Analysis on Channel Bonding/Aggregation for Multi-channel Cognitive Radio Networks

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***Abstract*—Channel bonding/aggregation techniques, which assemble several channels together as one channel, could be used in cognitive radio networks for the purpose of achieving better bandwidth utilization. In existing work on this topic, channel bonding/aggregation is focused on the cases when primary channels are time slotted or stationary as compared with secondary users' activities. In this paper, we analyze the performance of channel bonding/aggregation strategies when primary channels are not time slotted and the time scale of primary activities is at the same level as the secondary users', given that spectrum handover is not allowed. Continuous time Markov chain models are built in order to analyze the performance of such a network in terms of three parameters: system capacity for secondary users, forced termination probability and blocking probability. Numerical results show that channel bonding/aggregation does not increase achieved system capacity and it leads to higher blocking probability, but lower forced termination probability is obtained when this technique is used.**

***Index Terms*—Cognitive radio networks, channel bonding/aggregation, Markov chain analysis, performance evaluation.**

I. INTRODUCTION

Cognitive Radio Networks (CRNs) [1] [2], which are based on Cognitive Radio (CR) terminals and wireless networking technologies, have become a hot research topic these days. However, the spectrum used by CRNs is not dedicated. Primary Users (PUs) have priority to access the spectrum that is assigned to them and Secondary Users (SUs) can only use the spectrum opportunistically. Whenever a PU appears, SUs should stop their transmissions and vacate the channel.

In multi-channel cases, if there are several idle channels, SUs can make a decision whether to bond or aggregate them together as one channel for carrying out higher traffic load or still to treat them as individual channels. When two or more channels in the frequency domain are available, if these channels are contiguous with each other, they could be *bonded* as one SU channel. Otherwise these channels could be *aggregated* which means multiple channels at different frequencies are assembled as a common channel [3] [4]. There are several CRNs MAC strategies that use channel bonding or aggregation technologies [5]–[8]. In [5] and [6], the authors assume that the transmission of PUs is time slotted. In each slot, if there are no PU activities in the beginning of the slot when SUs sense these channels, PUs will not come up for the rest of the slot. In this case, it is proper for SUs to bond or aggregate these channels in that slot since the transmission of SUs will not be interuptted by any sudden appearance of PUs within that slot. In [7] and [8], the protocols are targeted at TV bands, which means that the occupancy of PU channels are static. As PU's absence largely exceeds SU's communication durations in this case, it is advantageous to combine several channels. It is demonstrated in the above related work that benefits have been achieved in CRNs when channel bonding or aggregation is employed. A link maintenance strategy for multichannel CRNs is introduced in [9]. In [10], the performance of an SU network when a PU channel could be divided into several SU channels is analyzed.

However, a more challenging scenario, where the time scale of primary activities could be at the same level as that of SU devices and the secondary network may use unslotted channels[1] on which the appearance of PUs may happen at any time, could exist. Since channel bonding or aggregation needs more than one channel, SUs have to wait to transmit until the required number of channels is available, leading to possible waste of opportunities as compared with the single-channel case. On the other hand, an ongoing SU transmission on the bonded or aggregated channels will be forced to terminate when a PU activity appears on any of those channels if spectrum handover [10] is not applied in the SU network. With these considerations, the performance of secondary networks using channel bonding or aggregation deserves to be re-investigated. By spectrum handover, it is meant that the ongoing SU transmission could switch to another vacant channel if a PU appears in the current channel in order to keep the continuity of the current transmission. It requires more complex hardware for SUs since the channel switching time should be as short as possible, and SUs should be able to sense other channels' status simultaneously while transmitting or receiving. In this paper, we focus on the performance of the secondary network in the case when channels are opportunistically available for SUs using different channel bonding or aggregation strategies and no spectral

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[1] Even if PUs work in a time slotted manner, SUs may not be able to take advantage of it as described in [6] if SUs cannot precisely distinguish these slots or PUs are not synchronized among channels. Moreover, it also happens if the channel sensing time required is comparable with the time slot for PUs. In this work, we also regard channels in these cases as *unslotted channels*.

handover is implemented. Continuous Time Markov Chain (CTMC) models are used in our analysis.

The rest of this paper is organized as follows. In Section II, the channel model and assumptions are given. In Section III, CTMC models are built based on three different strategies in order to analyze system performance. Numerical results and corresponding discussions are presented in Section IV, before the paper is concluded in Section V.

