CR-MEGA: Mutually Exclusive Guaranteed Access Control for Cognitive Radio Networks

Muhammad Shafiq, Seonghun Son, Jin-Ghoo Choi and Heejung Yu
Department of Information and Communication Engineering
Yeungnam University, Gyeongsan, Korea
Email: {shafiq.pu, seonghunie}@gmail.com, {jchoi, heejung}@yu.ac.kr

***Abstract*—In Cognitive Radio (CR) networks, unlicensed Secondary Users (SUs) can occupy the white spaces of spectrum channels when licensed Primary Users (PUs) do not use them. Hence, for the operation of CR networks, it is critical to coordinate spectrum accesses of SUs and protect the ongoing communication of PUs. In this paper, we propose a new medium access control protocol for SUs, called Mutually Exclusive Guaranteed Access for Cognitive Radio networks (CR-MEGA). CR-MEGA adopts a dual sensing approach (i.e., carrier sensing and spectrum sensing) to avoid packet collisions with faraway PUs as well as nearby SUs. Our scheme performs well even in the harsh condition with highly active PUs, but the advantage comes with the increased sensing delay. We analyze the throughput and delay of CR-MEGA using the Markov chain model, and investigate the impacts of various parameters with numerical results.**

Keywords*—*Cognitive radio networks; dynamic spectrum access; spectrum sensing; carrier sensing; CSMA/CA

I. INTRODUCTION

Spectrum access for wireless applications becomes a threat to its effectiveness due to the emerging demand of wireless enabling technologies such as Bluetooth, ZigBee, WiFi, 6LowPAN, etc., to connect the tremendous number of devices into the Internet [1]. The wireless devices will demand huge amount of radio spectrum in the near future but even now, we do not have much frequency band available. This incredible advancement has overwhelmed the limited resources of Industrial, Scientific and Medical (ISM) license-free bands, and so it can provoke the spectrum scarcity in future. Moreover, spectrum scarcity is also caused by the traditional static spectrum allocation strategy due to the substantial wastage of temporal and geographical white spaces in the licensed bands.

We can find various observations [2]–[5] that criticize the traditional static spectrum allocation paradigm, since transmissions by licensed users only cover the limited geographical spaces and consume spectrum resources for certain duration. For example, spectrum utilization even in urban areas of United States is limited to 20%–30% portion of the total available resources [4], which are statically allocated by the Federal Communications Commission (FCC)[1]. The notable wastage of spectrum, is therefore, necessitate the shift of conventional static spectrum allocation towards the dynamic spectrum allocation paradigm on the immediate basis.

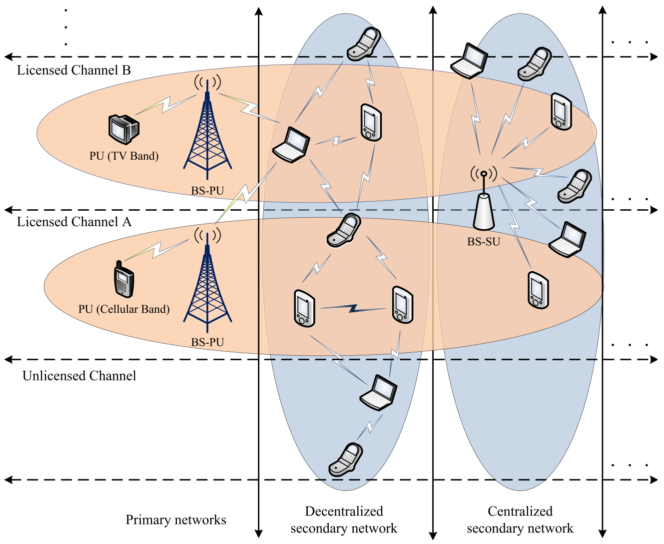


Fig. 1. Typical architecture of cognitive radio networks.

The FCC has agreed the proposal to permit licensed bands for unlicensed users in order to utilize the white spaces [4]. This acquiescence has eventually opened a gateway towards the promotion of cognitive radio (CR) [6]. This is one of the promising technologies to resolve the spectrum shortage issue because in CR networks, the wireless devices can exploit the white spaces of adjacent wireless systems opportunistically. CR technology has great potential to resolve the scarcity of spectrum resources and to meet the demand of bandwidth hungry applications for next generation wireless networks.

In CR networks, devices autonomously observe, orient, plan, learn, decide and act to exploit the white spaces [7] under the heterogeneous environment. The Secondary Users (SUs) not only imply to exploit the licensed spectrum opportunistically, but they are also required to maintain the transmission priority rights of Primary Users (PUs). In this connection, an CR transceiver dynamically scans the licensed spectrum to occupy the white spaces and intelligently shift its transmission or reception parameters to other frequency band, once it is claimed by the incumbent PU. Failing to maintain this priority, SU's transmission could cause harmful interference to PU [8]. Hence, mutually exclusive access to licensed band is an ultimate quality parameter of CR networks. However, it is very hard to be maintained by a nontrivial Medium Access Control (MAC) protocol due to several reasons such as vulnerable

---

[1] This is an independent official agency of the United States to control and regulate the spectrum licenses for interstate communications.

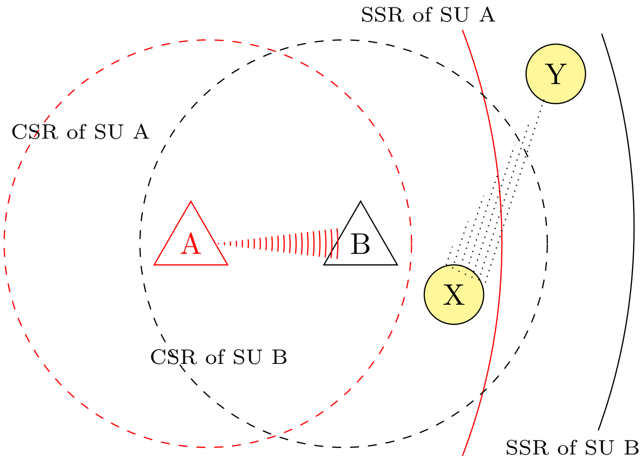


Fig. 2. Scenario of hidden primary node problem.

sensing ability of the sensor, non-cooperative heterogeneous environment, and unpredictable activity status by PUs.

