Design and Performance Analysis of Enhanced Directional MAC Protocols for Cognitive Radio Wireless Mesh Networks

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Abstract. This paper presents the design and analysis of directional random access MAC protocols for cognitive radio wireless mesh network (CRWMN). We have proposed three directional random access MAC protocols for CRWMNs using three different access mechanisms called Directional CSMA/CA MAC protocols for Cognitive Radio (DCR-MAC). An event driven simulator is used to make performance comparison for the three MAC protocols. Moreover, the performances of the DCR-MAC protocol for the three access mechanisms are also compared with an omni-directional CRMAC protocol in terms of average throughput and average packet delay. The performances of the proposed directional protocols show better performance for CRWMN.

Keywords: Cognitive radio wireless mesh network (CRWMN) · MAC protocol · Random access mechanisms · Directional MAC

1 Introduction

Directional antennas have many advantages over omni-directional antenna system in wireless networks like improving network capacity, reducing interference, increasing coverage area, improving spectrum usage, improving energy efficiency, and so forth [1–4].

In spite of the major benefits of directional antenna to the wireless domain, it has introduced new challenges to the MAC layer. The most popular MAC protocol in the wireless networks particularly in the wireless LAN and multi-hop wireless networks is the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The CSMA/CA MAC protocol might not be used with directional antenna without modification, because of the newly emerged challenges such as deafness, New Hidden Terminal Problem (NHT), Head-of-Line Blocking, Communication Range Under-Utilization, Neighbors Location Discovery, and MAC-Layer-Capture [5–7].

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2 Directional MAC Protocol for CRWMNs

In this section we are going to present our works which is the design of directional random access MAC protocol for cognitive radio networks (CRNs) in general and to CRWMNs in particular. WMN has either a chain or grid types of networking topology. In the WMNs the nodes are connected in such a way that traffic is generated in to or away from the mesh gateways (MGs). The mesh routers (MRs) located in the proximity of the MG are more congested than those which are located far away from the MRs.

We are proposing a CRWMN where the MRs and the MGs are equipped with multiple antenna systems. The MRs and the MGs are empowered by cognitive radio (CR) capabilities. The MRs and the MGs performs spectrum sensing using the multiple antenna systems so as to decrease the spectrum sensing time, and improves the PUs detection probability and decrease the probability of false alarm. By using beamforming techniques it is possible to improve the spectrum utilization efficiency of the opportunistically available spectrum, and the network capacity by allowing concurrent transmission [8, 9].

More importantly, to manage the traffic congestion created due to the mesh networking topology, it could be possible to assume MRs which are more closer to the MG to be equipped with more number of antenna in relative to the MRs which are located far away from the MG(s) to reduce the system complexity. It could also be possible to equip the MGs with Massive MIMO systems so as to communicate concurrently with more than one MR at time.

Due to limited mobility, the locations of the MRs or MGs are known as a result it is possible to use MAC-MU-MIMO for the signaling phase to broadcast the signaling to all the remaining mesh nodes. This operation will help to reduce the effect of new hidden terminal problem which is seen in directional communication.

Consider a CRN which has uniformly distributed N number of secondary users (SUs) in a square area and each one of them are equipped with multiple antennas. Let U be an arbitrary SU, where the transmission and interference area of U with range d covers M number of SUs when it operates in omni-directional modes. Let ρ be the node density, therefore the number of nodes for a coverage range of d is given by

$$\mathrm{M} = \pi \mathrm{d}^2 \rho \tag{1}$$

For a directional antenna with beam width of θ, the number of nodes which is going to be covered by the beam produced by any arbitrary node U is given by

$$\mathrm{M_b} = (\theta/2\pi)\pi \mathrm{d}^2 \rho = (\theta/2)\mathrm{d}^2 \rho \tag{2}$$

The maximum number of concurrent transmissions becomes

$$\mathrm{N_c} = \mathrm{M}/\mathrm{M_b} = \left(\pi \mathrm{d}^2 \rho\right)/\left(\frac{\theta}{2}\mathrm{d}^2 \rho\right) = 2\pi/\theta \tag{3}$$

Analytically it is possible to drive the average number of links that could be established among the M SUs which is presented below.