II. CHANNEL MODEL AND ASSUMPTIONS

Assume that there are two types of radios, PUs and SUs, operating in the same spectrum. The spectrum consists of M channels for PUs. PUs have priority to use the spectrum and can reclaim channels being used by SUs at any time. PUs are not aware of the existence of SU activities. Each SU can bond or aggregate multiple primary channels, N ($N \leq M$), for a packet or session transmission. Using channel bonding or aggregation techniques, an SU could take the advantages of using several separated channels, as well as neighbouring ones, as one channel at the same time [3] [6] [7]. For example, the situation at a particular time snapshot when $N = 2$ is illustrated in Fig. 1. In this example, the SUs combine two idle channels together as one SU channel in two different ways. In the first case, two idle, however separated channels (Ch.2 and Ch.5) are *aggregated*. In the second case, two neighbouring idle channels (Ch.8 and Ch.9) could be *bonded* as one channel.

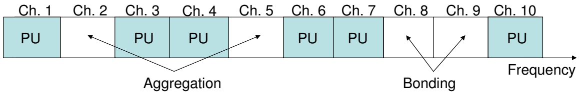

Fig. 1. Channels used by two types of systems with channel bonding or aggregation.

Assume that the packet or session arrivals of SU and PU systems are both Possion processes with arrival rates λ_S and λ_P respectively. The corresponding service times are exponentially distributed with service rates μ_S and μ_P in one channel. It is well known that if the Signal to Noise Ratio (SNR) in a channel is fixed, the channel capacity increases linearly with bandwidth. Assume further that all the channels are homogeneous and with similar SNR, then the total channel capacity is approximately linearly increasing with the number of bonded or aggregated channels. Therefore, the service rate of the bonded or aggregated N primary channels for an SU service is approximated[2] as N times of that in one channel. Denote the service rate of an SU service which assembles N channels as $\mu_{S,N}$, then $\mu_{S,N} = N \cdot \mu_S$. The unit for these parameters could be packets/unit of time or sessions/unit of time. Given concrete values for these parameters, e.g., 0.2 sessions/s and packet length in bits, the system capacity could be expressed in Kbps or Mbps. For this reason, in our analysis and results illustration, the unit of system capacity is not explicitly expressed.

It is assumed that SUs can precisely sense PU activities, and once an ongoing SU packet or session is interrupted by a PU activity, the SU packet or session is forced to terminate. In other words, the packet or session is dropped. For the sake of conciseness, we denote packet or session of the secondary network as service and use the term channel assembling to indicate both bonding and aggregation. In this analysis, we focus on the performance of the secondary network and assume that the services of the secondary network are independent of each other.

III. SYSTEM MODEL AND ITS ANALYSIS

The process of spectrum occupation can be modeled as a CTMC process. In this study, we investigate three channel assembling strategies, as follows:

1) *No assembling*: This strategy is without channel assembling. The secondary network treats different channels as separate channels and transmits services in these channels independently. That is, conventional scheme without channel assembling is applied with this strategy.
2) $N = W$: In this strategy, the secondary network assembles a fixed number of channels as one channel for SU transmission and it is referred to as $N = W$ where W is the number of to-be-assembled channels. For example, when $W = 2$, the secondary network assembles exactly two available channels to form one channel for one SU service. If there are four channels available, the secondary network can have two services each of which assembles two channels. In this case, for a particular SU service, it does not acquire extra channel even if more channels are available. It implies in this case that one or more (fewer than W) channels may be wasted even though there are one or more idle channels available when an SU service arrives.
3) $N \geq W$: This strategy consists in assembling all available channels at the time when an SU service attempts to access channels if the number of idle channels is larger than or equal to W. For instance, in the case of $N \geq 2$, at the time when an SU service arrives, if the number of available channels is larger than or equal to two, e.g., two or three, the secondary network assembles all of them as one channel for one SU service. In this strategy, during an SU service time period, if any PUs finish their transmissions and leave their channels, the ongoing SU service will not assemble those newly available channels but it is possible for new arrival SU services to use them if the number of these channels is sufficient. However, when an arriving PU takes any one of the assembled channels that is in use by an ongoing service of SU, the SU service will be dropped.