The typical CR network architecture can be classified into centralized and decentralized networks as shown in Fig. 1. The centralized network, also named as Wireless Regional Area Network (WRAN) [9], is usually supported by the centralized Base Station (BS). In general, a BS covers limited range for the provision of communication services to the SUs that are located in its serving zone. On the other hand, decentralized network, usually called as Cognitive Radio Ad Hoc Network (CRAHN), lacks centralized control due to infrastructure-less architecture. Nevertheless, the centralized control in WRAN looks more purposeful due to ease of coordination and better channel access among SUs. Meanwhile, cost efectiveness, less complexity, and ease of deployment have ultimately made the CRAHN more attractive. However, the lack of centralized BS causes many challenges in CRAHN such as the hidden primary node problem [10]–[12].

Fig. 2 illustrates the typical scenario of hidden primary node problem, where the dotted lines delineate the Carrier Sensing Range (CSR) and the solid lines represent the Spectrum Sensing Range (SSR), respectively. We see that a transmission between SU A and SU B is in progress. Meanwhile, PU X and PU Y are located outside the CSRs of SU A and SU B, respectively. In carrier sensing, channel idle for Data Interframe Spacing (DIFS) interval found by SU A can only ensure the silence of PUs located within its CSR but not that of PU X. Conversely, in spectrum sensing the ability of SU A is only limited to evaluate the status of PU X involved in transmission as a transmitter but not as a receiver. This is because of the inability of SU A to receive the transmission singles of PU Y to PU X. Therefore, the transmission of SU A to SU B will essentially affect the possible transmission of PU Y to PU X. This is because of the fact that PU Y is hidden from the SU A.

Usually, there exist a non-collaborative environment among primary and secondary networks. And, only the exchange of classical Request-To-Send (RTS) and Clear-To-Send (CTS) frames, as in CSMA/CA [13], does not guarantee the silence of hidden primary node in CR networks. Furthermore, availability of white spaces is time, space, and frequency dependent due to intrinsic properties of radio spectrum. Thus, purpose build MAC protocols are desirable to efficiently utilize the white spaces and avoid interference to PU.

We can find several MAC protocols in previous literature to resolve the hidden primary node problem in decentralized CR networks [14]–[16]. Especially, in [16], the secondary transmitter broadcasts a control frame named as Prepare-To-Sense (PTS) to begin the spectrum sensing operation with the secondary receiver. The transmitter and the receiver both simultaneously conduct the sensing operations to ensure the silence of adjacent PUs, then they can simply exchange the RTS and CTS frames as explained in traditional CSMA/CA standard [13]. However, this scheme could cause interference to PU since the PTS frame is transmitted bluntly without making sure the silence of PU.

In this paper, a mutually exclusive guaranteed access control protocol for cognitive radio networks, named as CR-MEGA, is proposed. CR-MEGA is based on the random access model, in which a four way handshaking mechanism is used to complement the benefits of carrier sensing and spectrum sensing. The secondary transmitter first performs the carrier sensing during the DIFS interval to ensure the silence of other SUs. When the channel is found free, the transmitter concedes the backoff process in order to avoid collisions with the other SUs. Later, the winning transmitter conducts the spectrum sensing in order to ensure the silence of adjacent PUs. When the channel is found clear from the activity of adjacent PUs, the transmitter broadcasts the Notify-To-Sense (NTS) frame. The NTS frame informs the secondary receiver to conduct the spectrum sensing operation as well. Otherwise, the transmitter undertakes the blocking operation for the fixed interval. On the other hand, the receiver responds with the Acknowledge-To-Sense (ATS) frame, if the channel is found clear from the activity of adjacent PUs. Otherwise, the transmitter also returns to the blocking operation and so holds the ATS frame.

The spectrum sensing operations are performed to ensure the silence of all the adjacent PUs to the transmitter and the receiver. When all the adjacent PUs are found inactive, transmitter and receiver then exchange the RTS and CTS frames, as part in classical CSMA/CA protocol [13]. This is so that to hold the other SUs from accessing the channel through the Network Allocation Vector (NAV) updating. The transmitter sends the DATA frame to the receiver after the successful sharing of RTS and CTS frames. Finally, the receiver sends the ACK frame as an acknowledgment of the DATA frame received successfully. This is the way the transmitter operates proactively to ensure the transmission opportunity and maintain priority to PU.

The rest of paper is organized as follow. Section II states the system model. Section III describe the proposed protocol. Section IV presents the performance analysis of the proposed protocol. Finally, the last section draws our conclusion.

II. SYSTEM MODEL

We consider N SUs in a single hop decentralized secondary network. All the SUs coexist with the PUs within the jurisdiction of the primary network. Both networks operate in a non-collaborative way since no communication exist between SUs and PUs. The communication in secondary network occurs on an error-free channel and packet loss takes place only due to collisions among SUs or interference with PUs. SUs can utilize the white spaces of the licensed channel whenever all the neighboring PUs are found inactive. However, the SUs are bound to vacate the channel, whenever it is claimed by the PU. The neighboring PU of each SU can be $active$ and $inactive$ with a binary probability π_1 and π_0, respectively.