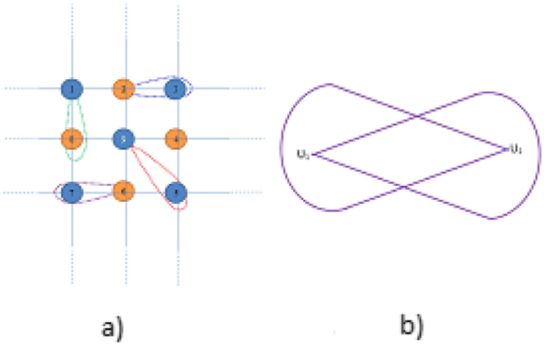


Fig. 1. (a) directional grid type mesh networking, (b) Pictorial representation of directional link between any arbitrary SUs

In Fig. 1(b) a directional communication link is presented between two SUs U1 and U2. When U1 establish link with U2, the area covered by the directional link is given by

$$A_{\text{link}} = \theta r^2 - \left(r^2/2\right)\tan(\theta/2) \tag{4}$$

The ratio of area of the surface covered by the directional communication to the disc surface area becomes /

$$A^{L}_{\text{ratio}} = (\theta r^2 - \left(r^2/2\right)\tan(\theta/2))/\pi r^2 = \left(\theta - \frac{1}{2}\tan\left(\frac{\theta}{2}\right)\right)/\pi \tag{5}$$

Then the maximum possible number of link that can be directionally established is given by

$$L_{\max} = \pi/\left(\theta - \frac{1}{2}\tan\left(\frac{\theta}{2}\right)\right) \tag{6}$$

Then, the average number of nodes covered with this directional communication given that a tagged node covers M nodes (uniformly distributed) in omnidirectional communication is given by

$$M' = MA^{L}_{\text{ratio}} = M\left(\theta - \frac{1}{2}\tan\left(\frac{\theta}{2}\right)\right)/\pi \tag{7}$$

Having this link successful, the remaining number of nodes which are eligible for establishing another concurrent successful communication is given by

$$M_1 = M - M' = M\left(1 - \left(\theta - \frac{1}{2}\tan\left(\frac{\theta}{2}\right)\right)/\pi\right) \tag{8}$$

Out of these M_1 nodes, the probability a node establishes a successful link without disturbing the initial communicating nodes is given by $\frac{M_1}{M}$. The remaining number of nodes which are eligible for establishing the next concurrent successful transmission is given by

$$M_2 = M - 2M' \tag{9}$$

Therefore, the minimum number of nodes which are eligible for establishing the last possible link is given by

$$\begin{aligned} M_{Lmax} &= M_{Lmax-1} - M' \\ M_{Lmax} &= M - L_{max}M' \\ M_{Lmax} &= M\left(1 - L_{max}\left(M\left(\theta - \tfrac{1}{2}\tan\left(\tfrac{\theta}{2}\right)\right)/\pi\right)\right) \end{aligned} \tag{10}$$

The probability of establishing the first link among any arbitrary pair of nodes from the M nodes domain is given by $\frac{M_0}{M}$, where $M_0 = M - 1$, for large number of nodes we can approximate $M_0 \cong M$. The probability of establishing a link with the remaining number of nodes without creating interference to the nodes of previously established link, is given by $\frac{M_i}{M}$, where $1 \le i \le L_{max}$, and M_i is the remaining number of nodes.

The average number of concurrent directional link can be calculated as follows

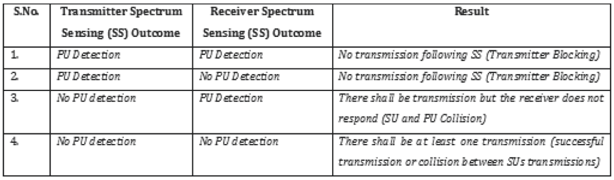
$$L_{avg} = \sum_{i=0}^{L_{maz}} M_i/M \tag{11}$$

Equation 3 shows that the maximum number of concurrent transmission is not dependent on the number of nodes, rather it is dependent on the radiation pattern (beamwidth) of the multiple antenna which is dependent on number of antenna elements, distance of separation between antenna elements and the excitation phase (it is analyzed in chapter three).

