A Dynamic Parallel-rendezvous MAC Mechanism in Multi-rate Cognitive Radio Networks: Mechanism Design and Performance Evaluation

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Abstract— **Parallel rendezvous multi-channel MAC mechanisms are regarded as an efficient method for media access control in cognitive radio networks since they do not need a control channel and use only one transceiver. However, existing parallel rendezvous MAC mechanisms assume that all channels have the same maximum capacity and channel availability for secondary users. In this paper, we propose a dynamic parallel rendezvous multi-channel MAC mechanism for synchronized multi-rate cognitive radio networks in which secondary users jump among different channels according to their own distinct hopping sequences and a node can adjust its hopping sequence according to channel conditions, in order to achieve higher system capacity. A Markov chain based model is designed to analyze the system capacity of the proposed mechanism. Numerical results show that the new mechanism can significantly improve system capacity of cognitive radio networks, compared with the traditional channel hopping MAC mechanisms.**

Index Terms— **Cognitive radio networks, MAC mechanism, Dynamic parallel-rendezvous, Markov chain, Performance evaluation.**

I. Introduction

Electromagnetic radio spectrum is one of the most valuable resources in wireless communications. With rapid increase of the wireless applications and products, unlicensed bands such as Industrial, Scientific and Medical (ISM) and Unlicensed National Information Infrastructure (UNII) have become over-crowded. On the other hand, a large portion of the assigned spectrum is used sporadically and a significant amount of the allocated spectrum remains under-utilized. Cognitive Radio (CR) [1], as a promising solution to efficiently utilize the unused spectrum, has become a hot research topic these days. However, the functions of cognitive radio devices become very limited if they do not form a network. Together with existing legacy infrastructure and/or ad hoc networking devices, CRs can form a Cognitive Radio Network (CRN). This new type of network is built based on CR terminals and wireless networking technologies, and can transport packets to facilitate emerging services and applications.

To form a CRN, Media Access Control (MAC) mechanisms are of great importance, especially for multi-channel CRNs. The MAC mechanisms for CRN can be grouped into two categories: centralized or distributed MAC mechanisms. The most eminent approach for centralized CRN MAC is IEEE 802.22 [2]. In this study, we focus on the distributed mechanisms. Existing distributed multi-channel CRN MAC mechanisms can be further categorized into two classes: single- or parallel-rendezvous MAC mechanisms [12].

For single-rendezvous MAC, it has a control channel as the rendezvous channel and Secondary Users (SUs) can exchange control information and negotiate parameter configurations for data transmission on this channel [4] - [11]. Furthermore, data channel combining technology can be used in control channel based mechanisms. With channel combining technology which can bind data channels that are not used by Primary Users (PUs) together, the MAC mechanisms can use the free spectrum more efficiently [7] [8] [11]. But these mechanisms usually need more complicated hardware which have two radios [7] or one radio and several spectrum sensors [11]. For other single-rendezvous multi-channel mechanisms without using data channel combining technology [5] [6] [9] [10], the control channel, however, can become a bottleneck under operations [3], or they need more transceivers on data channels, e.g., in [9].

Parallel rendezvous MAC mechanisms, on the other hand, do not need a common control channel. The basic idea behind parallel rendezvous mechanisms is that nodes jump among different channels according to their own sequences and the control information is exchanged at different channels when nodes meet. It has been demonstrated that parallel-rendezvous MAC mechanisms, like Multi-channel MAC (McMAC) [12] and Slotted Seeded Channel Hopping (SSCH) [13], generally outperform control channel MAC mechanisms in multi-channel cases [3]. Furthermore, parallel-rendezvous MAC mechanisms do not have a bottleneck like in the single rendezvous case and they are all based on a single transceiver. Parallel-rendezvous MAC mechanisms are originally used in multi-channel ad hoc networks, but have recently been extended to CRN by the authors of [14].

However, existing multi-channel parallel-rendezvous MAC mechanisms in multi-channel ad hoc networks and CRNs do not consider heterogeneous channel conditions. If the channels are unbalanced, for example, when different parameters, like diverse bandwidth and

Manuscript received April 25, 2009; revised August 14, 2009; accepted August 20, 2009.

doi:10.4304/jcm.4.10.752-765

maximum transmission power available for SUs and distinct transmission probabilities of PUs exist in different channels, a method needs to be adopted to adjust the communication according to these parameters. In this paper, we propose a dynamic channel hopping based parallel-rendezvous single transceiver MAC mechanism for synchronized CRNs. The main idea behind this work is to adjust the hopping sequence of SUs according to the datarate and channel availability of these channels. For comparison convenience, we refer to this method as Dynamic Parallel-rendezvous MAC protocol (DPR-MAC) while the method proposed in [14] is referred to as Datarate Independent MAC protocol (DRI-MAC).

The rest of this paper is organized as follows. Section II summarizes related work. Section III presents the proposed MAC mechanism. The system capacity of the proposed MAC mechanism is analyzed in Section IV using a Markov chain model. In Section V, numerical results and comparison with DRI-MAC are given. Finally, the paper is concluded in Section VI.

II. Related work

In this section, we give more detailed descriptions on a few related MAC mechanisms mentioned in Section I, categorized as distributed multi-channel MAC mechanisms: single-rendezvous or parallel-rendezvous.

A. Single-rendezvous MAC mechanisms

In single-rendezvous MAC mechanisms, channels are classified as either control channel or data channels.

1) C-MAC: Cognitive MAC (C-MAC) [10] is a time slotted CR MAC based on one transceiver. Time slotted here means that it splits a time period into different sub-periods for different usages. In this design, super-frames are defined for each channel which is further divided into a data transfer period, beacon period and quiet period. In different periods, nodes have different functions.

In this MAC, there are three type of channels: Rendezvous Channels (RC), Backup Channels (BCs) and data channels. This mechanism needs a control channel but not a dedicated one. To operate this mechanism, the RC is used as a control channel, and BC is the backup for RC. The mechanism chooses the best channel as the RC based on the traffic information obtained from the beacon. Data transmission may occur over different data channels. As a control channel is used, there exists a bottleneck. The selection and rendezvous pattern of RC in multi-hop cases is still a challenging task in C-MAC.

2) OS-MAC: Opportunistic Spectrum MAC (OS-MAC) [6] is a single transceiver based CR MAC mechanism. It needs a common control channel and uses SUs' group formation. The SUs exchange control information in the common control channel and communicate on different data channels. Fixed durations are used to form groups of SUs, to determine their channel occupancy status, and to exchange channel traffic load. In this MAC, there is a channel traffic balancing algorithm that can balance the load among different channels. For new data packets, the mechanism can choose a channel with less load and establish communication on it. However, the complexity of this mechanism is relatively high and the group formation introduces certain amount of overhead for the network.

3) KNOWS: KNOWS [11] is another CR MAC that uses channel combination technology and targets for TV bands. It also needs a dedicated control channel for control information exchange. It demands one transceiver and several spectrum sensors. The transceiver is in charge of control and data packet communications, and the spectrum sensors are responsible for gathering channel information. For data transmission, it combines channels that are not occupied by PUs as one data channel. The advantage of this channel combination is that it can avoid common control channel bottleneck, but the requirement for hardware is much higher, compared with the OS-MAC case.

From the above discussions, we can conclude that the MAC mechanisms that based on single-rendezvous channel (control channel) usually have problems like transmission bottleneck or high demand for hardware complexity.

B. Parallel-rendezvous MAC mechanisms

Different from single-rendezvous MAC mechanisms, parallel-rendezvous MAC mechanisms do not need a control channel and nodes establish communication simultaneously in different channels. The main motivation of parallel-rendezvous is to overcome the single control channel bottleneck problem [3].

1) SSCH: In SSCH [13], nodes jump among channels according to their hopping sequences. The sequences used are uniquely determined by the seed of a pseudo-random generator [3]. Each device picks multiple sequences and follows them in a time-multiplexed manner. For example, when node A has data to B, A waits until it is on the same channel as B. If A frequently wants to send data to B, A adopts one or more of B's sequences, thus increasing the time spend on the same channel. To let this mechanism work, the sender learns the receiver's current sequences via a seed broadcast mechanism.

This MAC is based on multiple sequences and the complexity of the MAC control is relatively high.

2) McMAC: McMAC is also proposed for multi-channel cases initially and it works properly in the 802.15.4 based equipments [12]. The main idea of McMAC is similar to that of SSCH, but the hopping sequence generating strategy of McMAC is simpler. In McMAC, each node has its own unique sequence and the sequence is generated by a pseudo-random generator. The seed of the sequence is the node's own MAC address. The pseudo-random generator that is used in McMAC is the Park-Miller random number generator: $\mathbf{X(t) = 16807 \cdot X(t-1) mod(2^{31}-1)}$, where $X(t)$ means the current number and $X(t-1)$ means the previous number.

Nodes in the McMAC network switch across the channels following their hopping sequences. The sequence of a node is broadcast and if other nodes want to communicate with a particular node, it should follow to the node's sequence and tune to the same channel to establish communication. Since the communication procedure in McMAC is quite similar to the MAC mechanism discussed in the next paragraph, we will describe it in more details there.

3) DRI-MAC: DRI-MAC is quite similar to McMAC but the difference is that it has a quiet period in the beginning of each time slot in order to check the presence of PUs.

