate on the current subchannel and the likelihood of another subchannel offering an improvement. This is achieved by utilizing the proposed channel quality metric β. In the presence of no interference β is equal to 1, while as interference increases $\beta \to 0$ as $\sum_{k=1,k\neq j}^{I} P_{r,ik} \to \infty$. As the value of β decreases, the potential of improvement to data rate by changing subchannel assignment increases. The metric β therefore 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. For $\zeta = 1$, the parameter has no impact on the $P_{explore}$. However, when $\zeta > 1$, it reduces $P_{explore}$. A careful choice of ζ in $P_{explore}$ 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; 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. $E[\beta]$ reflects the state of the channels visited by a user over period of time and $E[\beta] \to 0$ 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 Eqn. 7 $\mathrm{P}_{explore} \to 0$ also as $E[\beta] \to 0$. 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 is 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 $\mathrm{P}_{persist}$ in the next slot. $P_{persist}$ for such cases is given by:

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

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 $P_{\mathbf{persist}}$: When a user is in the persist state, it means it has been previously successful on it's current subchannel set. When it 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:

$$P_{reduce} = \frac{\beta + T_{lim}(1 - E[\beta])}{2}, \quad (9)$$

where T_{lim} is defined as:

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

where T_{active} is the number of time slots the user has been active in the network, and $\delta > 0$ is a parameter set sufficiently high that the estimate $E[\beta]$ accurately reflects the state of the channels in use. For example, if δ is set to $\delta = 1$ this will mean that even when for the case where the user has been active since only a few time slots $E[\beta]$ will have high influence on reducing CB selection when a user gets unsuccessful in transmissions. However, $E[\beta]$ is an estimate and it would be good for a user to collect more samples of β to have better estimate of $E[\beta]$. Hence, higher values for δ allows a user to take decision of reducing CB selection based on better estimates of $E[\beta]$.

Motivation for the use of $\boldsymbol{P_{\textbf{reduce}}}$: 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 is high, in which case a low SNR is likely the cause of the failed transmission. In the case of lower values of β 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 which in turn decreases the estimate $E[\beta]$. Low values of $E[\beta]$ 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 of the new set is greater than β 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-channel 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-channel model, under the SINR-channel 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.

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

1) 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.

π^{Sig} Method

a) Each user i **part**

Initialize $O_{k=max}$, and each element of the local binary subchannel status bit-map to 0
Update binary subchannel status bit-map 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 part

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

2) Subchannel selection and utilization:

- A user initializes a local binary subchannel status bit-map, the length of which is equal to the total number of usable subchannels. Each element of the bit-map is initialized to 0. The user sets it's current CB order $O_{k,i} = O_{max,i}$.
- After the initialization phase, a user then selects randomly with uniform probability an $O_{k,i}$ order subchannel set out of those subchannel sets that are currently free and its associated PU channel. The user communicates its subchannel selection to the SAS and senses the selected PU channel for the time period T_{sense}. One of two possibilities can occur: 1) The PU channel is found to be occupied; or 2) The channel is free.
- If the channel is found to be occupied, the user remains quiet. If the channel is found free, data is transmitted. One of two possibilities occur: 1) successful transmission; or 2) unsuccessful transmission.
- If the transmission is successful then the user enters a persist state and selects the same

subchannel set in the next time slot.

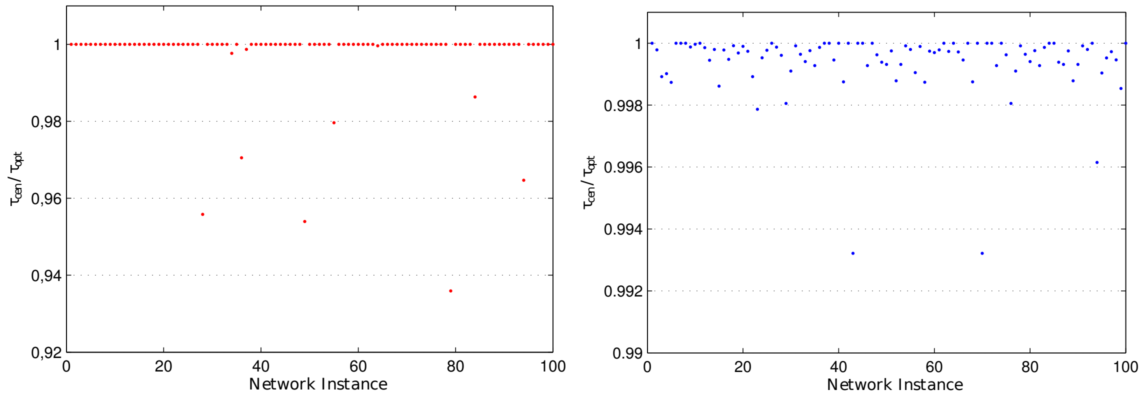
- If the transmission is unsuccessful then the user remains in an explore state. If there is no other subchannel sets of the order $O_{k,i}$ with status 0, according to the local binary subchannel status bit-map , then the user reduces $O_{k,i}$ by 1.
- The user updates the local binary subchannel status bit-map according to the bit-map received from the SAS, and returns to the subchannel selection step.