The proposed directional MAC protocols for CR system (DCR-MAC) are contention based protocols which are analyzed for the three access mechanisms, namely basic, RTS/CTS, and M-CTS mechanisms. Every transmission is performed directionally and reception is performed Omni-directionally between two SUs (SUs).

The DCR-MAC protocol operates as follows. DCR-MAC protocol operates in time slot bases. The time axis is divided in to time slots denoted by δ. An SU with a packet to transmit must performs carrier sensing, if it detects a signal from PU or SU, it will defer its transmission and continue its carrier sensing operation at the beginning of every time slots. A SU that detects no carrier will send a directional prepare to sense frame (DPTS) to the direction of the intended secondary receiver since it is assumed that every SU has location information of their neighbor SUs. Following the DPTS frame both of the users perform spectrum sensing to detect the presence of PU in their corresponding vicinity. The spectrum sensing outcomes might be either one of the following as presented in tabular form below (Table 1).

Table 1. Spectrum sensing outcomes of an arbitrary SU operating in sensing mode



S.No.	Transmitter Spectrum Sensing (SS) Outcome	Receiver Spectrum Sensing (SS) Outcome	Result
1.	*PU Detection*	*PU Detection*	*No transmission following SS (Transmitter Blocking)*
2.	*PU Detection*	*No PU Detection*	*No transmission following SS (Transmitter Blocking)*
3.	*No PU detection*	*PU Detection*	*There shall be transmission but the receiver does not respond (SU and PU Collision)*
4.	*No PU detection*	*No PU detection*	*There shall be at least one transmission (successful transmission or collision between SUs transmissions)*

Following the spectrum sensing operation outcomes, three contentions based medium access mechanisms for the directional CRN MAC protocol are proposed which essentially use multiple antenna technology. These access mechanisms are directional basic access mechanism, directional RTs/CTS mechanisms, and directional M-CTS access mechanism, which are shown in Figs. 2, 3 and 4. The basic operation principle of directional basic access and directional RTS/CTS access mechanisms is similar to the conventional IEEE 802.11 DCF protocols except its customization so as to suit the directional antenna and CRN behaviors.

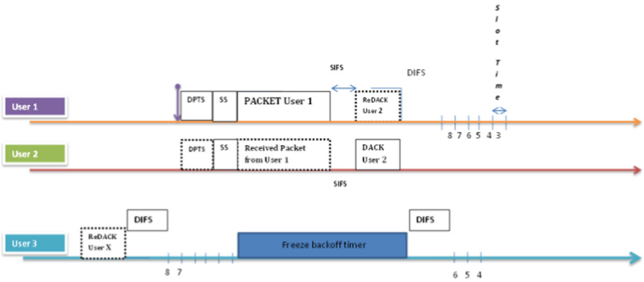


Fig. 2. Directional basic access mechanism for CRN

In the directional M-CTS access mechanism, a SU that wants to transmit make carrier sensing and if it does not detect any signal it sends PTS frame to the intended SU so as to reserve the coming slot for spectrum sensing and both of them perform spectrum sensing to detect the PU. The intended SU respond with RTS frame to the transmitting SU, following the RTS frame the transmitting SU transmit the data packet and if it is successfully received by the intended SU, the receiving SU will send an acknowledgment frame.