In DRI-MAC [14], each SU has its own pseudo-random hopping sequence and switches across the channels following the hopping sequence. SUs decide their own hopping sequence based on their unique ID and share the same hopping sequence generating algorithm. For a given SU, the hopping sequence is fixed. Each SU periodically broadcasts beacons with its own hopping sequences over an unused channel. Once a sender receives the hopping pattern information of the receiver, it can follow the receiver's hopping sequence to meet it if the sender has packets to the intended receiver. A quiet period is introduced in the beginning of each slot. During this period, every SU in difference channels keeps silence and listens to the channel to check whether there is a PU. If PUs are not there, the SUs deem it is proper to use the channel.

Figure 1 illustrates the principle of this parallel-rendezvous MAC mechanism. As illustrated in the figure, the two SUs, A and B, are on Channel 1 and Channel 4 respectively in Time Slot 1 (TS1) and will jump to Channel 3 and Channel 2 in TS2. In TS3, A would jump to Channel 2 if it has no packets to send. As A has data to send to B, A follows B's sequence and jumps to Channel 4 in TS3, instead of jumping to Channel 2. They will stay on the same channel till the transmission finished (as in TS3-TS6). During the transmission period, if PU appears (as in TS5), they will wait until the next slot and transmit if then the channel is idle again (as in TS6).

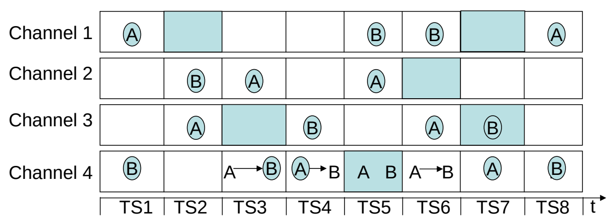

Figure 1. Illustrations of DRI-MAC. The highlighted slots mean that the time slots are used by PUs. A, B are SUs. TS1-8 mean time slots respectively. A, B with a circle denote their predefined hoping pattern.

A common feature of the existing parallel-rendezvous MAC mechanisms is that the sequences used are based on a pseudo-random sequence generator and they are statistically uniform distributed [17], regardless of channel conditions. In the following sections, we will present the DPR-MAC which can adjust the hopping sequence according to the channel parameters considered in order to achieve higher system capacity.

III. DPR-MAC MECHANISM DESCRIPTION

A. Channel model and system assumptions

Assume that each SU has only one transceiver. It means that SUs cannot transmit and receive messages at the same time. The transceiver of SU is Software Defined Radio (SDR) based that can dynamically use the channels assigned to PUs when they are not occupied. The same as in [7], [14], we assume also that there are G channels in the considered network and each channel assigned to PUs follows independent ON/OFF random process. The ON period means that the channel is occupied by the PU and the OFF period presents that the channel is vacant. Each licensed channel is time-slotted such that the PUs communicate with each other in a synchronized manner. The SUs, which are also synchronized with the PUs, opportunistically access the licensed spectrum when it is available [7]. The channel state for the ith channel can be found in Figure 2.

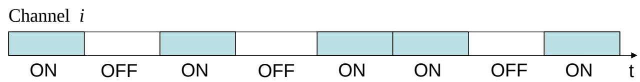

Figure 2. The ON/OFF channel state for the ith channel.

Let α_i be the probability that the ith channel transits from state ON to state OFF and β_i be the probability that the ith channel transits from state OFF to state ON, where $1 \leq i \leq G$. Then the state can be modeled as a simple two-state Markov chain as shown in Figure 3 [7], [14]. Theoretically, the availability of the ith channel for SUs, denoted by γ_i, can be presented as the steady state probability of the corresponding Markov Chain of the OFF state, i.e., the channel is not occupied by the PUs, which can be presented as $\gamma_i = \alpha_i/(\beta_i + \alpha_i)$, $1 \leq i \leq G$.

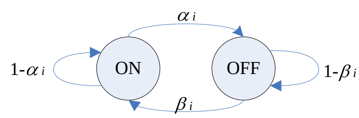

Figure 3. ON/OFF channel state transferring model.

For the ON/OFF channel model, assume that the transceiver of SU can sense precisely the signal of PUs' it receives in a particular channel that it tunes in. It is assumed that the statistic parameters of the PUs', i.e., the ON/OFF percentage in a channel is stable over a long enough time period compared with beacon intervals. The envisaged scenario for this investigation is that SUs are located in a limited geographic area while the coverage and distance scale of PUs are far larger than that of SUs, hence the SUs are covered by the same set of PU systems. This implies that the results of channel sensing by each SU in a particular channel is the same for all SUs. It is further assumed that all SUs are in close enough proximity to be able to communicate with each other using the same modulation scheme within a channel. We do not consider the mobility of SUs in this study.

Before giving the DPR-MAC mechanism description in details, we first discuss the channel parameters considered in DPR-MAC.

B. Channel parameters considered in DPR-MAC design

In conventional multi-channel cases, it is often assumed that the channel conditions are the same, but in CRNs the parameters among channels may be different. We consider two parameters, maximum datarate R_i available for SUs and channel availability γ_i in channel i in our MAC design. In order to protect PUs, the transmission power of SUs should be below a specific value so that the interference generated could be lower than the threshold at the PU receivers[1]. Since the PU equipments and their locations could be different in different channels, the maximum transmission power for SUs in different channels could be different. Besides, the bandwidth that SUs are allowed to utilize may be different from channel to channel. Therefore, each of these channels may have different maximum datarates R_i available for SUs [18]. In addition to R_i, the channel availability, γ_i, may be different in different channels because the usage pattern of these channels by PUs might be different. In real implementation, γ_j in channel j can be estimated by an SU in the following way [15]: $\gamma_j = (i_j(t_o)+1)/(i_j(t_o)+b_j(t_o)+2)$, where $i_j(t_o)$ and $b_j(t_o)$ are the number of time slots that channel j is idle and busy respectively during time period t_o [15].

Considering the above two parameters, we define the channel carrier capability, η_i, as the product of maximum datarate of a channel and its availability for SUs:

$$\eta_i = R_i \times \gamma_i. \tag{1}$$

As defined above, the channel carrier capacity is an indicator which reflects not only the maximum bits per second an SU could transmit but also the percentage of time when this channel can be used by SUs.

C. Dynamic parallel-rendezvous MAC

Like other multi-rendezvous MAC mechanism, the proposed MAC mechanism does not need a control channel. The channel sensing and data transmission strategies of DPR-MAC are similar to that of DRI-MAC. The difference is, however, that the hopping pattern is designed according to the channel carrier capability in our case. In what follows, we will first describe the basic channel hopping sequences and then propose the channel carrier capability aware hopping sequence.

[1]Even if it is assumed that SUs can sense the signal of PUs' transmission precisely, the transmission power of SUs should be limited because PU receivers could be within SUs' interference range but its corresponding PU transmitters could be out of the SUs' sensing range. In this case, although a channel is sensed as idle, the transmission power of SUs should be kept within a threshold in order to protect the potential PU receivers in that channel.

1) Basic hopping sequence: We adopt the sequence generation method that is used in McMAC [12] to generate basic sequences. To reduce computational overhead, the length of the sequence should be fixed to a particular value as at least 10 times larger than the number of channels [12].

2) Channel carrier capability aware hopping sequence: SUs use their basic channel hopping sequences to switch across different channels but they may deviate from their basic sequences when the channel carrier capability η_i are different among channels. More specifically, a portion of the basic hopping sequence should be adjusted according to η_i, while the rest of the sequence will still remain on the basic hopping sequences. For example, there are two channels that offer different datarates for SUs. The carrier capability of Channel 1, η_1 is higher than that in Channel 2, η_2. Suppose a snapshot of an SU's basic hopping sequence is [1, 2, 2, 1, 2, 1, 1, 2], which means that initially SUs will jump evenly between Channel 1 and Channel 2. According to DPR-MAC, however, as $\eta_1 > \eta_2$, more hops will be preferred to be allocated in Channel 1. The resulted sequence could then look like [1, 2, 1, 1, 2, 1, 1, 1], which leads to higher chance for channel access of Channel 1.

At the same time, the adjustment method must be carefully designed to avoid the phenomenon of co-behaviors which means that most SUs may end up all adjustment to the same channel which has the highest channel carrier capability. This undesired phenomenon not only induces congestion in that channel and degradation to throughput, but also wastes channel vacancy. We present the following method to avoid this phenomenon.

Assume that the carrier capability of the ith channel is η_i, $1 \leq i \leq G$. Let SU(i) be the SU that jumps onto the ith channel according to its basic hopping sequences in its next hop. Let $\overline{\eta} = \sum_{j=1}^{G} \eta_j / G$ and $A = \{Channel\ j | \eta_j > \overline{\eta}, j = 1 \cdots G\}$. The deviation method works as follows:

1. If $\eta_i \geq \overline{\eta}$, SU($i$)s which will jump onto channel i will remain in the basic sequence and do not deviate from channel i.

2. Else

(1) With probability $\eta_i/\overline{\eta}$, SU(i)s which plan to jump onto channel i will remain in the basic hop and do not deviate from channel i.

(2)With probability $(1 - \eta_i/\overline{\eta}) \cdot (\eta_j - \overline{\eta}) / \sum_{k \in A}(\eta_k - \overline{\eta})$, SU($i$)s will select channel j, $j \in A$.