The detection ability of the SU is vulnerable due to the imperfect sensing results. This situation may get worse under the low Signal-to-Interference-Noise Ratio (SINR) regime. Ultimately, incidences of misdetection and false alarm may happen, which can affect the performance of SUs. In misdetection, the sensor in SU announces the channel as idle while there is an ongoing transmission by PU. Then, the transmitter may continue transmission and cause interference to PU. The misdetection probability of SU a is written as

$$p_{\sigma,a} = 1 - p_{\upsilon,a}, \tag{1}$$

where $p_{\upsilon,a}$ is the detection probability of the SU a. However, in false alarm the sensor waste time by losing the transmission opportunity of the transmitter. The false alarm probability of SU a, as defined in [17], is given by

$$p_{\eta,a} = Q\Big(\sqrt{2\gamma+1}\cdot Q^{-1}(1-p_{\sigma,a}) + \sqrt{T_{cy}}\cdot\gamma\Big), \tag{2}$$

where false alarm probability, $p_{\eta,a}$, is the function of sensing period T_{cy}. $Q(\cdot)$ is the complementary distribution function of the standard Gaussian distribution, and γ is the received SINR measured at the secondary receiver when PU is active.

The detection probability of energy sensor in SU can be enhanced by adopting a matched filter detection or a cyclostationary features based spectrum sensing technique [18], [19]. Moreover, the MAC protocol can also improve the detection performance by keeping other SUs quite during the spectrum sensing period to avoid overestimation of signal's power. This lead controls the incidence of false alarm and misdetection.

We consider the single channel model for SUs and PUs. However, the proposed protocol is extendable to operate on multichannel model with minimal modifications.

III. PROPOSED MAC PROTOCOL

The proposed protocol, CR-MEGA, is inspired by the traditional CSMA/CA protocol. The both protocols are based on the random access model. Therein, the time is divided into equal time slots. So, the transmitters are only allowed to access the channel at the beginning of each slot. First of all, the intended secondary transmitters perform the carrier sensing for the DIFS interval. If the channel is found free for that period, then transmitters contend through the random backoff procedure to win the channel. The winning transmitter conducts the spectrum sensing, while the other transmitters concede the backoff procedure to avoid the collisions. As mentioned, our protocol enables the carrier sensing with the spectrum sensing so as to protect the priority rights of PUs. To this end, it uses the Notify-To-Sense (NTS) and Acknowledge-To-Sense (ATS) frames with the RTS/CTS procedure in a four way handshake between transmitter and receiver.

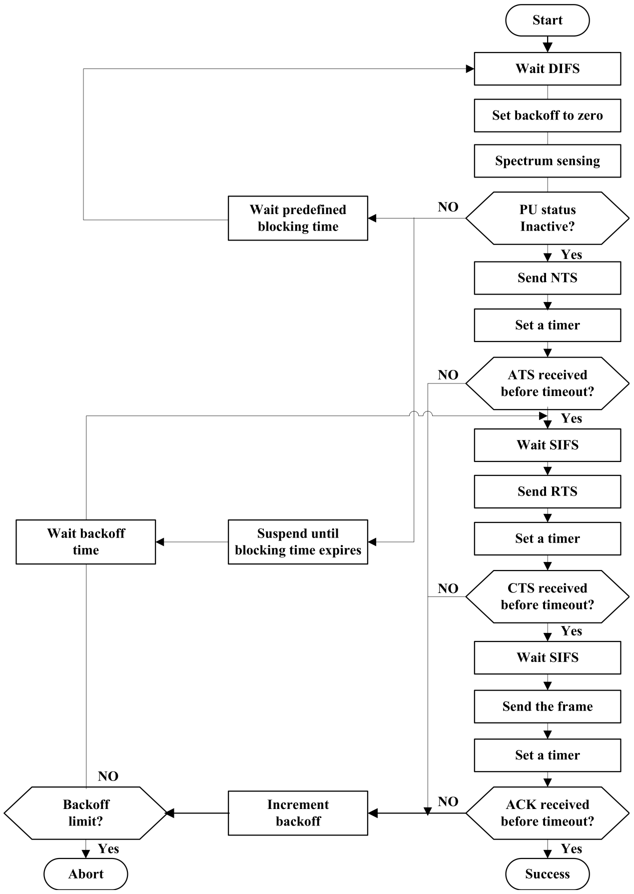


Fig. 3. Operation of secondary transmitters in CR-MEGA.

Right after the spectrum sensing, if the channel is free from the activity of adjacent PUs, the secondary transmitter broadcasts an NTS frame. This is so that the secondary receiver can also continue the spectrum sensing operation. Otherwise, the transmitter stops the transmission for a predefined blocking period to protect the PUs. Conversely, if the channel is free from the activity of hidden primary nodes, the receiver replies with the ATS frame. Otherwise, the receiver holds the ATS frame and returns into the blocking mode. If the ATS frame is received successfully, the transmitter broadcasts the RTS frame to keep the exposed secondary node silent until the CTS frame is received. Otherwise, the transmitter concedes the backoff procedure to hold the transmission. On the contrary, the receiver responds with the CTS frame to keep the hidden secondary node silent until the data transmission is over. Hence, the transmitter sends the DATA packet when it receives the CTS frame. Failing to do so, the transmitter returns to the backoff procedure. Otherwise, the receiver responds with the ACK frame to acknowledge the received DATA packet.