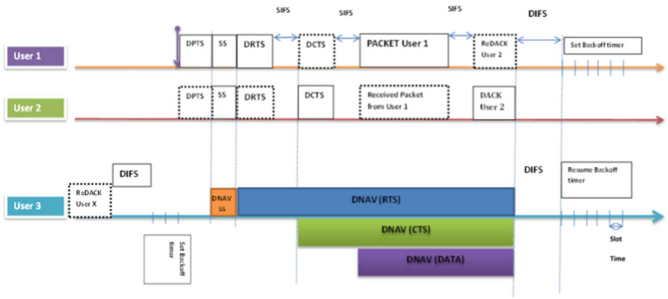


Fig. 3. Directional RTS/CTS access mechanism for CRN

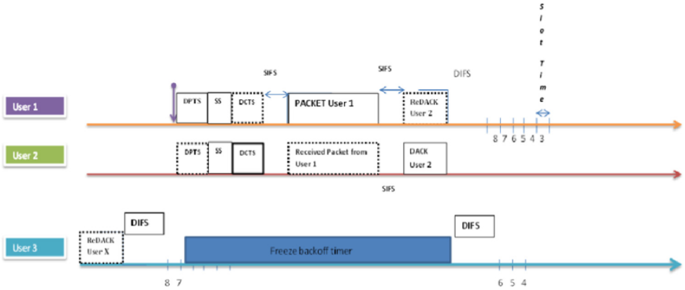


Fig. 4. Directional M-CTS access mechanism for CRN

The directional M-CTS access mechanism reduces one CTS frame and one SIFS compared to the directional RTS/CTS access mechanism, and compared to the directional basic access mechanism it introduces one RTS frame and one SIFS during a successful transmission process. When collision is detected on the channel, the amount of time an overhearing SU freezes its backoff timer will be smaller for the directional M-CTS access mechanism than the other two types. With respect to directional basic access, the hybrid access mechanism freezing time during collision is less than by the amount of time used to transmit a DATA packet, whereas with respect to directional RTS/CTS access mechanism the freezing time during collision is less than by the amount of time used to transmit an RTS frame.

3 Design and Performance Analysis of Directional CSMA/CA MAC Protocol for CRN (DCR-MAC)

In this section the design and analysis of directional CSMA/CA MAC protocols for CRNs are presented. The following assumptions are considered in the design and analysis of DC-RMAC. There is no SUs' mobility, every SUs knows the location of its neighbors, both transmission and reception are done in directional mode, the SUs always have packet to transmit (Saturated Condition), and there are M number of SUs under the omini-directional coverage of any arbitrary SU. The performance of DCR-

MAC for the three access mechanisms including the one that is proposed and analyzed in the previous chapter is presented. The proposed M-CTS access mechanism also shows better performance in the directional MAC protocol for the CRN. We have used different literatures for this work [11–23].

The packet transmission at each SU can be modeled as a single server queue system. Based on DCR-MAC, there exist five possible events occurring in directional packet transmission attempt between two arbitrary SUs. These are, Transmitter Blocking (E1), Collision between SUs' directional transmission to the direction of the same SU (E2), Collision between SU and PU transmission (E3), Receiver in Communication (E4), and Successful Directional Transmission (E5).

Now let's compute the probability and respective transmission period for each one of these events. First let's define two hypotheses on the status of neighboring PUs to an arbitrary SU. H0 represents the hypothesis that the neighboring PUs of a SU are not active, and H1 represents the hypothesis that the neighboring PUs of a SU are active. Let P_{H0} denotes the occurrence probability of event H0, and P_{H1} denotes the occurrence probability of event H1. Let's define additional variable V to denotes the probability a SU can access the channel, which can be expressed in terms of probability of false alarm (p_f), and probability of detection (p_d).

A SU can access the channel under two conditions; the first one is when the channel is idle and sensed idle by the SU, and the second one is when the channel is busy (it is being used by the PU(s)) but sensed idle by the SU. Therefore, the probability an arbitrary SU can access the channel is given by

$$V_k = \left(1 - p_{f,k}\right)P_{H0,k} + \left(1 - p_{d,k}\right)P_{H1,k} \tag{12}$$

Where k = 1, 2, 3, …, M

3.1 Transmitter Blocking (E1)

When a SU has a packet to transmit, first it performs carrier sensing. In the carrier sensing time if it doesn't detect any signal then it transmits prepare to sense (PTS) frame directionally to the intended secondary receiver. During the spectrum sensing period the transmitting SU may detect PUs and discontinue the communication, this is called transmitter blocking. The probability of this event considering an arbitrary SU, U1 as a transmitter is given by

$$P_{E1}^{D} = (1 - V_1) \tag{13}$$

The period of transmission failure due to event 1 for the three access mechanisms is given by

$$T_{E1}^{Dbas} = T_{E1}^{Drts} = T_{E1}^{Dmcts} = DPTS + SS + DIFS \tag{14}$$

When transmitter blocking occurs, the transmitting SU will defer its transmission for additional predefined blocking time (TB) but those SUs covered by the transmitting beam may attempt transmission after an additional time of DIFS if the channel is sensed idle at the beginning of the time slot.