Following above mentioned steps, SUs will jump according to the channel carrier capability η_i instead of equal chance access of the available channels, and the co-behavior problem is also avoided. The proof is given in Appendix A.

3) Beacons advertisement: An SU generates and uses the basic hopping sequence first. Based on its own observation and the basic hopping sequence, the SU can make a decision on which hops need to be adjusted according to the above algorithm. It then needs to inform the others the adjustment results in its periodical beacons. Since there is no control channel, the beacon message cannot be received by SUs that are not in the current beacon-sender's channel. In order to let most SUs receive the beacon message earlier with minimal overhead, we adopt the following dissemination scheme considering two cases according to the number of SUs in the network. Denote the number of SUs as N. If the number of SUs is few, i.e., $N \leq 2G-1$, we adopt scheme one. When $N > 2G-1$, scheme two is adopted. The reason for distinguish these two cases is that if the second scheme is adopted when $N < 2G-1$, the number of beacons generated according to scheme two will be larger than when scheme one is used. The goal of the beacon dissemination scheme is to inform as many SUs as possible in the network about the adjusted sequence, within as short beacon intervals as possible.

(1) $N \leq 2G-1$: An SU transmits beacon information to all these SUs in a unicast way, i.e., informs its new sequence to others one by one individually based on each node's hopping sequence. In this scheme, there are altogether $N-1$ beacons generated.

(2) $N > 2G-1$: In this scheme, there are three steps:
a) An SU selects $G-1$ other SUs according to its local information about other SUs' current hopping sequences such that in a particular time slot, named as planned slot, these SUs, including the original SU itself, can cover all these G channels. If these SUs cannot cover all G channels, it chooses a slot that SUs spread on different channels to the largest extent.
b) The SU unicasts the beacon information to these $G-1$ selected SUs and let them re-broadcast the beacon information on behalf of the original SU in the planned slot. In this beacon information, the IDs of the channels onto which the original SU wants the other SUs to broadcast are also included.
c) When the planned time slot arrives, these SUs will re-broadcast the beacon together on those channels. If there are other packets waiting for transmission, the SU will broadcast the beacon message first.

If a particular channel is occupied by PUs or on-going SU transmissions, or the SUs which are responsible for broadcasting on that channel are transmitting or receiving on another channel at that planned slot, these SUs can broadcast the beacon in the planned slot of the next hopping sequence period. The new hopping sequence for an SU is validated at the beginning of the next beacon interval. With this scheme, there are altogether $2G-1$ beacons generated.

4) Negotiation and transmission: Each SU keeps a queue for each destination to avoid head-of-line blocking [12], which occurs whenever traffic waiting to be transmitted prevents or blocks traffic destined elsewhere from being transmitted. In each slot, if it is not occupied by a PU, SUs can negotiate for data transmission. Negotiation is needed because an intended receiver may be in another channel as a transmitter. Therefore there is a risk of packet loss if data is transmitted directly. Without negotiation, furthermore, it is possible that two or more transmitters jump onto the same channel for data transmission, resulting in collision. Negotiation which is done after the quiet period, can avoid such potential collisions. When negotiations are successfully done, data transmission can be carried out.

If two SUs cannot finish their transmission within a time slot, they will continue using the same channel for data exchange at the next time slot, which escapes the switching penalty. An ongoing transmission between two SUs may be interrupted by sudden channel occupancy of PUs. In this case, the communicating pairs will pause and hold transmission if the channel is occupied by any PUs again during their data transmission. In order to guarantee that the not-yet-finished transmission has the highest priority, the unfinished transmission can start immediately after the quiet period while new transmitters will sense the channel after the quiet period and negotiate for transmission.

IV. SYSTEM CAPACITY ANALYSIS

In this section, we analyze the system capacity of the DPR-MAC. System capacity here means the total amount of bits per second the SUs in this system can obtain, considering injected traffic load into the system and specific value of channel carrier capability. For ease of expression, we assume there are two types of channels with maximum datarate R_1, R_2 and channel availability γ_1, γ_2 respectively, each type having M channels. Thus the total number of channels is $2M$. Furthermore, it is also assumed in this analysis that there is no sensing failure in the channel sensing stage. The analysis is based on the situation when the adjustment information of SUs is ideally distributed. Table I gives the parameters used in the system capacity analysis.

Assume further that in different nodes, the average data flow length generated *in bytes* is the same and that the data flow length, which is integer multiples of the time slot length follows independent geometrical distribution. Since there are two type of channels with different datarates, different channel datarates will introduce different data flow length in number of time slots, i.e., different value of μ in geometrical distribution, denoted as μ_1 and μ_2. The probability of the length L_i of a data flow in time slots can therefore be expressed as $P(L_i = l_i)$=$\mu_i(1-\mu_i)^{l_i-1}$, $i = 1, 2$ for channel type 1 and 2 respectively. Since a data flow is transmitted on the same channel, it has the same μ during its transmission, no matter how many slots it takes.

Denote the switching penalty as T_{sw}. The switching penalty happens only at the first time slot of a successful communication session. Therefore, the average switching penalty with the number of time slots that a data transmission uses in channel type 1 and 2 is adopted as $\overline{T}_{sw}^{i} = T_{sw}/\overline{L_i}$, where $\overline{L_i}$ is the average number of slots that a data flow transmission takes in channel type i, $i = 1, 2$. Denote the datarate, the length of time slot, and the length of quiet period by R_i, T_s, and T_q. The average flow length in bytes can be presented by

TABLE I.
PARAMETERS FOR PERFORMANCE ANALYSIS.

Notation	Parameters Description
$2M$	The number of channels in 2 kinds; M channels for R_1 & R_2 respectively. $G = 2M$.
N	The number of SUs.
N_r	The total number of SUs that is ready to transmit or receive at the beginning of the tth slot on all channels.
u_i	The number of SU pairs that successfully negotiate in the tth slot in channel type i, $i = 1, 2$.
v_i	The number of SU communication pairs that finish data exchange at $(t-1)$th slot in channel type i, $i = 1, 2$ and become ready at the beginning of the tth slot.
c_i	The number of channels which have at least one idle potential receiver in the tth slot in channel type i, $i = 1, 2$.
e_i	The number of idle channels in the tth slot in channel type i, $i = 1, 2$.
d_i	The number of channels that are idle and have at least one idle potential receiver in them in the tth time slot in channel type i, $i = 1, 2$.
k_i	The number of communication pairs in the $(t-1)$th slot in channel type i, $i = 1, 2$.
m_i	The number of communication pairs in the tth slot in channel type i, $i = 1, 2$.
w	The number of SUs that have data to send in the tth slot.
λ	The probability that an idle SU generates data flow.
μ_i	The probability that a pair of transmitting SUs finish data exchange and release the channel in channel type i, $i = 1, 2$.
γ_i	The probability that the PUs do not use the channels in channel type i, $i = 1, 2$.

$(T_s - T_q - \overline{T_{swi}}) \cdot R_i/\mu_i$, where $i = 1, 2$. Given $T_s >> \overline{T_q}$ and $T_s >> \overline{T}^i_{sw}$, for the same average length of data flow in bytes, we can ignore $\overline{T}^i_{sw}$ and approximately get that $R_i/R_j = \mu_i/\mu_j$, $\forall \mu \leq 1$.

Based on the above discussions, in any time slot, the system state can be presented by the number of SU communicating pairs in two types of channels, i.e., (P_1, P_2). We can use a discrete-time Markov chain to analyze the system capacity. State transfer happens when at least one communication pair finishes transmission or a pair begins to transmission in either of these two channel types. Figure 4 presents a Markov chain in the case that there are two types of channels, and each type has only one channel in it. The first element presents the number of communicating pairs in channel type 1 and the second one presents that in channel type 2. For example, state 10 means that there is one communicating pair in channel type 1 and no communicating pair in channel type 2. In this example, there is only one channel of each type, the number of each element is up to 1 and there are altogether 4 states. It is easy to extend it to two types of channels with several channels in each type and the difference is that the number of states of the Markov chain will be much larger.

In the following subsections, we will deduce first the state transfer probability of the Markov chain from $t-1$ to t, i.e., $P(m_1, m_2|k_1, k_2)$ and then get the steady state probability $\pi_{i,j}$, where $i, j \in [0, M]$. Finally, based on the probabilities obtained, the system capacity can be calculated.

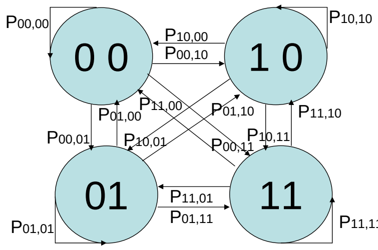

Figure 4. A Markov chain model for system capacity analysis.