The detailed operation of the secondary transmitter under the CR-MEGA system is illustrated in Fig. 3. We also mention that CR-MEGA shares the similar backoff procedure as that in standard CSMA/CA to avoid packet collisions among SUs. At the beginning of each transmission, the value of initial contention window $W_i = 2^m$ slots with the backoff stage $m = 0$. Hence, the value of backoff counter is chosen among $(0, W_m - 1)$ slots at randomly. The blockoff counter runs, when the channel is idle for DIFS interval, and continues to decrease by 1 for each slot. Whenever the backoff counter reaches to 0, the transmitter attempts for the packet transmission. On the contrary, the contention window size is doubled after each backoff with the increment in previous backoff stage, i.e., $m+1$, up to the upper bound $W_M = 2^M$ slots. Our protocol, however, adopts the blocking procedure along with the standard backoff procedure to protect the PUs. For each blocking operation, the transmitter stops the transmission activity for a predefined period. Meanwhile, the transmitter suspends the backoff counter until the blocking period is expired.

The spectrum sensing operations at the transmitter and the receiver could cause long sensing delay that can compromise the system performance. To this end, we can compensate the spectrum sensing delay by a design parameter, in which the MAC layer alternatively enables the fast sensing [20] and the fine sensing [21] techniques in the system. Usually, fine sensing is accomplished in a very short time as less than 1 ms. However, its performance is vulnerable under the low SINR regime because of the inability to distinguish the signal from the background noise. On the contrary, fine sensing requires long sensing time as the 25 ms to finish the sensing operation. It has better sensing performance due to cyclostationary feature detection but on the cost of long sensing delay.

The design of NTS frame contains the symbols of receiver address, packet type, and spectrum sensing duration as that in PTS [16]. In addition, NTS frame contains the symbol of sensing type to balance the sensing delay with the system performance. However, the structure of ATS frame contains the symbols of transmitter address and packet type only.

A. Data Transmission Procedure

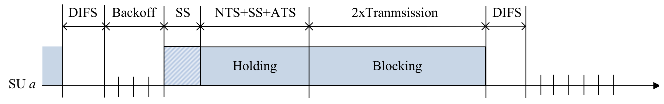
We now analyze the data packet transmission procedure of the CR-MEGA protocol. Every secondary transmitter attempts for data packet transmission, whenever its backoff counter is 0 and packet queue is non-empty. There exist one of the four mutually exclusive instances in the packet transmission attempt of the transmitter in each time slot, denoted as δ. These possible instances are: 1) Blocking at the secondary transmitter; 2) NTS-NTS collision; 3) Blocking at the secondary receiver; and 4) Successful transmission, which are denoted as $\Gamma_i, i = 1, \ldots, 4$. We henceforth calculate the encounter probability and the elapsed time of each possible incidence when it takes place. In this connection, the *channel clearance* probability of SU a is given as

$$\psi_a = (p_{\sigma,a}\pi_1) + (1 - p_{\eta,a})\pi_0, \tag{3}$$

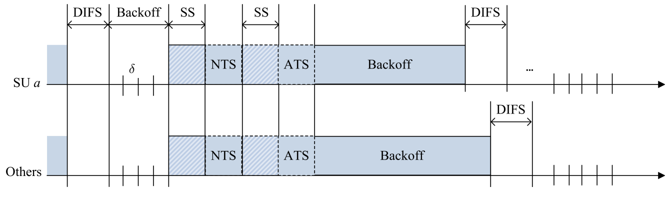
where π_1 is the active probability and π_0 is the inactive probability of the adjacent PUs, $p_{\sigma,a}$ is the misdetection probability as defined earlier, and $p_{\eta,a}$ is the false alarm probability of the SU a, respectively. Thus, SU a decides the inactivity of the neighboring PUs with the probability ψ_a.

Suppose that SU a has won the channel with the backoff counter 0, and then it has done the spectrum sensing operation. In this operation, incidence Γ_1 happens, when it finds the neighboring PUs active with probability

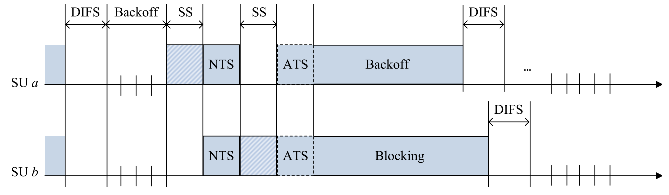
$$p_{1,a} = 1 - \psi_a. \tag{4}$$



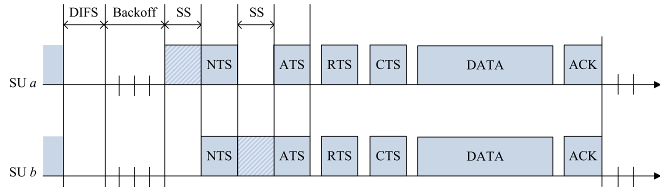
(a) Blocking at the secondary transmitter.



(b) NTS-NTS collision.



(c) Blocking at the secondary receiver.



(d) Successful transmission.

Fig. 4. NTS/ATS/RTS/CTS access mechanism in CR-MEGA.

Right after the Γ_1 happens, SU holds the transmission until the holding period is expired. The length of the holding period equals to that of $NTS+SS+ATS$, which is set to keep pace among the transmitters. Then, SU a undertakes the blocking period to protect the PUs. However, the length of blocking period is set equal to the twice of the data transmission period. As shown in Fig. 4(a), the t_1 time for which the SU a holds the transmission is given as

$$t_{1,a} = SS + HLP + DIFS. \tag{5}$$

where SS and HLP represent the length of spectrum sensing and that of holding period at the transmitter.