According to these channel assembling strategies, different CTMC models can be built. Since the first strategy is a special case of the second strategy when $N = 1$, the same occurs with their CTMC models. For the third strategy, a different CTMC model is developed. In the following subsections, we will firstly present the CTMC model for the first and

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[2] If the vacant channels are neighboring to each other, the guard band between channels can be utilized for data transmission when channel bonding is implemented. On the other hand, a larger guard band is required at the band edges. In order to keep coherence, we ignore these details.

second strategies, and then analyze the performance of the third strategy based on another CTMC model.

A. CTMC analysis for strategies of $N = W$

In this strategy, the states of CTMC models are characterized by an integer pair (i, j), where i is the total number of PU communicating pairs using their allocated channels while j is the total number of SU communicating pairs using these channels. Based on the traffic assumptions of both PUs and SUs, the feasible state transitions could then be analyzed. For example, when $i + Nj \leq M - N$, $j \geq 1$ and $i \geq 1$, we have the state (i, j) and the corresponding transitions as shown in Fig. 2. The one step transition rates from state (i, j) to the other states that it can reach are shown as

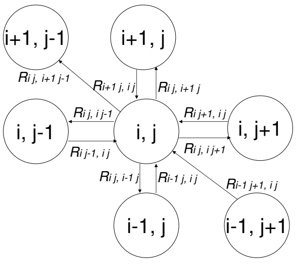

Fig. 2. State transitions for the strategies one and two.

$$
\begin{cases}
R_{i,j;i+1,j-1} & = \lambda_P Nj/(M-i), \\
R_{i,j;i+1,j} & = \lambda_P (M - Nj - i)/(M-i), \\
R_{i,j;i,j-1} & = j\mu_{S,N}, \\
R_{i,j;i,j+1} & = \lambda_S, \\
R_{i,j;i-1,j} & = i\mu_P.
\end{cases}
$$

Outgoing transitions from states where $i = 0$, $j = 0$ or $M - N < i + jN \leq M$ are the same as given above while the transitions which would lead to an unfeasible state are removed. Fig. 3 illustrates a CTMC model when $M = 6$ and $N = 2$ as an example.

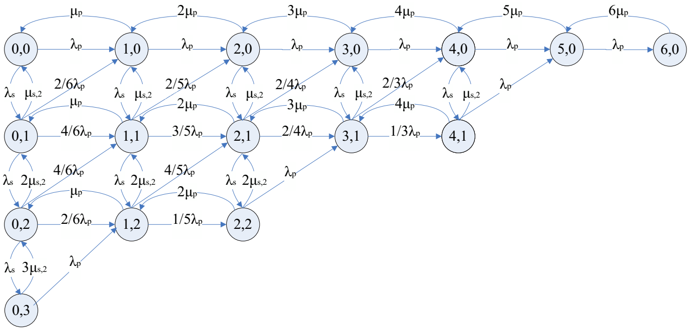

Fig. 3. Markov chain for strategy two when $M = 6$ and $N = 2$.

Based on the states and the transition rates, global balance equations could be built. Let $\pi_{i,j}$ be the state probability and Ψ denote the set of feasible states of the Markov chain, $\Psi := \{(i,j) \mid i, j \geq 0;\ i + Nj \leq M\}$, where $\psi_{i,j} = 1$ if $(i,j) \in \Psi$, and 0 otherwise. Then the balance equations can be written as

$$
\begin{aligned}
&[j\mu_{S,N} + i\mu_P + \lambda_S \psi_{i,j+1} \\
&+ \lambda_P(\psi_{i+1,j} + \psi_{i+1,j-1} - \psi_{i+1,j}\psi_{i+1,j-1})]\pi_{i,j}\psi_{i,j} \\
&= (i+1)\mu_P \pi_{i+1,j}\psi_{i+1,j} + (j+1)\mu_{S,N}\pi_{i,j+1}\psi_{i,j+1} \\
&+ \lambda_P \pi_{i-1,j+1}\psi_{i-1,j+1} N(j+1)/[M-(i-1)] \\
&+ \lambda_P \pi_{i-1,j}\psi_{i-1,j}[M-(i-1)-Nj]/[M-(i-1)] \\
&+ \lambda_S \pi_{i,j-1}\psi_{i,j-1},
\end{aligned}
\tag{1}
$$

where $i = 0, 1, 2, ..., M$ and $j = 0, 1, 2, ..., \lfloor M/N \rfloor$. Once the probabilities for steady-state of the Markov chain are obtained, the forced termination probability, the blocking probability and the capacity of the secondary network can be calculated.