A. State transition probability

Given the number k_1 of communicating pairs in the $(t-1)$th time slot in channel type 1, the number v_1 of communicating pairs that become ready at the beginning of tth time slot follows binomial distribution, i.e., $P(v_1|k_1) = \binom{k_1}{v_1}(\mu_1)^{v_1}(1-\mu_1)^{k_1-v_1}$, $0 \leq v_1 \leq k_1$. The expression is similar for channel type 2. Then the number of nodes that is ready to transmit or receive at the beginning of the tth time slot N_r is: $N_r = N - 2(k_1 - v_1) - 2(k_2 - v_2)$, $0 \leq k_1, k_2, \leq \phi$, $\phi = min(M, N/2)$. The probability that w number of SUs have data to send at the tth time slot can be presented as $P(w|k_1, v_1, k_2, v_2) = \binom{N_r}{w}\lambda^w(1-\lambda)^{(N_r-w)}$, where $0 \leq w \leq N_r$. The number of idle SUs which are ready to receive data, denoted by potential receiver X_r, is $X_r = N_r - w$. Statistically, the idle SUs in channel type 1 and 2 denoted as X_{r1} and X_{r2} will be $X_{r1} = ||\eta_1/(\eta_1+\eta_2) \cdot X_r||$ and $X_{r2} = X_r - X_{r1}$.

Denote by $P(c_1|k_1, v_1, X_{r1})$ the conditional probability of c_1 number of channels onto which at least one idle potential receiver will jump at the tth time slot, given that there are X_{r1} SUs potential receivers in channel type 1. This is analogous to put X_{r1} balls into M urns and then get the probability that there is c_1 urns that are not empty. The solution can be found in [14] even though there is a slight difference[2], as shown in Appendix B. As the probability of c_1 is not correlated to k_1, v_1, given X_{r1}, we get $P(c_1|k_1, v_1, X_{r1}) = P(c_1|X_{r1})$. The same result applies to channel type 2.

Denote by $P(e_1|k_1, v_1, X_{r1}, c_1)$ the probability that there are e_1 number of the idle channels in channel type 1, given that there are k_1 communication pairs in $(t-1)$th time slot and v_1 pairs of SUs that have finished communications at the end of $(t-1)$th time slot. Then,

$$\begin{aligned} &P(e_1|k_1, v_1, X_{r1}, c_1) = P(e_1|k_1, v_1) \\ &= \tbinom{M-k_1+v_1}{e_1}\gamma_1^{e_1}(1-\gamma_1)^{M-k_1+v_1-e_1}. \end{aligned} \tag{2}$$

Denote by $P(d_1|k_1, v_1, X_{r1}, c_1, e_1)$ the conditional probability that d_1 number of the channels that are idle and have at least one idle potential receiver, given e_1 idle channels and c_1 channels that have at least one idle

[2]In [14], capacity calculation of channel with exactly one transmitter is considered. In our analysis, we consider the channels with one or more available potential receivers, which include the situation that several transmitters may contend for channel access at the same time slot on the same channel. The successful communication pair will still be only one after the negotiation process.

potential receiver in channel type 1. According to the hypergeometric distribution [3], [14], we obtain

$$P(d_1|k_1, v_1, X_{r1}, c_1, e_1) = P(d_1|c_1, e_1) = \binom{e_1}{d_1}\binom{M-e_1}{c_1-d_1}/\binom{M}{M-c_1}, \quad (3)$$

where $0 \leq d_1 \leq c_1$.

For channel type 1, combining the above two equations, we get

$$P(d_1|k_1, v_1, X_{r1}, c_1) = P(d_1|k_1, v_1, c_1) = \sum_{e_1=0}^{M-k_1+v_1} P(d_1|c_1, e_1)P(e_1|k_1, v_1) \quad (4)$$
$$= \sum_{e_1=0}^{M-k_1+v_1} \frac{\binom{e_1}{d_1}\binom{M-e_1}{c_1-d_1}}{\binom{M}{M-c_1}} \binom{M-k_1+v_1}{e_1}\gamma_1^{e_1}(1-\gamma_1)^{M-k_1+v_1-e_1}.$$

We approximate the probability that a receiver has data flow to be sent by a transmitter with $w/(N-1)$ [3]. Then we can approximately[3] calculate the probability that u_1 number of the SUs pairs that successfully negotiate on these d_1 channels at the tth time slot [14], $P(u_1|k_1, v_1, w, c_1, d_1)$, as

$$P(u_1|k_1, v_1, w, c_1, d_1) = P(u_1|k_1, v_1, w, d_1) = \binom{d_1}{u_1}\left(\frac{w}{N-1}\right)^{u_1}\left(1-\frac{w}{N-1}\right)^{d_1-u_1}. \quad (5)$$

Since $u_1 = m_1 - (k_1 - v_1)$, we give the probability

$$P(m_1|k_1, v_1, w, c_1, d_1) = \binom{d_1}{m_1-(k_1-v_1)}\left(\frac{w}{N-1}\right)^{m_1-(k_1-v_1)}\left(1-\frac{w}{N-1}\right)^{d_1-(m_1-(k_1-v_1))}. \quad (6)$$

For channel type 1, by using the Eqs. (4) and (6), and $P(c_1|X_{r1})$, we can obtain that

$$P(m_1|k_1, v_1, w, Xr_1) = \sum_{c_1=0}^{M}\sum_{d_1=0}^{c_1} P(m_1|k_1, v_1, w, c_1, d_1) \times P(d_1|k_1, v_1, X_{r1}, c_1)P(c_1|X_{r1}). \quad (7)$$

Similar expression for Eqs. (2)-(7) can be easily found for channel type 2.

Note that $P(m_1|k_1, v_1, w, Xr_1)$ and the corresponding $P(m_2|k_2, v_2, w, Xr_2)$ are probabilities analyzed in different types of channels and they are independent. Thus the joint probability can be expressed as

$$P(m_1, m_2|k_1, v_1, k_2, v_2, w, Xr_1, Xr_2) = P(m_1|k_1, v_1, w, Xr_1) \cdot P(m_2|k_2, v_2, w, Xr_2). \quad (8)$$

With our hopping sequence adjustment method, statistically, the probability of Xr_1 and Xr_2 can be expressed as

$$P(X_{r1} = j, X_{r2} = N_r - w - j) = \binom{N_r-w}{j}(\eta_1/(\eta_1+\eta_2))^j(\eta_2/(\eta_1+\eta_2))^{N_r-w-j}. \quad (9)$$

[3]For simplicity, we approximate that the utilization probability of idle channels with more than one potential receiver is the same as the case with only one potential receiver in the analysis, since differentiating channels according to the number of potential receivers will introduce extreme complexity in the analysis. However, we are aware of that it is less likely that several intended receivers will be unavailable at the same time in practice.

Then, we can obtain

$$P(m_1, m_2|k_1, v_1, k_2, v_2, w) = \sum_{j=0}^{N_r-w} P(m_1, m_2|k_1, v_1, k_2, v_2, w, Xr_1, Xr_2) \times P(X_{r1} = j, X_{r2} = N_r - w - j). \quad (10)$$

It is obviously that $P(v_1|k_1)$ and $P(v_2|k_2)$ are independent, then it is found that

$$P(v_1, v_2|k_1, k_2) = P(v_1|k_1)P(v_2|k_2). \quad (11)$$

With the help of $P(w|k_1, v_1, k_2, v_2)$, we can finally compute

$$P(m_1, m_2|k_1, k_2) = \sum_{v_1=0}^{k_1}\sum_{v_2=0}^{k_2}\sum_{w=0}^{N_r} P(m_1, m_2|k_1, v_1, k_2, v_2, w) \times P(w|k_1, v_1, k_2, v_2)P(v_1, v_2|k_1, k_2). \quad (12)$$

B. Steady-state probability

Known the transition probabilities, we can calculate the probability for steady-state of the Markov chain. The steady-state probability is given by

$$\Pi = \Pi\mathbf{P}, \quad (13)$$

where Π is a row vector whose elements, $\pi_{i,j}$, sum to 1 as shown in Eq. (14), and $\pi_{i,j}$ is the steady-state probability with i and j communicating pairs in channel type 1 and 2 respectively. **P** is the transition matrix, formed by $P(m_1, m_2|k_1, k_2)$, as

$$\mathbf{P} = \begin{bmatrix} P(0,0|0,0) & P(0,1|0,0) & \cdots & P(M,M|0,0) \\ P(0,0|0,1) & P(0,1|0,1) & \cdots & P(M,M|0,1) \\ \vdots & \vdots & \vdots & \vdots \\ P(0,0|M,M) & P(0,1|M,M) & \cdots & P(M,M|M,M) \end{bmatrix}.$$

The sum of all probabilities would be unity, as

$$\sum_{i,j} \pi_{i,j} = 1. \quad (14)$$

By solving Eqs. (13) and (14), we can find all steady-state probabilities, $\pi_{i,j}$, for $0 \leq i, j \leq M$.

If the Markov chain is irreducible and aperiodic, then there is a unique stationary distribution. In this case, $\mathbf{P}^\kappa$ converges to a rank-one matrix in which each row is the steady distribution Π, i.e.,

$$lim_{\kappa \longrightarrow \infty}\mathbf{P}^\kappa = \mathbf{E}\Pi, \quad (15)$$

where **E** is the column vector with all entries equaling to 1 and κ is the exponent of **P**. This character of Markov chains can be used to verify the validity of our analysis[4].

C. System capacity

The transmissions that are not finished in $(t-1)$th time slot may be buffered in the tth time slot because of the presence of PUs. Denote $\overline{N_{t1}}(k_1, v_1, \gamma_1)$ as the average number of ongoing communication pairs of SU that exchange data in tth time slot in channel type 1 [14] as,

$$\overline{N_{t1}}(k_1, v_1, \gamma_1) = \sum_{i=0}^{k_1-v_1} i\binom{k_1-v_1}{i}\gamma_1^i(1-\gamma_1)^{k_1-v_1-i}. \quad (16)$$

[4]Indeed, we calculated $lim_{\kappa \longrightarrow \infty}\mathbf{P}^\kappa$ and find that it converges to Π and $\sum_{i,j}\pi_{i,j} = 1$ from the numerical results. The validity of the analysis is therefore verified.