Suppose that SU a has found the clear channel and it has broadcast the NTS frame. Ultimately, it waits for the ATS frame to be heard from the receiver. However, the ATS frame is not necessarily received by the SU a due to the collision of multiple NTS frames. We have defined this incidence as a Γ_2, which can happen with the probability

$$p_{2,a} = \psi_a\left(1 - \prod_{n=2}^{N}\left(1 - \vartheta_n\tau_n\psi_n\right)\right), \tag{6}$$

where τ_n is the transmission probability of SU n and ϑ_n is its queue non-empty probability and ψ_n is its channel clearance probability. However, $1 - \vartheta_n\tau_n$ is the probability that SU n does not involve in transmission. Hence, the second part in equation indicates that NTS of at least one SU out of n SUs, where $n = 2, \ldots, N$, collides with the NTS of SU a. As shown in Fig. 4(b), the length of Γ_2 period is given as

$$t_{2,a} = NTS + 2SS + ATS + DIFS. \tag{7}$$

We consider that the SU a has broadcast the NTS frame and so it expects to receiver the ATS frame from the SU b. However, the SU b is not likely to respond with the ATS frame due to the activity of hidden primary node. This situation refers to the incidence Γ_3, in which the corresponding receiver of the SU a is blocked with the probability

$$p_{3,a} = \psi_a (1 - \psi_b) \left(\prod_{n=3}^{N} \big(1 - \vartheta_n \tau_n \psi_n\big) \right), \tag{8}$$

where ψ_b is the channel clearance probability of SU b. The last part in equation indicates that none of the n SUs, where $n = 3, \ldots, N$, collides with the SU a. Fig. 4(c) shows the length of Γ_3 period, which is written as

$$t_{3,a} = NTS + 2SS + ATS + DIFS. \tag{9}$$

Now, we consider the incidence of successful transmission between the SUs a and b. In this case, SU a sends the NTS frame and receives the ATS frame successfully, since the channel is clear at the both ends. Then, the exchange of RTS and CTS frames ensures the transmission opportunity due to the NAV updating. Thus, SU a sends the DATA frame and SU b returns the ACK frame to finalize the transmission. For SU a, the encounter probability of incidence Γ_4 is as follows:

$$p_{4,a} = \psi_a \psi_b \big(1 - \vartheta_b \tau_b\big) \times \left(\prod_{n=3}^{N} \big(1 - \vartheta_n \tau_n \psi_n\big) \right). \tag{10}$$

As shown in Fig. 4(d), the length of Γ_3 period that is the elapsed time for the successful transmission is given as

$$\begin{aligned} t_{4,a} = {} & NTS + 2SS + ATS + RTS + CTS \\ & + DATA + 4SIFS + ACK + DIFS, \end{aligned} \tag{11}$$

where ACK and $DATA$ account for the transmission period of an ACK frame and that of an DATA frame, respectively. However, $SIFS$ is the length of Short Interframe Spacing as that is used in CSMA/CA to shift the transceiver mode.

IV. PERFORMANCE ANALYSIS

In this section, we evaluate the performance of our CR-MEGA protocol in terms of normalized throughput and average delay. To this end, we model the backoff process in CR-MEGA system with the two dimensional Markov chain model. As illustrated in Fig. 5, the Markov chain model has backoff states being the values of two random processes of backoff counter b and backff stage m at slot time t. We note that our Markov model is similar to that in [22] due to the common backoff process. However, keeping in view the autonomous status of primary network, we used the blocking probability p_b as the measure of PU's activity. The blocking probability p_b shares the similar meanings to that of PU's active probability π_1 under the perfect sensing environment. This is because that the sensor in SU a cannot encounter the incidence of false alarm and/or misdetection under an ideal scenario. For the sake of simplicity and ease of notations, however, we henceforth assume that both terms are equal such that $\pi_1 = p_b$.

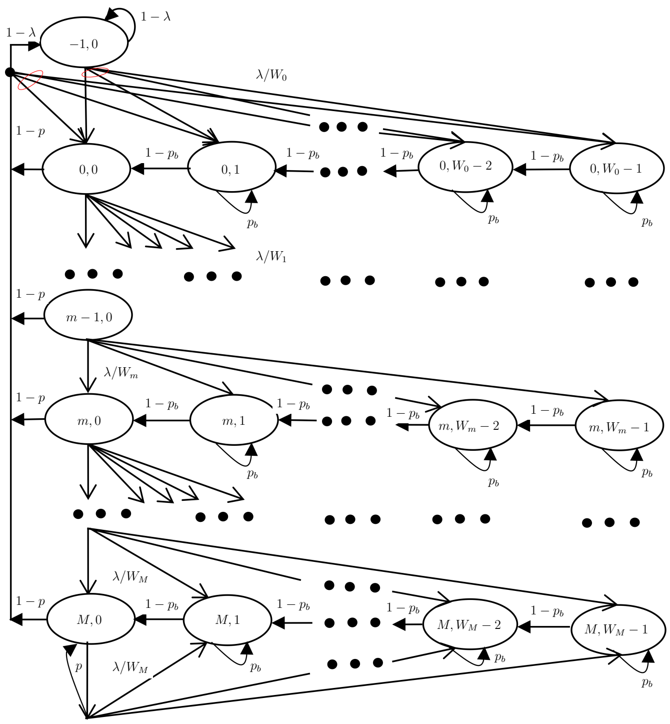


Fig. 5. Backoff process Markov chain model in CR-MEGA.

For each blocking, SU a freezes its backoff counter with the probability p_b. Otherwise, it releases the counter with probability $1 - p_b$. However, it concedes the backoff process for each packet collision among the SUs. Similarly, the SU a's transmission fails due to collision with the probability p and it succeeds with the probability $1 - p$.

We now directly refer to the results of [22] for stationery probability on state $b_{0,0}$ as (12), where λ denotes the packet arrival rate. And, the collision probability p is given as

$$p = \left[1 - (1 - \tau_a)^{N-1}\right] + \left[(1 - \tau_a)^{N-1} \times \pi_1\right], \tag{13}$$

where the first term refers to the probability that at least one arbitrary SU out of $N - 1$ users transmits in the same slot and creates collision. And, the second term accounts for the probability that the channel is blocked. However, the transmission probability of the transmitter in [22] remains unchanged as (14). We recall that τ_a is the packet transmission probability of SU a with the backoff counter 0.