The capacity of the secondary network is defined as the total rate of service completions per time unit [10], as shown below,

$$
\rho = \sum_{i=0}^{M} \sum_{j=0}^{\lfloor (M-i)/N \rfloor} \pi_{i,j} j \mu_{S,N}. \tag{2}
$$

The blocking probability P_b is given by

$$
P_b = \sum_{i=0}^{M} \pi_{i,\lfloor (M-i)/N \rfloor}. \tag{3}
$$

Forced termination represents a disruption of an ongoing SU service. When there occurs the state transition from state (i, j) to state $(i+1, j-1)$, one of the SUs will experience forced termination. The forced termination probability can therefore be expressed as the mean forced termination rate, R_f, divided by the mean arrival rate of SU services or that of the commenced SU services [11].

$$
P_f = R_f/\lambda_S^* = \sum_{i=0}^{M-1} \sum_{j=0}^{\lfloor (M-i)/N \rfloor} \frac{Nj\lambda_P}{(M-i)\lambda_S^*} \pi_{i,j}. \tag{4}
$$

In Eq. (4), λ_S^* will be either λ_S or $(1 - P_b)\lambda_S$. If P_f represents the fraction of forced terminations over all the arriving SU services, then $\lambda_S^* = \lambda_S$. In contrast, if P_f represents the fraction of forced terminations of SU sessions over those commenced, i.e., the blocked ones are not taken into account, then $\lambda_S^* = (1 - P_b)\lambda_S$. In this paper, we adopt $\lambda_S^* = (1 - P_b)\lambda_S$.

B. CTMC analysis for strategy of $N \geq W$

In this subsection, we develop a CTMC model to evaluate the system performance for strategy $N \geq W$ presented above with $W \leq M$. As mentioned above, the service rate of N assembled primary channels is $N\mu_S$. The states of this CTMC model are represented by $(i, j_M, j_{M-1}, \ldots, j_W)$, where i is the total number of PU communicating pairs using these channels while j_M,…,j_W is the number of SU communicating pairs that assemble M,…,W channels respectively, where $j_M M + j_{M-1}(M-1) + \ldots j_W W \leq M - i$. Let $\boldsymbol{x} = (i, j_M, \ldots, j_W)$ represent a state of the CTMC as defined

TABLE I
TRANSITIONS FROM A GENERIC STATE $\boldsymbol{x} = (i, j_M, \dots, j_W)$.

	Destination state	Rate	Conditions
PU departure	$(i-1, j_M, \dots, j_k, \dots, j_W)$	$i\mu_P$	$i > 0$
SU departure	$(i, j_M, \dots, j_k - 1, \dots, j_W)$	$kj_k\mu_S$	$j_k > 0$
PU arrival	$(i+1, j_M, \dots, j_k, \dots, j_W)$	$\dfrac{M - b(\boldsymbol{x})}{M - i}\lambda_P$	$i \le b(\boldsymbol{x}) < M$
PU arrival; a SU occupying k channels is forcedly terminated	$(i+1, j_M, \dots, j_k - 1, \dots, j_W)$	$\dfrac{kj_k}{M - i}\lambda_P$	$i < M$, $j_k > 0$, $k = W, \dots, M - i$
SU arrival	$(i, j_M, \dots, j_k + 1, \dots, j_W)$	λ_S	$k = M - b(\boldsymbol{x}) \ge W$

above. We denote by $b(\boldsymbol{x})$ the total number of used channels at state $\boldsymbol{x}$

$$b(\boldsymbol{x}) = i + \sum_{k=W}^{M} kj_k.$$

Let $\mathcal{S}$ be the set of feasible states

$$\mathcal{S} := \{\boldsymbol{x} \mid i, j_M, \dots, j_W \ge 0;\ b(\boldsymbol{x}) \le M\}.$$

Table I summarizes the state transitions in this case. Using the transition rate, the steady-state probabilities of the Markov chain can be obtained. Let us denote by $\pi(\boldsymbol{x})$ the probability of state $\boldsymbol{x} = (i, j_M, \dots, j_W)$. Then the blocking probability P_b, the system capacity ρ, and the forced termination probability P_f can be expressed as follows,

$$P_b = \sum_{\substack{\boldsymbol{x} \in \mathcal{S} \\ M - b(\boldsymbol{x}) < W}} \pi(\boldsymbol{x}), \tag{5}$$

$$P_f = R_f / \lambda_S^* = \frac{\lambda_P}{\lambda_S^*} \sum_{\substack{\boldsymbol{x} \in \mathcal{S} \\ i < M}} \frac{b(\boldsymbol{x}) - i}{M - i} \pi(\boldsymbol{x}), \tag{6}$$

$$\rho = \sum_{\boldsymbol{x} \in \mathcal{S}} \sum_{k=W}^{M} kj_k\mu_S \pi(\boldsymbol{x}), \tag{7}$$

where $\lambda_S^* = (1 - P_b)\lambda_S$.