Then the total system capacity, denoted as S which is the sum of data transmitted over channel type 1 and 2, denoted as S_1 and S_2, can be expressed as:

$$S = S_1 + S_2. \tag{17}$$

where

$$S_1 = (T_s - \overline{T_{sw1}} - T_q) \cdot R_1/T_s \times \sum_{k_1=0}^{\phi}\sum_{k_2=0}^{\phi}\sum_{m_1=0}^{\phi}\sum_{m_2=0}^{\phi}\sum_{v_1=0}^{k_1}\sum_{v_2=0}^{k_2} P(k_1,m_1,v_1,k_2,m_2,v_2)\times [\overline{N_{t1}} + m_1 - (k_1 - v_1)], \tag{18}$$

and

$$\begin{aligned} P(k_1,m_1,v_1,k_2,m_2,v_2) &= P(m_1,v_1,m_2,v_2|k_1k_2)\pi_{k_1,k_2} \\ &= P(v_1,v_2|k_1,k_2,m_1,m_2)P(m_1,m_2|k_1k_2)\pi_{k_1,k_2} \\ &= P(v_1,v_2|k_1,k_2)P(m_1,m_2|k_1k_2)\pi_{k_1,k_2}. \end{aligned} \tag{19}$$

Similar expressions can be found for S_2 from Eqs. (16), (18) and (19).

The above analysis result can also be extended to a more general case where there are more than two types of channels. That is, denote N_c as the number of channel types, we can form a Markov chain with N_c elements and each element stands for the number of communicating pairs on channels with the same datarate. In this case, Eq. (9) should be revised as a multinomial distribution instead of binomial distribution, as shown in Eq. (20).

$$P(X_{r_1} = x_{r_1}, X_{r_2} = x_{r_2}, \cdots X_{r_{N_c}} = x_{r_{N_c}}) \tag{20}$$
$$= \begin{cases} \frac{(N_r-w)!}{x_{r_1}!\cdots x_{r_{N_c}}!} & (\frac{\eta_1}{\eta_1+\cdots\eta_{N_c}})^{x_{r_1}}\cdots(\frac{\eta_{N_c}}{\eta_1+\cdots\eta_{N_c}})^{x_{r_{N_c}}}, \\ & when \sum_{i=1}^{N_c} x_{r_i} = N_r - w. \\ 0, & otherwise. \end{cases}$$

Correspondingly, Eq. (10) can be expressed as:

$$\begin{aligned} &P(m_1,\cdots m_{N_c}|k_1,v_1,\cdots k_{N_c},v_{N_c},w) \\ &= \sum_{\sum_{i=1}^{N_c} x_{r_i}=N_r-w} P(X_{r_1} = x_{r_1}, X_{r_2} = x_{r_2}, \cdots X_{r_{N_c}} = x_{r_{N_c}}) \\ &\times P(m_1,\cdots m_{N_c}|k_1,v_1,\cdots k_{N_c},v_{N_c},w,X_{r_1},\cdots X_{r_{N_c}}). \end{aligned} \tag{21}$$

Other parts of the analysis when there are more than two types of channels are quite similar to that of two types of channels. With the analysis of probability, we can find the steady state of Markov chain and finally get the total system capacity in this more complicated case.

D. An estimation of beacon messages dissemination

In this subsection, the probability of the beacon messages dissemination after a given period is estimated, and the probability of a particular node that can receive the beacon information after a certain numbers of beacon intervals is also given. In this estimation, we focus on the second scheme in Subsection III. C. 3), when $N > 2G-1$.

Assume that there are two types of channels with the same channel availability γ but different datarates R_1 and R_2, and $R_1 > R_2$. Let $P_{og,2}$ be the probability of an SU transmission that has not finished in the previous time slot in channel type 2. Given the same flow length in bytes and traffic load in both of the channel types, the same probability for channel type 1, $P_{og,1}$, could be expressed as $P_{og,2}R_2/R_1$. For the simplicity of estimation, we consider the stage when uniform distributed hopping sequences are used in our following calculation.

1) Probability for successful beacon dissemination: Since the second step in scheme 2 consumes time in slots scale while the third step uses time in hopping sequence periods scale, we consider the dissemination period used for SUs broadcasting beacon messages in the planned slot on behalf of the original SU. As the beacon dissemination time is determined by the latest distributed beacon on a channel, we analyze the probability for channel type 2, i.e., the low datarate channel. On a low-datarate channel, the probability that a channel is occupied could be expressed as $P_{occ} = 1 - \gamma + \gamma P_{og,2}$. The probability, $P_{succ|idle}$, that an SU can successfully broadcast the beacon in the planned slot when the channel is idle is $P_{succ|idle} = (1 - \frac{2MP_{og,1}+2MP_{og,2}}{N})P_{access}$, where $P_{access} = min(1, \frac{G}{N-2MP_{og,1}-2MP_{og,2}})$, and it is the probability that the SU can successfully access the channel in the worst case when all the SUs within that channel are receivers, given the equal channel access probability of each SU on that channel. Then the successful beacon transmission probability in a planned slot can be obtained by $P_{succ} = P_{succ|idle}P_{idle} = P_{succ|idle}(1 - P_{occ})$. The successful transmission probability after ι planned slots, i.e., ι hopping sequence periods, $P_{succ,\iota}$ could be expressed as $P_{succ,\iota} = 1 - (1 - P_{succ})^{\iota}$. Given the length of hopping sequence and time of each slot, the probability of the beacon messages dissemination after a particular time can then be estimated.

2) Probability of beacon information reception for an SU: In this paragraph, we estimate the probability of a particular node that can successfully receive beacon information after a beacon broadcast period. According to the scheme, we can imagine that the best case is that the beacon could be sent in the planned slot simultaneously on all these channels, and all the SUs can hear it. The worst case happens when beacons on different channels occur in planned slots in different sequence periods.

When an SU unicasts the beacon to another SU, the probability that an SU on the same channel happens to overhear the beacon, P_{oh}, is $(1 - \frac{2MP_{og,1}+2MP_{og,2}}{(N-1)})/G$. After this procedure, the probability, P_{unic}, which indicates the cases when an SU does not receive the beacon is $\frac{N-1-(G-1)}{N-1}(1 - P_{oh})^{G-1}$. When an SU broadcasts the beacon on the SU's channel according to the SU's sequence in a planned slot, the probability, P_{no_hm}, that the SU happens not to be on that channel is $\frac{2MP_{og,1}+2MP_{og,2}}{N-1} + \lambda_o(1 - \frac{2MP_{og,1}+2MP_{og,2}}{N-1})$, where λ_o is the probability that the SU leaves the sequence denoted channel. The probability, P_{out}, that when the same beacon is broadcast on other channels and the SU happens to hear it is $\lambda_o(1 - \frac{2MP_{og,1}+2MP_{og,2}}{N-1})\frac{1}{N-1}\frac{N}{G}$. Then the probability, P_{no_recv} that an SU cannot recieve a beacon can be expressed as: $P_{unic}P_{no\_hm}(1 - P_{out})^{G-1}$. The probability that a beacon was received after a beacon interval is 1-P_{no_recv}. Then the probability that after U intervals could be approximated[5] by $1 - P^U_{no\_recv}$.

V. Numerical Results and Discussions

In this section, based on the analysis in IV, the numerical results and comparison of DPR-MAC and DRI-MAC are given. We investigate the performance in term of system capacity with respect to channel datarate, channel availability, and channel carrier capability. In the first part we assume that the two kinds of channels have the same value of channel availability γ, i.e., $\gamma_1 = \gamma_2$, and the results are according to the channel datarate R_i. In the second part we will show the results that the two types of channels have the same datarate but different channel availabilities γ_i. In the third part we give the results with both different channel availabilities γ_i and different datarates R_i, namely, channel carrier capability. The last part is the overhead and the beacon dissemination estimation.

A. Performance evaluation given identical channel availability γ

1) Parameters configuration: In this section, we will give the results when the two kinds of channels have the same channel availability γ but with different datarates R_i. The parameters used to calculate the system capacity is as follows: $T_s = 1000\ \mu s$, $T_q = 10\ \mu s$, $T_{sw} = 100\ \mu s$, $R_1 = 2\ Mbps$, and $R_2 = 10\ Mbps$. With this time slot and datarate, it is enough to finish negotiation in a small portion of a time slot [3] and we have also $T_s >> T_q$ and $T_s >> \overline{T}^i_{sw}$, which are in accordance with the discussions in Section IV.

2) System capacity as a function of λ: Fig. 5 depicts the system capacity according to λ by using the DPR-MAC and DRI-MAC protocols, where the number of channels at each carrier capability is set as $M = 3$ and $M = 4$ respectively. Other parameters are fixed as $N = 20$, $\gamma = 0.7$ and $\mu_1 = 0.05$, $\mu_2 = 0.25$. With these parameter settings, we can estimate that the average data flow length is $2Mbps * (1000\mu s - 10\mu s - 100\mu s/20)/0.05/8 \approx 5KB$. This implies that the time slots needed for transmitting this data flow are respectively 20 slots at R_1 and 4 slots at R_2, on average.