A. Normalized Throughput

We analyze the performance of the system under the CR-MEGA protocol with the following assumptions:

- The sensing environment is perfect such that there is no provision of false alarm and misdetection.
- The channel is error-free and packets only drop due to collisions among SUs.

$$b_{0,0} = \frac{2(1-2p)(1-p)}{\left[(1-2p)(W_0+1) + pW_0(1-(2p)^m) + 2(1-2p)(1-p)\frac{1-\lambda}{\lambda}\right]}, \tag{12}$$

$$\tau_a = \sum_{i=0}^{m} b_{i,0} = \frac{2(1-2p)}{\left[(1-2p)(W_0+1) + pW_0(1-(2p)^m) + 2(1-2p)(1-p)\frac{1-\lambda}{\lambda}\right]}, \tag{14}$$

- There is no limit for packet transmission attempts such that a transmitter can continue to transmit until the packet is transmitted, successfully.
- The secondary network is single hop and it has no collaboration with the primary network.
- There is no common control channel in the secondary network such that control and data packets both are transmitted in the single shared channel.

Let throughput of a CR system is the relationship

$$S = \frac{\text{Average data transmitted in a slot}}{\text{Average length of a slot}}. \tag{15}$$

The average data transmitted in a slot, as calculated in [23], is given by $p_t p_s E[D]$. p_t be the probability that at least one user, say as SU a, among the N users transmitting in the current slot, which is written as

$$p_t = 1 - (1-\tau_a)^N, \tag{16}$$

$p_s = p_{4,a}$ as that in (10). $E[D]$ is the average data in bits with the PHY and MAC headers to be transmitted in a given transmission rate. However, the average length of a slot includes the probability of idle, probability of success, and that of collision for each slot, which is given as

$$E[\theta] = (1-p_t)\delta + p_t T_s ps + p_t(1-p_s)T_c \tag{17}$$

where $T_c = t_{1,a} = t_{2,a} = t_{3,a}$ and $T_s = t_{4,a}$, as that in (5), (7), (9) and (11), respectively. We dropped the subscript a, as all the transmitters are assumed to have equal sensing ability, to avoid confusion. Thus, (15) can be written as

$$S = \frac{p_t p_s E[D]}{(1-p_t)\delta + p_t T_s ps + p_t(1-p_s)T_c}. \tag{18}$$

B. Average Delay

We now evaluate the average packet delay under the CR-MEGA system. To this end, we used the similar approach as that is described in [24] since the backoff process is shared and standard. The average packet delay that a packet concedes for the successful transmission is given as

$$X = E[H] \cdot E[\theta], \tag{19}$$

where $E[H]$ refers to the average length of the slots that a packet observes until its successful transmission, $E[\theta]$ is the average length of a slot that we already obtained in (17). Hence, the $E[H]$ as in [24] is readily given as

TABLE I. DEFAULT PARAMETERS IN ANALYSIS

Symbol	Value
PHY header	120 bits
MAC header	272 bits
DATA (or Payload)	1024 Bytes
NTS frame	160 bits + PHY header
ATS/ACK frame	112 bits + PHY header
Channel bit rate	1 Mbps
Activity rate of adjacent PU	0.1
Spectrum sensing time	0.5 ms
DIFS time	50 μs
SIFS time	10 μs
Slot time	20 μs
Maximum backoff stage	5
Initial (or Minimum) contention window size	32
Maximum contention window size	1024

$$E[H] = \sum_{k=0}^{m} = \left[\frac{(p^k - p^{m+1})\frac{W_k+1}{2}}{1-p^{m+1}}\right]. \tag{20}$$

$E[H]$ does not holds for the packets that have been dropped. Only the packets that have been successfully delivered with $p^k - p^{m+1}$ probability are considered to derive the average packet delay. The term $\frac{(p^k - p^{m+1})}{1-p^{m+1}}$ states that a packet reaches the k-th stage in the backoff process of the transmitter.

C. Results and Discussion

We now discuss the performance results of the proposed protocol. Unless otherwise specified, the parameters used in the analysis are summarized in Table I.

Fig. 6 describes the effect of the number of SUs N over the normalized throughput S at the different sizes of the minimum contention window. We observe that S curve increases first, then decreases monotonically with the increase in N. This is because of the fact that secondary network remains unsaturated at the small N while it creates collisions at the large N, so decrease in throughput. When the network is saturated, throughput of the system reaches to its maximum stage due to the increase in packet rate and successful transmission. However, the gap between the S curves is attributed due to the different sizes of the minimum contention window. At the small N, the small window outperforms the large windows. This is because that the large window wastes more channel in the backoff compared to the small windows at the small N. Conversely, the large window outperforms the small windows at the large N because it can better resolves the collisions.

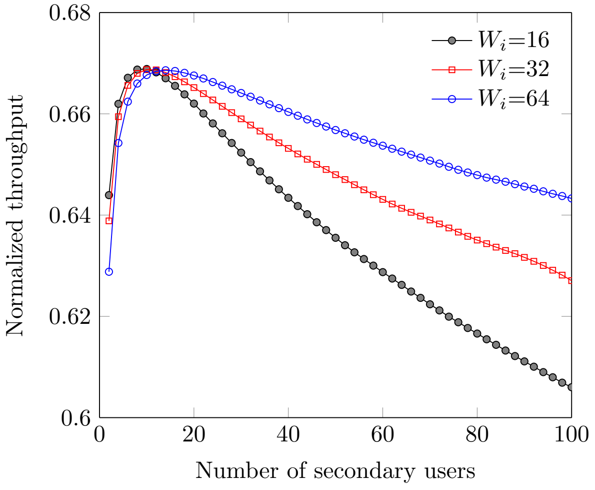


Fig. 6. Normalized throughput vs. size of network.