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:

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



(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.

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 throughput 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 the 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

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

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 V.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 V.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 Eqn. 12. For example, for $I = 4$ users, using Eqn. 12, $\mathbf{P}$ can be calculated as:

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

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.

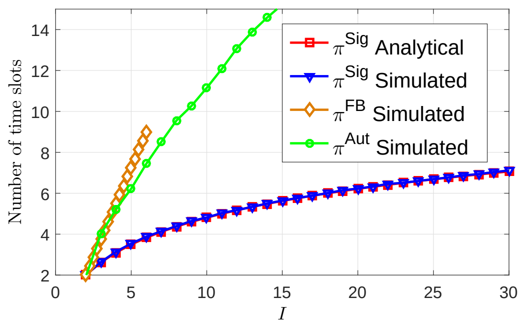


Fig. 4: Expected time to converge to conflict free subchannel selections of the π^{Sig} and π^{FB} methods as a function of I users, under collision-channel model. The number of available subchannels $|\mathcal{S}_p|=I$, and $O_{max,i}=1\forall i$

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-channel model where the number of available subchannels $|\mathcal{S}_p|$

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

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.

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:

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

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. Average sum data rate results are plotted by performing simulations using several Monte Carlo runs and in each Monte Carlo run calculations are done using Eq. 13.

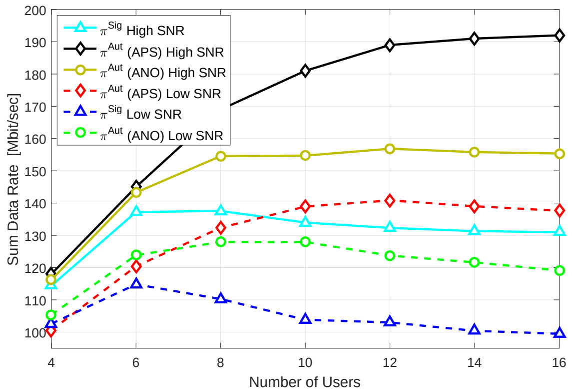


Fig. 5: Average sum data rate achieved by the π^{Aut} and π^{Sig} methods as a function of I, with $|\mathcal{S}_p| = 8$, $N_R = 50m$, and users with heterogeneous CB capabilities. i.e, maximum CB capabilities are uniformly selected from $O_{max,i} = 1$ to $O_{max,i} = |\mathcal{S}_p|$

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 throughput. 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.

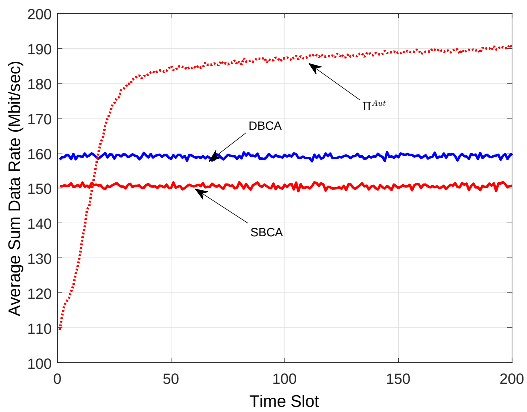


Fig. 6: Performance comparison of the proposed π^{Aut} method with the SBCA and the DBCA methods. Average sum data rate achieved by the methods as a function of time slot index, with $|\mathcal{S}_p| = 8$, $N_R = 50m$, and 8 users with maximum CB capability of bonding 3 subchannels.

In Fig. 6 we present a comparison of average sum data rate achieved by the proposed π^{Aut} method with the SBCA and the DBCA methods. It can be seen from the figure that of the three distributed CB methods, the π^{Aut} method achieves the highest sum data rate for the network. The reason for this is as follows: the SBCA and the DBCA methods do not utilize any adaptation in the choice of CB selections, whereas, the proposed π^{Aut} method utilizes adaptive CB, where adaptations are in the choice of CB selections taking into account the channel quality metric β. The adaptive π^{Aut} method enables the users to select those CB selections that increase the likelihood of achieving higher data rates, as compared to the SBCA and the DBCA methods that do not employ adaptations in CB selection.