From Fig. 5, one can observe that the system capacity is 0 when $\lambda = 0$ or 1. This is because that when $\lambda = 0$, there is no traffic and in the case of $\lambda = 1$, there are no receivers. When $\lambda = 1$, all SUs have data to transmit. SUs will leave their own channels and come to the intended receivers' channels for communication. In this case, theoretically, every SU deviates from its hopping sequence denoted channel thus these SUs cannot find each other. When λ is small, SUs do not generate many data flows. This means that the totally generated traffic load by SUs is so light that it does not even saturate the channels that have lower datarate. As a result, the system capacity difference between these two MAC protocols is not significant in this case, with both $M = 4$ and $M = 3$. However, when traffic load becomes heavier, the advantage of the proposed mechanism is evident. As shown in Fig. 5, over a wide range of λ, significant system capacity improvement has been achieved by DPR-MAC, compared with what is obtained by its counterpart, DRI-MAC. For example, at $\lambda = 0.5$, DPR-MAC reaches capacity of 16 $Mbps$ while 14 $Mbps$ is obtained by DRI-MAC, indicating that an improvement of 14% has been achieved.

[5]Since after the first beacon interval, the SU will use the new adjusted sequence, then the probability is an approximation.

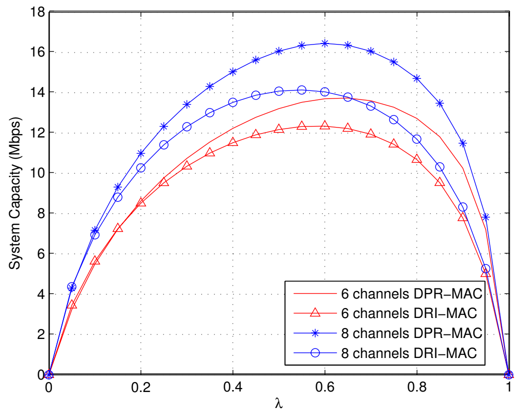

Figure 5. System capacity comparison of DPR-MAC and DRI-MAC as a function of λ.

Comparing the difference between $M = 3$ and $M = 4$, one can observe that when the channel number is larger, the enhancement is more significant. This is because that when M is greater, more channels with high datarate are available for SUs. With our proposed method, SUs get better chance to transfer their data flows over the higher datarate channel, leading to increased total system capacity.

Note also that in [14], the peak value of system capacity is achieved around $\lambda = 0.25$ and the system capacity becomes lower when λ gets larger. It is because that in [14] it calculates the channels with exact one transmitter in $P(c_1|k_1, v_1, X_{r1})$. When the sending probability (λ) becomes larger, the probability of channels with exact one transmitter will be lower. Consequently, the system capacity is lower. In contrast, in our scheme, we consider the channel with one or more potential receivers (see footnote 2), which means that the number of channels that has two or more transmitters are also counted in, because after negotiation these channels can also be used. Consequently, the DRI-MAC curves shown in Fig. 5 are also obtained considering one or more receivers. Therefore, the peak value is obtained when λ is around 0.55 for DRI-MAC.

3) Impact of PUs channel occupancy on system capacity: Fig. 6 shows the performance with different value of channel availability γ, when $\lambda = 0.7$, $N = 20$ and $\mu_1 = 0.05$, $\mu_2 = 0.25$. The differences between the system capacity achieved by DPR-MAC and DRI-MAC grow with the rising of γ. The enhancement between the two methods when $M = 4$ is larger than that when

$M = 3$, which means the proposed method is more beneficial when the number of channels is larger.

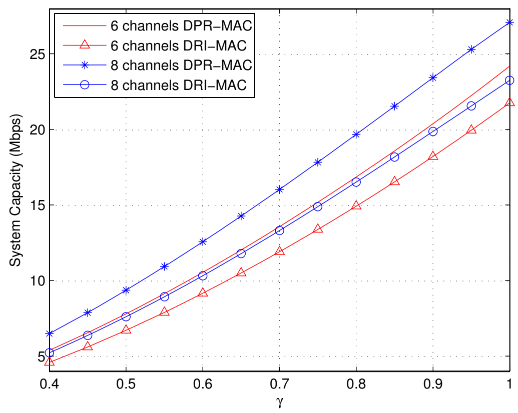

Figure 6. System capacity comparison of DPR-MAC and DRI-MAC as a function of γ.

When $\gamma = 1$, which means that there are no PUs in the channels, the maximal system capacity and the enhancement between the two methods are observed. In this case, when all channels are available for SUs, an improvement of 17.5% and 11.2% has been observed for $M = 4$ and $M = 3$ respectively.

4) Impact on system capacity by the number of SUs: Fig. 7 shows the system capacity of DPR-MAC and DRI-MAC with the number of SUs N when $\lambda = 0.7$, $\gamma = 0.7$, $\mu_1 = 0.05$, $\mu_2 = 0.25$. In Fig. 7, DPR-MAC outperforms

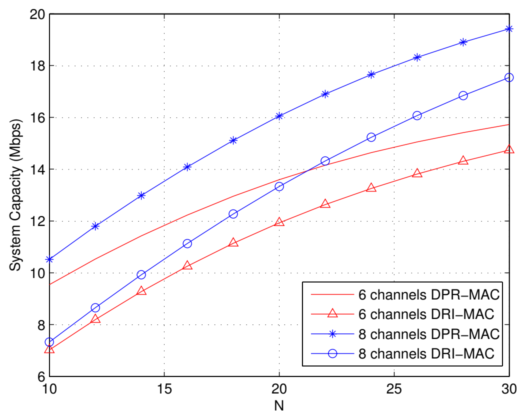

Figure 7. System capacity comparison of DPR-MAC and DRI-MAC as a function of N.

DRI-MAC for all ranges of the investigated values. This is because that more SUs jump to the higher datarate channels according to the proportion of datarate in two types of channels rather than uniform hopping sequences, leading to higher total system capacity. Interestingly in this case, larger differences are observed when N is smaller, with both $M = 3$ and $M = 4$. It is because that when the number of SUs is smaller, the system is far from saturation. At the same time, idle SUs have many data flows to send since $\lambda = 0.7$ which indicates a high transmission probability for SUs. Once one communication pair is re-allocated from the low datarate channel to high datarate channel, it contributes more to the achieved total system capacity. For instance, assume that there are four ongoing data flows in the system, two of each type. If one of the two low datarate flows is re-allocated to the high datarate channel, the total capacity will be significantly increased since we have now three out four flows using the high capacity channel. When the number of SUs gets larger, the probability that more channels are occupied by communicating pairs will be higher. In other words, with a large N the channels are close to saturation and there is less room for capacity improvement no matter how you balance the hop sequences of the SUs. This explains why the difference between the two methods becomes smaller as N increases.

5) Impact on system capacity by channel datarate: Fig. 8 depicts the differences between DPR-MAC and DRI-MAC when the datarate of R_1 is fixed into 2 $Mbps$ and $\lambda = 0.7$, $\gamma = 0.7$, $N = 20$, while datarate of R_2 is as a variable. In order to ensure the average length of data flows *in bytes* on different channels are the same, μ_1 is fixed as 0.05 while μ_2 is 0.05, 0.1, 0.15, 0.2, 0.25, 0.3 when R_2 equals to 2, 4, 6, 8, 10, 12 $Mbps$ respectively. Fig. 8 illustrates that the improvement of the

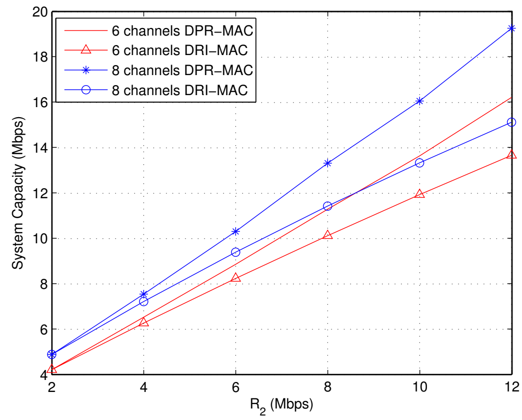

Figure 8. System capacity comparison of DPR-MAC and DRI-MAC as R_2 varies.

new method increases when the datarate of R_2 increases because the difference between channels is larger. Note that when $R_2 = R_1$, the capacity of different methods is the same because in this case, the hops according to the new strategy is also uniform distributed, which implies that DRI-MAC is actually a special case of DPR-MAC. The enhancement is evident when R_2 is three or more times larger than R_1. When R_2 is two times larger than R_1, the improvement is not obvious. Considering the beacon overhead, if the R_2 is less than two times of R_1, the DRI-MAC can be adopted.

B. Performance evaluation given identical datarate

1) Parameters configuration: In this subsection, we give the results when the two types of channels have the same datarate R_i but different channel availabilities γ_i. The parameters used are as follows: $R_1 = R_2 = 10$

$Mbps$, $\mu = 0.2$, $\gamma_1 = 0.9$, $\gamma_2 = 0.6$,. $T_s = 1000$ μs, $T_{sw} = 100$ μs, and $T_q = 10$ μs.