3.2 Directional Transmission Collision Between SUs (E2)

DRTS failure occurs when more than one DRTS are sent to the direction of the intended receiver at the same time slot. At this time, the intended receiver fails to respond to the DRTS due to collision. Let us consider U2 as the receiver and U1 as the transmitter, and drive an expression for the probability of directional collision.

$$\begin{aligned} \mathrm{P_{DRTS}} &= \mathrm{prob.}\{\text{RTS transmission to } \mathrm{U_2'}\text{s direction at any time slot}\} \\ &= \mathrm{prob.}\{\text{a SUcan access the channel at any time slot}\}\mathrm{x} \\ &\quad \mathrm{prob.}\{\text{packet transmission by a SU at any time slot}\}\mathrm{x} \\ &\quad \mathrm{prob.}\{\text{packet transmission to the direction of } \mathrm{U_2}\} \end{aligned}$$

$$\mathrm{P_{DRTS,k}} = \mathrm{V_k}\tau_\mathrm{k}\beta/2\pi c(\beta)$$

$$\mathrm{P'_{DRTS,k}} = \mathrm{prob.}\{\text{a SU do not transmit DRTS in the direction of } \mathrm{U_2} \text{ at any time slot}\}$$

$$\mathrm{P'_{DRTS,k}} = 1 - \mathrm{P_{DRTS,k}}$$

$$\mathrm{P'_{DRTS,k}} = 1 - (\mathrm{V_k}\tau_\mathrm{k}\beta/2\pi)\mathrm{c}(\beta)$$

$$\begin{aligned} \mathrm{P} = \mathrm{prob.}\{&\text{none of the SUs among} \\ &(\mathrm{M}-2) \text{ transmit DRTS in the direction of } \mathrm{U_2} \text{ at any time slot}\} \end{aligned}$$

$$\mathrm{P} = \prod_{\mathrm{k}=1}^{\mathrm{M}-2}\left(1 - \mathrm{P_{DRTS,k}}\right)$$

$$\mathrm{P} = \prod_{\mathrm{k}=1}^{\mathrm{M}-2}(1 - (\mathrm{V_k}\tau_\mathrm{k}\beta/2\pi)\mathrm{c}(\beta))$$

$$\begin{aligned} \mathrm{P} = \mathrm{prob.}\{&\text{at least one SU among} \\ &(\mathrm{M}-2) \text{ transmit DRTS in the direction of } \mathrm{U_2} \text{ at any time slot}\} = 1 - \mathrm{P} \end{aligned}$$

$$\mathrm{P} = 1 - \prod_{\mathrm{k}=1}^{\mathrm{M}-2}(1 - (\mathrm{V_k}\tau_\mathrm{k}\beta/2\pi)\mathrm{c}(\beta))$$

The probability of DRTS failure is given by

$$\mathrm{P^D_{E2}} = \mathrm{V_1P} = \mathrm{V_1}\left\{1 - \sum\nolimits_{\mathrm{k}=2}^{\mathrm{M}}(1 - (\mathrm{V_k}\tau_\mathrm{k}\beta/2\pi)\mathrm{c}(\beta))\right\} \tag{15}$$

Where K = 3, 4, …, M.

Due to collision there is transmission failure, and the period of this transmission failure for the three access mechanism is given by

$$T_{E2}^{Dbas} = DPTS + SS + DDATA + SIFS + DACK + DIFS \tag{16a}$$

$$T_{E2}^{Drts} = DPTS + SS + DRTS + SIFS + DCTS + DIFS \tag{16b}$$

$$T_{E2}^{Dmcts} = DPTS + SS + DCTS + DIFS \tag{16c}$$

3.3 Collision of SU's Directional RTS with PU Transmission (Receiver Blocking) - (E3)

During the spectrum sensing time if the intended secondary receiver (U2) detects the presence of PU(s), it will fail to respond to the DRTS frame sent from the intended secondary transmitter (U1). This is called receiver blocking only when there is only one SU (U1) transmitting to the direction of the intended secondary receiver.