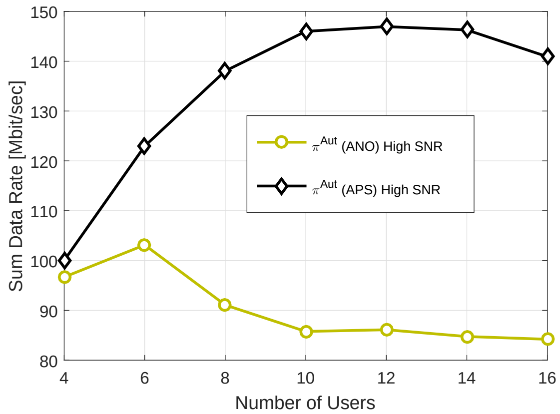


Fig. 7: Average sum data rate achieved by the π^{Aut} under the APS and ANO CB selections as a function of Number of users I, where $|\mathcal{S}_p| = 8$, and ACI$=5\%$. Users are with heterogeneous CB capabilities. i.e, maximum CB capabilities are uniformly selected from $O_{max,i} = 1$ to $O_{max,i}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

Average data rate under adjacent channel interference (ACI):

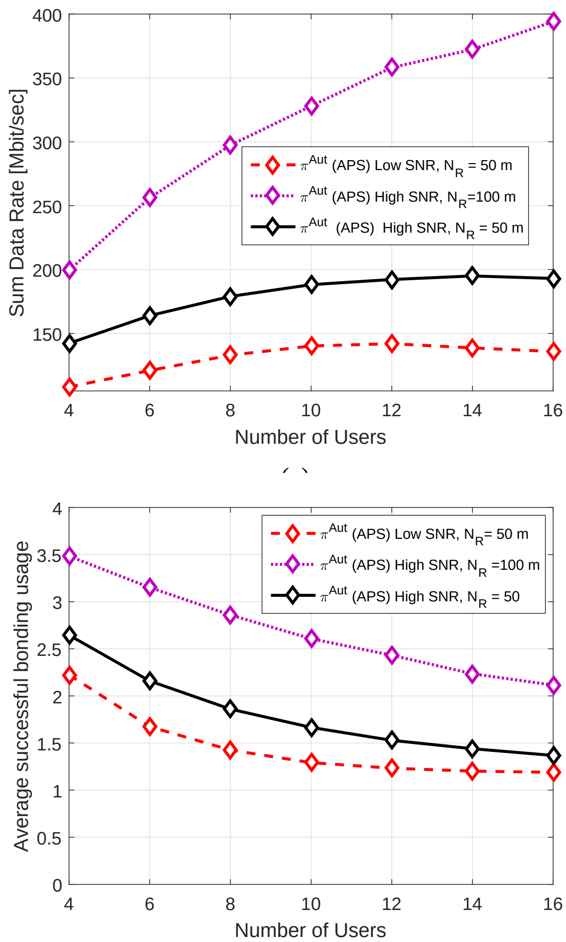
In Fig. 7 we evaluate the impact of Adjacent Channel interference (ACI) on performance of the π^{Aut} method under the APS and ANO CB selections. ACI is set to 5% which means 5% of a user's transmit power is leaked to its adjacent subchannels. We consider high SNR scenario (with the same parameters as 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



(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.

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 average successful bonding order usage is greater than one for all studied cases. However, it is also true that as the ratio of users to available subchannels is increased then the average bonding order that a user can successfully utilize is decreased. When the ratio of users to available subchannels is increased then ultimately there comes a point where CB can be of no benefit to a user as 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 as compared to the scenarios when no bonding is utilized.

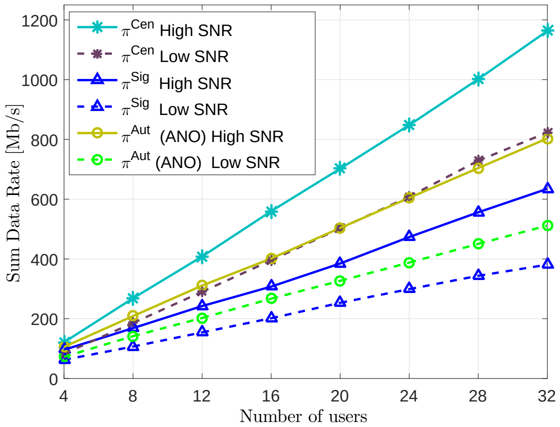


Fig. 9: Average sum data rate comparison between the π^{Aut}, π^{Sig} and the π^{Cen} methods as a function of Number of users I. Number of subchannels is increased with the number of users, i.e., $|\mathcal{S}_p| = I$

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 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

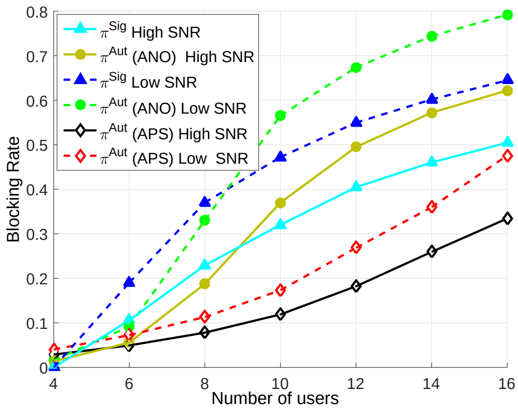


Fig. 10: User blocking rate of the π^{Aut} and π^{Sig} methods as a function of Number of users I

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 channel models to analyze the problem of CB. We present a fully autonomous CB method designed under the SINR channel model, π^{Aut}, in which users utilize only their limited 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 channel 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-channel 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-channel 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-channel 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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