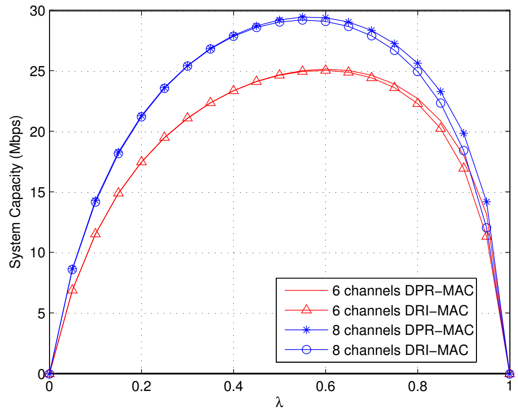

Figure 9. System capacity comparison of DPR-MAC and DRI-MAC with λ.

2) System capacity as a function of λ: Fig. 9 shows the system capacity of different MAC mechanisms as λ varies, when $N = 20$, $M = 3$ and 4 respectively. From the figure we can observe that the trend of Fig. 9 and Fig. 5 is quite similar, but the difference is that for the performance between the two MAC mechanisms, the difference in Fig. 9 is slight. The reason is as follows. From the adjustment method we proposed, in statistic sense, it has a probability of $\gamma_1/(\gamma_2 + \gamma_2) = 3/5$ for each SU to jump into the higher γ side. Compared with the probability in different datarates cases, like 2 $Mbps$ in channel type 1 and 8 $Mbps$ in channel type 2 which introduce $R_1/(R_1 + R_2) = 4/5$, the probability in the first case is lower. On the other hand, from Eq. (18), we can see that if the datarate in channel type 2 is four times higher than that in channel type 1, the improvement will be more significant compared with the different channel availabilities cases when the datarates on different channels are equal. Consequently, the improvement of the new method in the case with identical R_i is not as much as that when R_i is different.

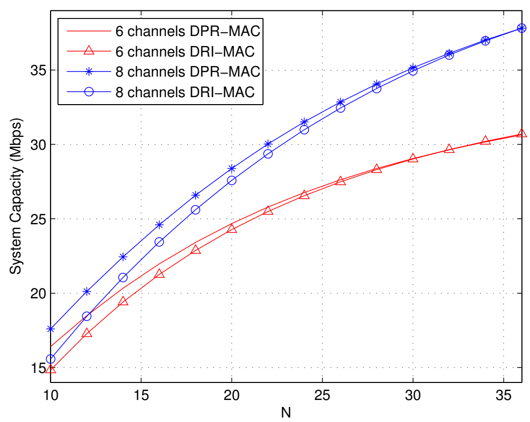

Figure 10. System capacity comparison of DPR-MAC and DRI-MAC with N.

3) Impact on system capacity by the number of SUs: Fig. 10 gives the system capacity with the variable of the number of SUs. The trend of these curves is close to that in Fig. 7, but the difference between these curves in Fig. 10 is smaller than that in Fig. 7. The reason for the similar performance between these curves in Fig. 10 is the same as we discussed in the above paragraph.

Fig. 10 also illustrates that when the number of SUs gets larger, the performance between these two MAC mechanisms gets closer, and it is more evident than that in Fig. 7. The reason for this is the same as we discussed above that with the increasing number of N, the channels are close to saturation and there is less room for capacity improvement no matter how to balance the hop sequences of the SUs.

4) Impact of PUs channel occupancy on system capacity : In this case, the system capacity as a function of γ_2 is given in Fig. 11 when γ_1 is fixed as 0.9. From this figure we can see that when γ_2 is smaller, which means the difference between γ_1 and γ_2 is larger, the performance of DPR-MAC is much better than that of DRI-MAC. The reason is quite obvious, since the larger difference between the channels' availabilities, the more benefit the MAC can get if it can adjust there hop sequences to the higher availability channel rather than the equal chance hopping sequence.

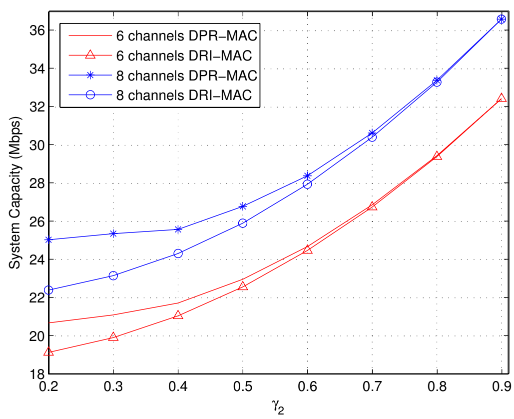

Figure 11. System capacity comparison of DPR-MAC and DRI-MAC with γ_2.

From Figs. 9-11, as a whole, it can be observed that the improvement of DPR-MAC is not as significant as that in Figs. 5-8. This is because that the datarate R_i between different channels could be quite large and its effect is more straightforward in different datarates cases while the difference of channel availabilities γ between channels in real cases is not often so large.

Furthermore, in all the above numerical results and discussions, there has been an important assumption that the channel sensing is accurate. If there are any sensing errors, say, SUs failed to sense the existence of PUs' activities, there will be a high probability of transmission failure due to packet collision. In this case, the channel availability will affect the performance more than what is observed from our analysis. In a more constrained case, if a successful transmission of a packet needs several consecutive time slots that is not occupied by PUs, the system capacity is more sensitive to channel availability. For example, if a packet needs 3 consecutive free time slots for successful transmission and if $\gamma = 0.9$, the approximate successful transmission probability is $0.9^3 = 0.729$ while for $\gamma = 0.6$ this probability would be only 0.216. Then in this case, channel availability would have higher impact on the total system capacity. Correspondingly, the channel hopping adjustment strategy should also be revised in order to adapt to this situation.

C. System capacity with channel carrier capability

The above results are either from given identical channel availability or from given identical channel datarate, which are special cases of channel carrier capability. In the following paragraphs, the results of system capacity as a function of the combined parameters are given.

1) Parameters configuration: The parameters used to calculate the system capacity is as follows: $N = 20$, $M = 4$, $T_s = 1000\ \mu$s, $T_{sw} = 100\ \mu$s, $T_q = 10\ \mu$s, $\mu_1 = 0.05$, $\mu_2 = 0.25$, $R_1 = 2\ Mbps$, and $R_2 = 10\ Mbps$. In this subsection, we only examine the system capacity as a function of λ.

2) System capacity as a function of λ: Fig. 12 illustrates the results of DPR-MAC and DRI-MAC when R_i and γ_i are different and channel carrier capability is adopted. For comparison, it also shows the results of adjusting hopping sequences according to one of these two parameters, i.e., R_i and γ_i in this case. In Fig. 12, *Channel availability only* means that SUs adjust the hopping sequences according to channel availability without considering R_i. It is the same case with *datarate only*. In this figure, we have γ_1=0.6 and γ_2=0.9. It is shown that

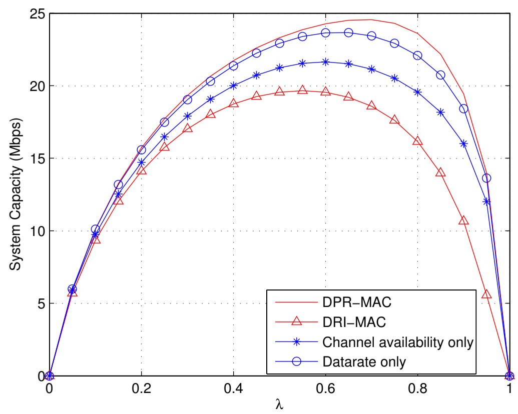

Figure 12. System capacity comparison among different hopping strategies when $R_1 < R_2$ and $\gamma_1 < \gamma_2$.

the hopping adjustment according to the channel carrier capability η is the most efficient mechanism and the DRI-MAC is the worst one. Note that both the datarate and the channel availability of channel type 2 are higher than that in channel type 1, the results of adjustment according to channel availability and datarate are better than the DRI-MAC. Adjusting according to datarate is more efficient than adjusting according to channel availability because the former one leads to larger difference in carrier capability. But both of them are not as good as the adjustment according to channel carrier capability η.

Fig. 13 shows the results of DPR-MAC and DRI-MAC when R_i and γ_i are different when channel carrier capability is adopted. The different parameters used in Fig. 13 compared with that in Fig. 12 are that the channel availabilities in two types of channels are exchanged, i.e., γ_1= 0.9 and γ_2=0.6. It is illustrated in the figure that the adjustment according to γ alone is not as good as the DRI-MAC because the adjustment according to γ leads more SUs to low carrier capability channels, i.e. channel type 1. On the other hand, the result of adjustment according to datarate which brings more SUs to jump onto the channels with higher channel carrier capability is quite close to that of the DPR-MAC. Even if adjustment according to the datarate brings more SUs in the type of channels with higher channel carrier capability, the result of this adjustment is not better than in the way of adjusting according to the channel carrier capability, which verifies the rationale of adjusting hopping sequence according to channel carrier capability η.

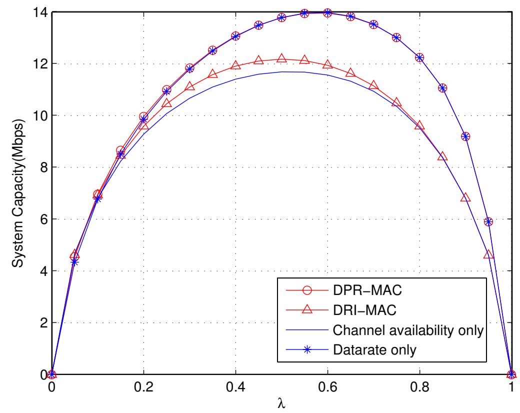

Figure 13. System capacity comparison among different hopping strategies when $R_1 < R_2$ but $\gamma_1 > \gamma_2$.