$$P_{E3}^{D} = V_1(1 - V_2)\sum\nolimits_{k=3}^{M}(1 - (V_k\tau_k\beta/2\pi)c(\beta)) \tag{17}$$

The period of transmission failure due to receiver blocking is given by

$$T_{E3}^{Dbas} = DPTS + SS + DDATA + SIFS + DACK + DIFS \tag{18a}$$

$$T_{E3}^{Drts} = DPTS + SS + DRTS + SIFS + DCTS + DIFS \tag{18b}$$

$$T_{E3}^{Dmcts} = DPTS + SS + DCTS + DIFS \tag{18c}$$

3.4 Receiver Already in Communication (E4)

This is event happens when the intended SU (U2) is already in communication with another SU which is not in the direction of the intended secondary transmitter (U1). The case when the U2 is acting as transmitter and receiver are different. At this time the intended secondary transmitter cannot respond to the DPTS/DRTS sent by the intended Secondary receiver (U2), which is the unique case that we experience due to beamforming. When it is acting as a receiver collision will occur and it is considered in case 2. Our interest is when U2 is acting as a transmitter in the direction other than U1, the probability is given by

$$\begin{aligned} P_{E4}^{D} = \text{prob.}\{&U_2 \text{ transmit to another SU not in the direction of } U_1 \\ &\text{at the time slot when } U_1 \text{ is sending DRTS to the direction of } U_2\} \end{aligned}$$

$$P_{E4}^{D} = \underbrace{V_1 V_2 \tau_2 \left(1 - (\beta/2\pi)c(\beta)\right)}_{\textcircled{1}} \underbrace{\prod\nolimits_{k=3}^{M} \left(1 - (V_k \tau_k\, \beta/2\pi)\, c(\beta)\right)}_{\textcircled{2}} \tag{19}$$

Where 1 and 2 represent probability of U2 transmission other than U1 direction and the probability the remaining (M-22) SUs do not transmit in the direction of U2.

The period of transmission failure due to this event for the three access mechanism is given by

$$T_{E4}^{Dbas} = DPTS + SS + DDATA + SIFS + DACK + DIFS \tag{20a}$$

$$T_{E4}^{Drts} = DPTS + SS + DRTS + SIFS + DCTS + DIFS \tag{20b}$$

$$T_{E4}^{Dmcts} = DPTS + SS + DCTS + DIFS \tag{20c}$$

3.5 Successful Directional Transmission (E5)

Successful directional transmission between the intended secondary transmitter (U1) and the intended secondary receiver (U2) is accomplished when both of them detects no PU, and U2 is not communicating with another SU (U2 is not transmitting) and U1 is the only transmitter in the direction of U2 at that time slot. The probability of successful directional transmission is given by

$$P_{E5}^{D} = V_1 V_2 (1 - \tau_2) \prod\nolimits_{k=3}^{M} \left(1 - (V_k \tau_k \beta/2\pi) c(\beta)\right) \tag{21}$$

The period of successful transmission for the three access mechanisms is given by

$$T_{E5}^{Dbas} = DPTS + SS + DDATA + SIFS + DACK + DIFS \tag{22a}$$

$$T_{E5}^{Drts} = DPTS + SS + DRTS + SIFS + DCTS + SIFS + DDATA + SIFS + DACK + DIFS \tag{22b}$$

$$T_{E5}^{Dmcts} = DPTS + SS + DCTS + SIFS + DDATA + SIFS + DACK + DIFS \tag{22c}$$

Then, for an arbitrary SU which is in transmission mode the sum of the probabilities of the following expression holds true

$$P_{E5}^{D} = 1 - \left(P_{E1}^{D} + P_{E2}^{D} + P_{E3}^{D} + P_{E4}^{D}\right)$$

$$P_{E5}^{D} = 1 - P_{Dtf} \tag{23}$$

Where $P_{Dtf} = P_{E1}^{D} + P_{E2}^{D} + P_{E3}^{D} + P_{E4}^{D}$

The following possible events could be detected when an arbitrary SU (U1) is in listening mode (backoff state). An arbitrary SU who is in listening mode could detect the channel idle (no PU and SU transmission), or it detects PU signal only, or it may detects both SU and PU signals (PU-SU collision detection). Generally, we can classify the detection output as idle channel or busy channel detection. Now let's derive expression for the occurrence probability of these events and the corresponding time length that U1 will defer. By the time when the backoff timer become zero and finds the channel idle, the node will start transmitting.