IV. NUMERICAL RESULTS

In this section, based on the above analyses, numerical evaluations of the system capacity, the forced termination probability and the blocking probability of the *secondary network* are presented. In what follows, we illustrate the case when $M = 6$ as an example. Unless otherwise stated, the basic parameters are configured as $\lambda_P = 0.05$, $\lambda_S = 0.68$, $\mu_S = 0.2$, and $\mu_P = 0.6$, and then one of these parameters is varied at a time while others are kept the same for each illustration. In all the following figures, *No assembling* means that the first strategy is used.

A. System capacity for secondary users

Fig. 4 shows the system capacity of the secondary network as a function of λ_P. From this figure, we can observe that the system capacity of the secondary network declines as λ_P increases. Comparing the system capacity of different strategies, *No assembling* has achieved the highest performance. The main reason for lower capacity with channel assembling is that more SU requests are blocked since multiple channels are required, as illustrated later in Fig. 10. Higher capacity is also achieved for $N = 2$, and 3 as compared with $N = 4$, 5 and 6 because parallel services are allowed in the former cases.

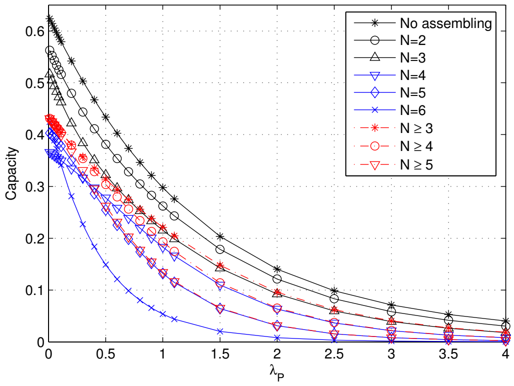

Fig. 4. System capacity as a function of λ_P.

The curves of $N = 4, 5, 6$ have some crosses which can be observed when $\lambda_P < 0.5$. The reasons are as follows. When $M = 6$ and $N = 4, 5, 6$, there is at most one ongoing SU service at any time instant. When λ_P is smaller than 0.1, i.e., the arrival rate of PU activity is very low, it is beneficial if more channels are assembled since higher service rate is achieved and more opportunities are used. In this case, $N = 6$ is better than $N = 4, 5$. But as λ_P grows larger, which means more channels could be occupied by PU activities, the probability of obtaining channel access in the scheme of $N = 4$ is higher than that when $N = 6$. Therefore, the system capacity when $N = 4$ is higher than $N = 6$.

For the strategies of $N \ge W$, initially, the performance of them is in between of the strategies of *No assembling*, $N = 2$, and 3 which could have more than one service, and $N = 4, 5$, or 6 which allows only one service. It is because with a lower λ_P, they could easily assemble a large number of channels together as one channel. When λ_P is higher, the performance of them converges to that of the minimum number of channels they support, i.e., W.

In Fig. 5 and Fig. 6, we plot the system capacity as a function of λ_S and μ_S respectively when the activity of PU is very low as $\lambda_P = 0.05$, i.e., the channels are not efficiently used by PUs. Since in this case the performance of the strategies when $N \geq W$ is quite close to each other as observed in Fig. 4, we plot only the strategy $N \geq 4$ as an example.

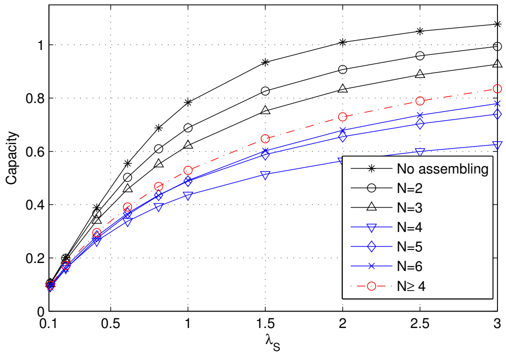

Fig. 5. System capacity as a function of λ_S.