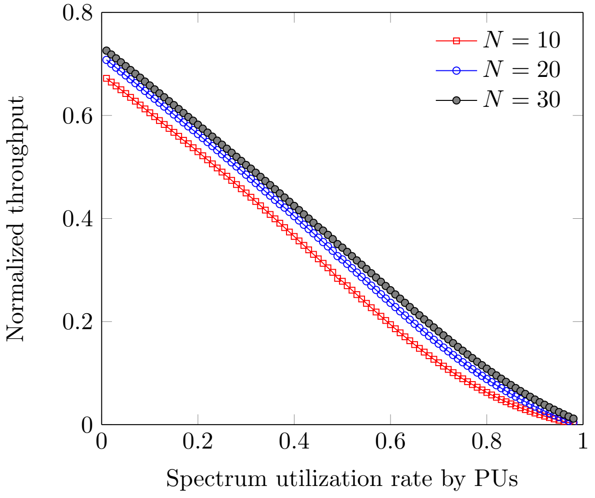


Fig. 7. Normalized throughput vs. activity rate by PU.

Fig. 7 shows the effect of spectrum utilization rate by PU over the normalized throughput at different values of N. We varied the activity rate of PU π_1 within 0 to 1 scale and observe that the values of S decrease with the increase in π_1. When activity rate by PU increases, secondary network more an more likely to generate spectrum access to the primary network due to increase in blocking probability, and so decrease in throughput. However, the gap in S curves is attributed due the different number of SUs, N. We witness that the higher value of N outperforms the lower values of N, because it can improve packet rate and so increase the throughput.

Fig. 8 exhibits the effect of packet arrival rate λ over the throughput. We see that secondary network achieves saturation until a certain limit with the increase in packet arrival rate, and then enters into steady state. This phenomenon can be explained due to the fact that during the transition of secondary network from the unsaturated state to the saturated state, the behavior of S curve is dominated by p_s and λ. That is why the performance of network remains poor at small value of λ. However, after achieving the saturated state it becomes stable and no more aggravated by the increase in λ.

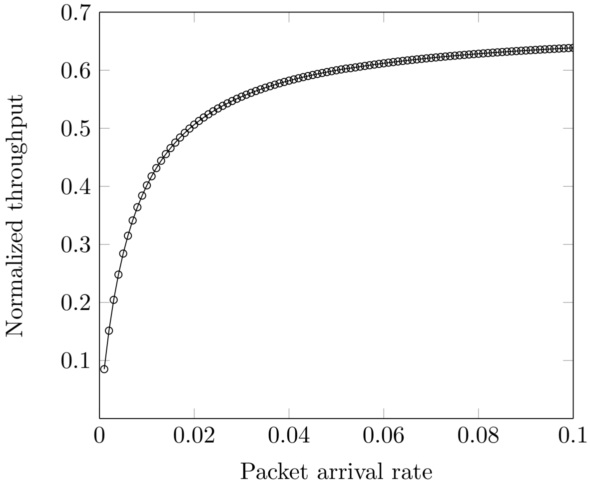


Fig. 8. Normalized throughput vs. packet arrival rate.

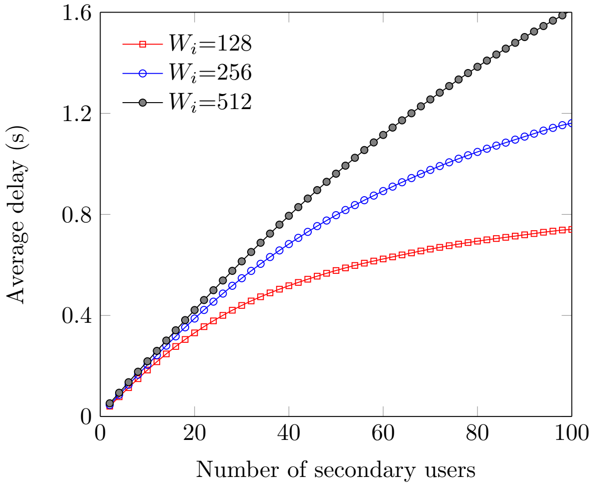


Fig. 9. Average delay vs. size of network.

Fig. 9 demonstrates the effect of the number of SUs N over the average packet delay X at different sizes of minimum contention window. We see that values of X curve keep monotonically increasing with the increase in N until a certain limit and then become steady. This is because that p increases with the increase in N due to large packet collisions. Eventually, SUs take large backoff to maximize p_s. But, each packet is more and more likely to stay in the buffer queue for the long time and thus increase in delay. However, the values of X curve become steady due the following two reasons: 1) the p_s is not aggravated by the collisions after a certain limit; 2) The backoff stages are limited due to the upper bound M. Hence, X curve is no more affected after the saturation sate. Further, we also observe that large window size can produce large backoff. In return, every data frame concedes higher delay to be transmitted successfully.

V. CONCLUSION

In this paper, we have proposed the CR-MEGA protocol, a new multiple access control scheme for CR networks. Under CR-MEGA, each secondary transmitter conducts carrier sensing and spectrum sensing before sending DATA frames, in order to protect the ongoing communication of PUs. When the channel is clear, the transmitter sends a PTS frame and triggers spectrum sensing at the receiver. Otherwise, it becomes blocked and holds the transmission for a predefined time. After receiving the PTS frame, the receiver can return an ATS frame when the channel is sensed clear. If the channel is not clear, the receiver also undertakes the blocking operation since there exist active hidden PUs. When both transmitter and receiver are not blocked, they exchange the standard RTS/CTS frames to avoid the hidden/exposed SUs. Successful exchange of the control frames allows the transmitter to send a DATA and the receiver replies with an ACK in sequence. In this way, our protocol minimizes the interference to active PUs. However, the dual sensing approach has the shortcoming of large sensing delay. To evaluate the performance of CR-MEGA, we have analyzed the protocol through the Markov chain model in terms of throughput and delay. Numerical results show that our scheme is suitable for non-collaborative CR networks since its performance is insensitive to the network size.