3.6 Idle Channel Detection (E6)

This event occurs when the arbitrary SU which is in listening state detects no transmission from both the PUs and SUs at the time slot. The arbitrary SU may detect the channel idle for either one of the following scenarios: when all the SUs detects the channel idle but there is no transmission to the direction of the detecting SU, or when all the M-1 SUs detects the channel busy due to false alarm and defer their transmission, or when some of the SUs detects the channel idle but do not transmit to the direction of the detecting SU and the remaining SUs detect the channel busy due to false alarm and defer their transmission, or when all the M-1 SUs detect the channel idle but they do not transmit (in back off state). The probability of idle channel detection expression for an arbitrary SU can be derived as follows.

The probability all of the SUs detects the channel idle but there is no directional transmission to the direction of the detecting SU is given by

$$P_{ID1}^{D} = PH_0(1 - p_f)\prod_{k=1}^{M-1}(1 - (V_k\tau_k\beta/2\pi)c(\beta))$$

The probability all of the M-1 SUs detects the channel busy due to false alarm and defer their transmission is given by

$$P_{ID2}^{D} = PH_0(p_f)$$

Therefore, the probability of idle channel detection by an arbitrary SU is given by

$$P_{E6}^{D} = \left(P_{ID1}^{D} + P_{ID2}^{D}\right)$$

$$P_{E6}^{D} = PH_0(1 - p_f)\sum\nolimits_{k=1}^{M-1}(1 - (V_k\tau_k\beta/2\pi)c(\beta)) + PH_0(p_f) \qquad (24)$$

At this time U1 will decrement its back off timer by 1 at the end of the current time slot.

Now let's analyze the probability of busy channel detection by an arbitrary SU in terms of PU signal detection only, SU signal detection only, and in terms of both PU and SU signal detection.

3.7 Only PU's Signal Detection (E7)

An arbitrary SU may detect PU signal only when one of the following events occurs; when all of the SUs detect the channel busy and defer their transmission, or when all of the M-1 SUs detect the channel idle but do not want to transmit to the direction of the detecting SU, or when some of the SUs detect the channel idle and transmit to the direction other than the detecting SU and the remaining SUs may detect the channel busy and defer transmission or the remaining SUs may detect the channel idle but do not want to transmit (may be in back off state). The probability expression of only PU signal detection by an arbitrary SU is given by the sum of the following probabilities.

The probability all of the SUs detect the channel busy and defer their transmission is given by

$$P^{D}_{PU1} = PH_1 p_d$$

The probability all of the M-1 SUs detect the channel idle but do not transmit to the direction of the detecting SU is given by

$$P^{D}_{PU2} = PH_1(1 - p_d) \prod_{k=1}^{M-1} (1 - (V_k \tau_k \beta / 2\pi) c(\beta))$$

Therefore, the probability of PU signal detection by an arbitrary SU is given by

$$P^{D}_{PU} = P^{D}_{PU1} + P^{D}_{PU2}$$

$$P^{D}_{E7} = PH_1(1 - p_d) \prod\nolimits_{k=1}^{M-1} (1 - (V_k \tau_k \beta / 2\pi) c(\beta)) + PH_1 p_d \tag{25}$$

At this time the detecting SU will freeze its backoff timer for some time duration depending on the access mechanisms (for our case it freezes for a time length of T^{D}_{E1}).

3.8 Only SU's Signal Detection (E8)

An arbitrary SU detects only SU(s) signal when one of the following conditions are satisfied. When all the SUs detect the channel idle and only one SU transmit to the direction of the detecting SU and the receiving SU can communicate with the transmitting SU (at this time the SU detects a successful transmission), or when all the SUs detect the channel idle and more than two SUs transmit in the direction of the detecting SU (at this time the SU detects collision), or all the SUs detects the channel idle and only one SU transmit in the direction of the detecting SU but the intended receiver might already been in communication with other SU not in the direction of the detecting SU, or when some of the SUs detect the channel busy due to false alarm and defer transmission but when the remaining SUs transmit to the direction of the detecting SU (at this time collision of SUs transmission is detected by the detecting SU). The expression for the probability of detecting PU signal only is derived below.