Fig. 5 depicts the system capacity of the secondary network as λ_S varies. With the increasing arrival rate of SU services, the system capacity of the secondary network increases dramatically initially, and grows smoothly afterwards because the network is close to saturation. The performance curves of the assembling strategies rank from high to low as $No\ assembling$, $N = 2$, 3, and $N \geq 4$, $N = 6$, 5, 4 respectively when the network is about to be saturated. With the top three curves where several parallel services are supported, higher system capacity is achieved since other services may survive even if one of them is disrupted by PUs' appearance.

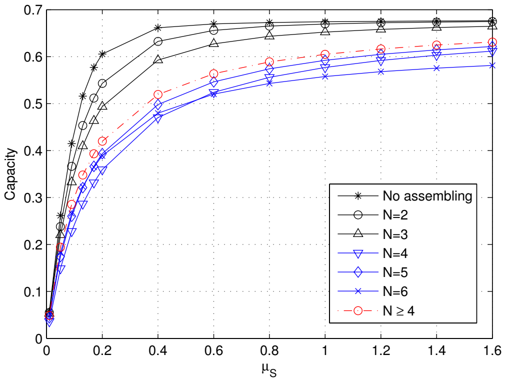

Fig. 6. System capacity as a function of μ_S.

We now evaluate the system capacity of the secondary network by looking at the impact of μ_S in Fig. 6. One can observe from this figure that all the curves increase dramatically when μ_S increases from 0.01 to 0.6 and afterwards they grow smoothly. As μ_S grows, more services could be finished within short time, and the performance of the secondary network becomes better. Again, the strategy without channel assembling has achieved the highest performance in this case, which approaches the upper bound, as the offered SU arrival rate $\lambda_S = 0.68$.

The performance of $N = 6$ is better than that of $N = 5$ and 4 initially and becomes worse afterwards in Fig. 6. This is because that when μ_S is small, i.e., with a longer SU service, the larger number of assembled channels can provide a shorter service time and consequently more services could be commenced. But when μ_S becomes larger, the advantage of larger number of assembled channels is not obvious since the service time is relatively short and the system capacity is close to the static value given the SU arrival rate. In this case, the scheme $N = 4$ surpasses $N = 6$ since it has higher access probability as compared with $N = 6$.

B. Forced termination probability

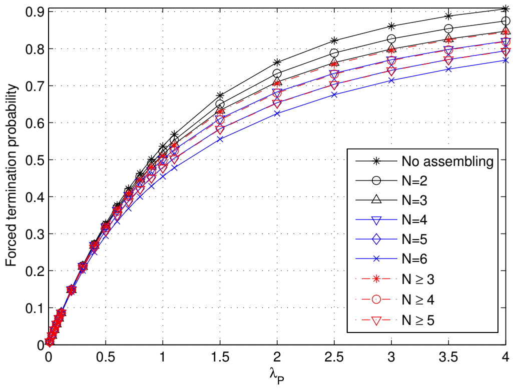

Fig. 7. Forced termination probability as a function of λ_P.

The second performance parameter concerned is forced termination probability. In Fig. 7, the forced termination probability is shown as λ_P varies. We can observe from this figure that the forced termination probabilities of all these strategies also grow since more SU services will be forced to terminate as PUs become more active. The more channels the secondary network assembles, the lower forced termination probability it has. The difference of forced termination probability among strategies becomes larger as λ_P grows.

Since the forced termination probability of different strategies is quite close to each other in all cases when $\lambda_P = 0.05$, we show the curves when medium PU traffic is injected, i.e., $\lambda_P = 0.5$ as a function of λ_S and μ_S in Fig. 8 and Fig. 9 respectively.

We set λ_S as variable to illustrate the forced termination probability in Fig. 8. From this figure, we can observe that the curves are quite smooth, showing that the forced termination probability is not sensitive to the arrival rate of SU services. The forced termination probability of $No\ assembling$ is the highest, while $N = 6$ has the lowest P_f on the whole. From this aspect, we can conclude that the benefit of channel assembling is represented by the lower forced termination probability. Comparing the strategies of $N \geq W$, similarly, the schemes with larger number of assembled channels achieve lower forced termination probability.