REFERENCES

[1] D. Evans. “The Internet of Things: How the Next Evolution of the Internet is Changing Everything.” Cisco Internet Business Solutions Group, 2011.

[2] T. Renk, K. Clemens, and J. Friedrich. “A cognitive approach to the detection of spectrum holes in wireless networks.” In Consumer Communications and Networking Conference, 2007. CCNC 2007. 4th IEEE, pp. 1118-1122. IEEE, 2007.

[3] R. Chiang. “Feasibility investigation of cognitive radio systems.” PhD diss., ResearchSpace@ Auckland, 2009.

[4] FCC, ET. “Docket No 03-222 Notice of proposed rule making and order.” Technical Report: 1-21, Dec., 2003.

[5] D. Cabric, M. S. Shridhar, W. Daniel, B. Robert, and W. Adam. “A cognitive radio approach for usage of virtual unlicensed spectrum.” In 14th IST mobile and wireless communications summit, 2005.

[6] J. Mitola and G. Q. Maguire. “Cognitive radios: making software radios more personal.” IEEE Pers. Commun., vol. 6, no. 4, pp. 13-18, 1999.

[7] S. Haykin. “Cognitive radio: brain-empowered wireless communications.” IEEE J. Sel. Areas Commun., vol. 23, no. 2, pp. 201-220, 2005.

[8] R. Zhang and Y.-C. Liang. “Investigation on multiuser diversity in spectrum sharing based cognitive radio networks.” IEEE Commun. Lett., vol. 14, no. 2, 2010, pp. 133-135.

[9] The IEEE 802.22 WRAN working group website. [Online]. Available: http://www.ieee802.org/22/ page 4, 2008.

[10] G. Ganesan, and L. Ye. “Cooperative spectrum sensing in cognitive radio networks.” In New Frontiers in Dynamic Spectrum Access Networks, 2005. First IEEE Int. Symposium on, pp. 137-143. IEEE, 2005.

[11] G. Ganesan, and L. Ye. “Agility improvement through cooperative diversity in cognitive radio.” In Global Telecommunications Conference, 2005. GLOBECOM’05. IEEE, vol. 5, pp. 2505-2509. IEEE, 2005.

[12] D. Cabric, T. Artem, and B. Robert. “Spectrum sensing measurements of pilot, energy, and collaborative detection.” In Military communications conference, 2006. MILCOM 2006. IEEE, pp. 1-7. IEEE, 2006.

[13] IEEE standard for Wireless LAN-Medium Access Control and Physical Layer Specification, P802.11, Nov. 1997.

[14] S. C. Jha, U. Phuyal, M. M. Rashid and V. K. Bhargava. “Design of OMCMAC: An Opportunistic Multi-channel MAC with QoS Provisioning for Distributed Cognitive Radio Networks.” IEEE Transactions on Wireless Communications, Vol. 10, No. 10, 2011, pp. 3414-3425.

[15] Q. Zhao, L. Tong, A. Swami and Y. Chen. “Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework.” IEEE Journal on Selected Areas in Communications, Vol. 25, No. 3, 2007, pp. 589-600.

[16] Q. Chen, W. Wai-Choong, M. Mehul, and L. Ying-Chang. “MAC protocol design and performance analysis for random access cognitive radio networks.” IEEE Journal on Selected Areas in Communications 31, no. 11, 2013, pp. 2289-2300.

[17] D. Wong, S. Zheng and Y. Liang. “Cognitive multi-channel mac protocols with perfect and imperfect sensing.” In Communications (ICC), 2011 IEEE International Conference on, pp. 1-5. IEEE, 2011.

[18] Y.-C. Liang, Y. Zeng, E. Peh, and A. T. Hoang. “Sensing-throughput tradeoff for cognitive radio networks,” IEEE Trans. Wireless Commun., vol. 7, no. 4, 2008, pp. 1326-1337.

[19] I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury. “CRAHNs: Cognitive radio ad hoc networks.” Ad Hoc Networks Journal (Elsevier), vol. 7, no. 5, 2009, pp. 810-836.

[20] H. Arslan, T. Yucek. “Spectrum sensing for cognitive radio applications.” In Cognitive Radio, Software Defined Radio and Adaptive Wireless Systems, Springer Netherlands press, pp. 263-289, 2007.

[21] P. D. Sutton, K.E. Nolan, and L.E. Doyle. “Cyclostationary signatures in practical cognitive radio applications.” IEEE Journals on Selected Areas in Communications, vol. 26, no. 1, 2008, pp. 13-24.

[22] S. Kumar, S. Nirmal, R.M. Chandra, and A. Arun. “Throughput analysis of primary and secondary networks in a shared IEEE 802.11 system.” IEEE Transactions on Wireless Communications, vol. 12, no. 3 2013, pp. 1006-1017.

[23] G. Bianchi. “Performance analysis of the IEEE 802.11 distributed coordination function.” IEEE Journal on selected areas in communications, vol. 18, no. 3, 2000, pp. 535-547.

[24] P. Chatzimisios, B. Anthony, and V. Vasileios. “IEEE 802.11 packet delay-a finite retry limit analysis.” Global Telecommunications Conference, 2003. GLOBECOM’03. IEEE. Vol. 2, pp. 950-954, IEEE, 2003.