D. Extra overhead estimation of DPR-MAC

Now we approximately calculate the extra overhead introduced by DRA-MAC due to the required dissemination of the hop sequence adjustment information. In the estimation, the calculation is based on an assumption that the whole hopping sequence is disseminated, which reflects the highest possilbe overhead for beacon information dissemination. Assume that there are 20 SUs, 4 channels with 2 $Mbps$ and 4 channels with 10 $Mbps$, the hopping period is 128 hops and beacon interval is 5 seconds. We can get the average overhead as [128*3*1+(128*3+3)*7+(128*3+48)*7]*20/5=24.468 $Kbps$, where 128 means that there are 128 hops, 3 means that 8 channels can be presented in 3 bits. The calculation has three parts. The first part presents the beacons that are broadcast by the SU itself. The second part presents beacons in the unicast procedure by the original SU.

The third part presents the beacons that are re-broadcast by other SUs. Since the other SUs that re-broadcast the beacon in the planned slot have to attach the MAC address of original SU, it has extra 48 bits due to the length of a MAC address.

From the above estimation, we can conclude that the extra overhead introduced by DPR-MAC is pretty small. This indicates that the additional mechanism cost by the proposed MAC is pretty low, typically in the order of a few $Kbps$, in order to achieve possibly a few $Mbps$ capacity improvement. Anyhow, it is beneficial to consider this effect for our mechanism design, so that further improvement can be achieved.

E. Beacon dissemination of DPR-MAC

Now we estimate the dissemination time of a beacon and the probability an SU can receive a beacon after beacon intervals. The parameters used in this analysis is as follows: $\gamma = 70\%$, $P_{og,2} = 70\%$, $R_1 = 10\ Mbps$, $R_2 = 2\ Mbps$, $G = 2M = 8$, $N = 20$, $\lambda_o = 50\%$, the sequence has 128 hops and $T_s = 1\ ms$.

From our estimation in IV. D, the probability that a beacon is delivered on the low datarate channel after 2, 3, 4, 5, 6 seconds is 73.18%, 86.71%, 93.41%, 96.73%, 98.23% respectively. The probability of an SU that can receive such beacon information can after 1, 2, 3, 4 beacon intervals is 82.51%, 96.94%, 99.47%, 99.91% respectively. Note that the probability is calculated considering the worst case. In the normal cases, the same probability could be achieved in shorter time. These values indicate that the beacon information could be delivered with a high probability within 5 seconds, and in this case, an SU could receive this information with a high probability within two beacon intervals, i.e., 10 seconds.

VI. CONCLUSIONS

In this paper we have proposed a channel-hopping based dynamic parallel-rendezvous channel carrier capability aware MAC mechanism for cognitive radio networks with one transceiver. Based on our scheme, SUs can adjust their hopping sequences according to either datarate, channel availability or a combination of them (as carrier capability) in order to improve system performance. A mathematical model has been developed to analyze the performance of the proposed MAC mechanisms. Numerical results and comparison between DPR-MAC and DRI-MAC show that our proposed mechanism generally outperforms the existing one. The difference of the achieved system capacity between DRI-MAC and DPR-MAC is more obvious in the case of identical channel availability than in the case of identical datarate. Moreover, adjusting the channel sequence according to channel carrier capability leads to the best system capacity gain in the examined cases. The improvement compared with DRI-MAC is more significant when more channels are available for SUs, fewer SUs are in the network, and the carrier capabilities between difference channels are larger.

APPENDIX I
PROOF OF CHANNEL HOPPING MECHANISM

Proposition: Let L_i be the likelihood of an SU that will hop onto the channel i after using the above mentioned method. For every channel i, $L_1{:}L_2\cdots\ L_G{=}\eta_1{:}\eta_2\cdots\eta_G$.

Proof: Because the SUs jumps according to the uniformly generated sequence before adjustment, the probability of an SU jumps onto channel $i, 1 \le i \le G$, is equal. Let us arrange the set of G channels according to the value of η_j as $\{1, 2, \cdots, l, l+1, \cdots, G\}$ such that $\eta_j \le \overline{\eta} \Leftrightarrow j \le l$ and $\eta_j \le \eta_i \Leftrightarrow i < j$. Let $B \in \{channel\ j | \eta_j < \overline{\eta}, j = 1, 2, \cdots G\}$. After the adjustment, we can see that

$$L_{1,2\cdots l} = \eta_{1,2\cdots l}/\overline{\eta} \quad and$$
$$L_{l+1,l+2\cdots G} = 1 + \frac{\sum_{i\in B}(1-\eta_i/\overline{\eta})\cdot(\eta_{l+1,l+2,\cdots G}-\overline{\eta})}{\sum_{k\in A}(\eta_k-\overline{\eta})}.$$

We should prove that

$$1 + \frac{\sum_{i\in B}(1-\eta_i/\overline{\eta})\cdot(\eta_{l+1,l+1,\cdots G}-\overline{\eta})}{\sum_{k\in A}(\eta_k-\overline{\eta})} = \eta_{l+1,l+2\cdots G}/\overline{\eta}.$$

When $j > l$, we can see that

$$\begin{aligned}
&1 + \sum_{i\in B}(1-\eta_i/\overline{\eta})\cdot(\eta_j-\overline{\eta})/\sum_{k\in A}(\eta_k-\overline{\eta}) \\
&= 1 + \frac{\sum_{i\in B}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})}\cdot\frac{\eta_j-\overline{\eta}}{\overline{\eta}} \\
&= \frac{\sum_{i\in \eta}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})}\cdot\frac{\eta_j}{\overline{\eta}} + 1 - \frac{\sum_{i\in B}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})} \\
&= \frac{\sum_{i\in B}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})}\cdot\frac{\eta_j}{\overline{\eta}} + \frac{\sum_{k\in A}(\eta_k-\overline{\eta})+\sum_{i\in B}(\eta_i-\overline{\eta})}{\sum_{k\in A}(\eta_k-\overline{\eta})} \\
&= \frac{\sum_{i\in B}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})}\cdot\frac{\eta_j}{\overline{\eta}} \\
&= \frac{\eta_j}{\overline{\eta}}.
\end{aligned}$$

Now we can conclude that:
$L_1{:}L_2\cdots L_G{=}\eta_1/\overline{\eta}{:}\eta_2/\overline{\eta}\cdots\eta_G/\overline{\eta} = \eta_1{:}\eta_2\cdots\eta_G$.

APPENDIX II

We give the solution for the probability, $P(c|\vartheta, M)$, that there is c non-empty urns if we put ϑ balls into M urns by the model given in [14].

Let $o(\vartheta)$ be the stochastic process representing the number of urns each of which has exactly one ball given there are ϑ balls, and $n(\vartheta)$ as the stochastic process representing the number of urns each of which has at least two balls. Then, we obtain a two-dimensional process $\{o(\vartheta),\ n(\vartheta)\}$ that is a discrete-time Markov chain as shown in Fig. 14 [14].

The one-step transition probabilities are as follows [14]:

$$\begin{cases}
p(i,j|i,j) = \frac{j}{M}, & 0 \le i,j \le M \\
p(i+1,j|i,j) = 1 - \frac{i+j}{M}, & 0 \le i \le (M-1), j \ge 0 \\
p(i-1,j+1|i,j) = \frac{i}{M}, & 0 \le i \le M, 0 \le j \le (M-1) \\
p(x,y|i,j) = 0; & |x-i| \ge 2 \text{ or } |y-j| \ge 2
\end{cases}$$

where $(i+j) \le M$ holds.

Then the probability that c non-empty urns given ϑ balls and M urns can be calculated as:

$$P(c|\vartheta, M) = \sum_{o(\vartheta)+n(\vartheta)=c} P_\vartheta(o(\vartheta), n(\vartheta)),$$

where $P_\vartheta(o(\vartheta), n(\vartheta))$ is the state probability of $\{o(\vartheta),\ n(\vartheta)\}$ after ϑ steps.

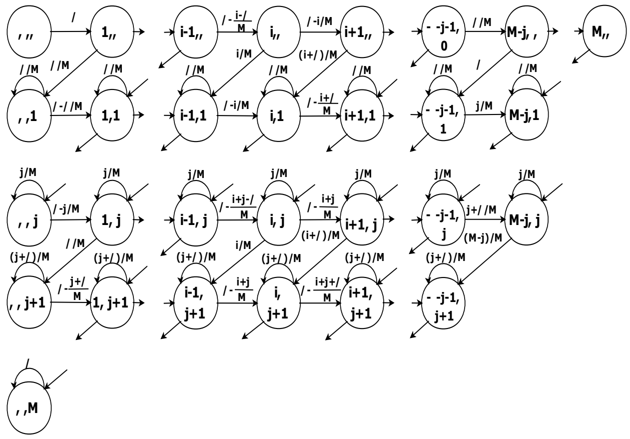

Figure 14. The two-dimensional Markov chain for the probability that there is c non-empty urns if we put ϑ balls into M urns [14].

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