Fig. 9 illustrates the forced termination probability as a function of μ_S. The curves decline as μ_S grows since with shorter service time the probability of being interrupted by PUs will be lower for SU services. The advantage of channel assembling can be easily observed from this figure. The more

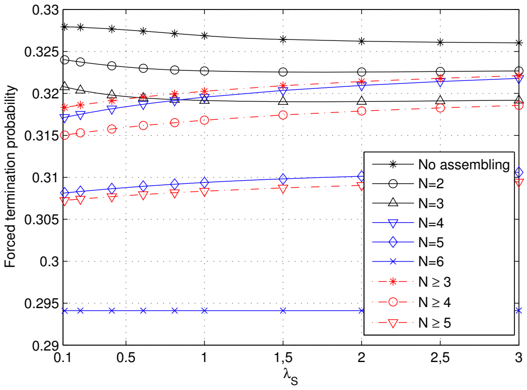

Fig. 8. Forced termination probability as a function of λ_S when $\lambda_P = 0.5$.

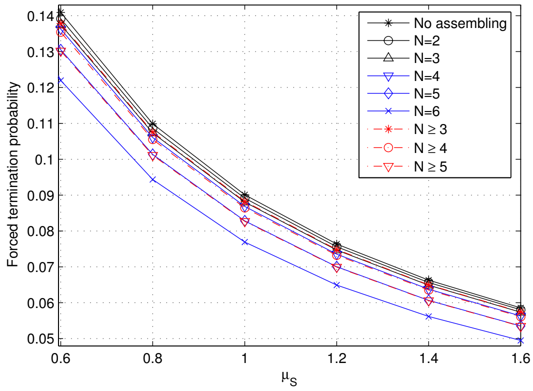

Fig. 9. Forced termination probability as a function of μ_S when $\lambda_P = 0.5$.

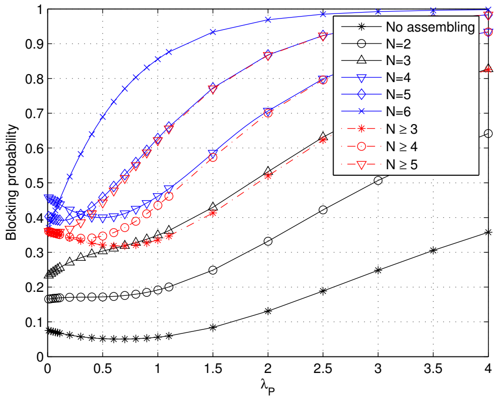

Fig. 10. Blocking probability as a function of λ_P.

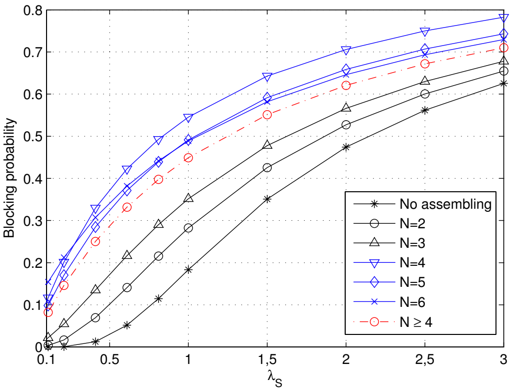

Fig. 11. Blocking probability as a function of λ_S.

channels it assembles, the lower forced termination probability it achieves.

C. Blocking probability

In this subsection, blocking probability is investigated according to different parameters. Fig. 10 shows the blocking probability as λ_P varies. In this figure, the blocking probability increases as λ_P grows. As expected, the strategy $No\ assembling$ has the lowest blocking probability since it could access channels even if there is only one idle channel. For this reason, the strategy $N = 6$ has the highest blocking probability with a large λ_P since it has to wait until all six channels are idle before a service is initiated. For the strategies when $N \geq W$, similar to the system capacity, the blocking probability of them is in between of the cases of $No\ assembling$, $N = 2$, 3 and $N = 4, 5, 6$ initially, and converges to that of the strategies with the minimum number of channels they support.

Interestingly, we can observe that some of these curves decline initially with the increasing λ_P. The reason is that when λ_P is very small, most of channels are occupied by SUs and new arrival SU services are blocked by the ongoing SU services. When λ_P is larger, more SU services are interrupted by PUs before they could finish, pre-emptying more channels for other new SU arrivals. More specifically, an arriving PU may evacuate several channels, but it will occupy only one of those free channels. In this case, the blocking probability is lower for some strategies. But it does not mean that the system capacity of them could be better because even if more services could be supported, they could not finish due to interruptions by PUs. When λ_P becomes larger, most of the channels are taken by PUs and the blocking probability of SUs becomes higher again.

Fig. 11 shows the blocking probability as a function of λ_S. One can observe from this figure that the blocking probability for an SU service increases when λ_S becomes larger. Comparing different strategies, we can find that $No\ assembling$ has the lowest blocking probability followed by $N = 2$ and $N = 3$. It is interesting that in the category of only one simultaneous SU service exiting in the network, i.e., $N = 4, 5$, and 6, $N = 4$ has the highest blocking probability in most cases. This is because that there is only one SU service in the network at a time and the service rate of SU is not high. With more assembled channels, i.e., higher service rate, the network could finish service faster, thus more traffic could be carried out in the network. The performance of $N \geq 4$ is in between of these groups since this strategy assembles all available channels whenever the number of them is larger than three, then the blocking probability is lower than that when $N = 4, 5, 6$.

Moreover, how μ_S affects the blocking probability is examined in Fig. 12. As shown in this figure, the blocking

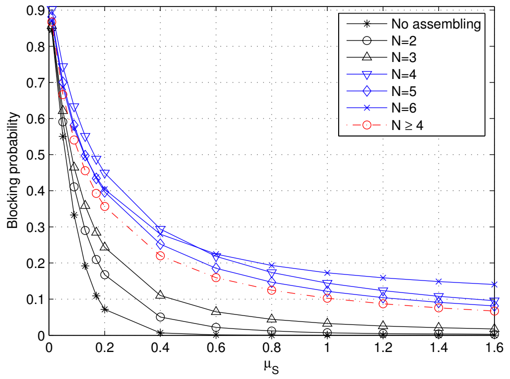

Fig. 12. Blocking probability as a function of μ_S.

probability of SU services becomes lower as μ_S grows. *No assembling* still has the lowest blocking probability. In the group of $N = 4, 5, 6$, the blocking probability of $N = 6$ is lower initially but becomes higher than $N = 4, 5$ as μ_S increases. It is coincident with the analysis in system capacity.

D. Summary and discussions

Comparing the strategies of conventional single channel transmission with the strategies with channel assembling, we argue that there is no benefit for channel assembling in terms of the total achieved system capacity and blocking probability when the system is not time slotted or the behavior of PUs is dynamic. The benefit is however that lower forced termination probability is achieved. We have also investigated the performance of a larger network with 10 multiple channels and similar results have been observed.

When channel assembling is employed, the strategies that assemble few channels, i.e., $N = 2$ and $N = 3$, have higher capacity and lower blocking probability since several parallel SU services are allowed in these cases. Meanwhile, the forced termination probability is higher in most of these cases. In other words, when a larger number of channels are assembled, the performance of SU services will be deteriorated with lower system capacity and higher blocking probability, but improved with lower forced termination probability.

For strategies that allow only one SU service at a time instant, i.e., $N = 4$, 5, or 6, the performance is quite different under different conditions. When there are more opportunities for SUs, i.e., with smaller λ_P and larger μ_P, the strategy with more assembled channels is more beneficial in terms of system capacity and blocking probability since more channels could be used for transmission. When λ_P becomes larger, ρ and P_f will be lower while P_b higher with larger number of channels assembled. For the strategies of $N \geq W$, they have higher system capacity compared with $N = 4, 5, 6$ when λ_P is small since they assemble all available channels as one channel in the beginning in a dynamic manner. With smaller W, higher capacity and lower blocking probability are achieved while higher forced termination probability is suffered.

Finally, we would like to emphasize that the system capacity presented above is considered from the whole secondary network's point of view. If we look at the picture from an individual SU service's perspective, the conclusion will be different. That is, the successful SU service will enjoy higher data rate, shorter service time and lower forced termination probability by using the assembled higher-bandwidth channel to carry its traffic, however, at a cost of higher blocking probability of other SUs' access attempts.

V. CONCLUSIONS

This paper analyzes channel assembling strategies for CRNs under the scenarios when channels are not time slotted, the time scale of PU activities are comparable with that of the secondary networks, and spectrum handover is unavailable. CTMC models are built according to different channel assembling strategies. The obtained numerical results show that the system capacity with channel assembling is generally lower than what is achieved by conventional single channel transmissions. This means that no channel bonding/aggregation is preferred for a dynamic network in the sense of system capacity. When channel bonding/aggregation is activated, better performance is observed for schemes which allow parallel SU transmissions, i.e., when fewer channels are assembled. This conclusion indicates that one should not bond or aggregate too many channels when designing a channel assembling strategy.

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