The probability all of the SUs detect the channel idle and only one SU transmit to the direction of the detecting SU and the receiving SU can communicate with the transmitting SU (at this time the SU detects a successful transmission) is given by

$$P_{ST}^{D} = PH_0(1-p_f)\binom{M-1}{1}((V_x\tau_x\beta/2\pi)c(\beta))V_y\left(1-\tau_y\right)\prod_{k=1}^{M-2}(1-(V_k\tau_k\beta/2\pi)c(\beta))$$

The detecting SU shall defer its transmission for a period of T_{E5}^{D} which is given by Eq. (22).

The probability all of the SUs detect the channel idle and more than two SUs transmit in the direction of the detecting SU (at this time the SU detects collision) is given by

$$P_{SSC}^{D} = PH_0(1-p_f)\sum_{k=1}^{M-1}\binom{M-1}{k}\{\prod_{y=1}^{k}\left(V_y\tau_y\frac{\beta}{2\pi}c(\beta)\right)\prod_{x=k+1}^{M-1}((1-(V_k\tau_k\beta/2\pi)c(\beta))\}$$

At this stage, the listening node defer its transmission for a period of T_{C}^{D} which is given by

$$T_{C}^{Dbas} = PTS + SS + DATA + DIFS \tag{26a}$$

$$T_{C}^{Drts} = PTS + SS + RTS + DIFS \tag{26b}$$

$$T_{C}^{Dmcts} = PTS + SS + DIFS \tag{26c}$$

The probability all the SUs detects the channel idle and only one SU transmit in the direction of the detecting SU but the intended receiver might initiate communication with other SU which is not in the direction of the detecting SU at the same time slot is given by

$$P_{SDC}^{D} = PH_0(1-p_f)\binom{M-1}{1}(V_x\tau_x(\beta/2\pi)c(\beta))V_y\tau_y(1-(\beta/2\pi)c(\beta))\prod_{k=3}^{M-1}(1-(V_k\tau_k\beta/2\pi)c(\beta))$$

At this time the detecting node defer its transmission for a period of T_{E4}^{D}.

The probability all of the (M-2) SUs detects the channel idle and only one SU transmission is detected but this communication might be interrupted due to the invisible directional communication to the detector. The invisible directional communications may happen in one of the following conditions. The first condition is when the intended SU receiver receives more than one request in different direction at the same time slot (for example more than one RTS frames or DATA packet), at this time the intended receiver fail to respond to any of the SUs, as a result of which communication failure could be detected by the detecting SU (we may call this event as collision at the intended SU receiver). The second condition is observed when there is at least one transmission to the direction of the intended transmitter and the intended transmitter may receive more than one acknowledgments (for example more than one CTS or ACK frames) at the same time slot which results in communication failure detection at the detecting SU (we may call this event as collision at the intended SU transmitter.

The probability of detecting communication failure by an arbitrary detecting SU due to a collision observed at the intended SU receiver is given by

$$P_{TFRC}^{D} = PH_0(1-p_f)\binom{M-1}{1}(V_x\tau_x(\beta/2\pi)c(\beta))V_y(1-\tau_y)$$
$$\sum_{k=1}^{M-3}\binom{M-3}{k}\{\prod_{z=1}^{k}(V_z\tau_z(\beta/2\pi)c(\beta))\prod_{x=k+1}^{M-3}((1-V_k\tau_k(\beta/2\pi)c(\beta))\}$$

Since every user start transmission at the beginning of a time frame, the time period the detecting SU defer its transmission for this event is given by T_{E4}^{D}.

The probability of detecting communication failure by an arbitrary detecting SU due to a collision observed at the intended SU transmitter is given by

$$P_{TFTC}^{D} = PH_0(1-p_f)\binom{M-1}{1}(V_x\tau_x(\beta/2\pi)c(\beta))V_y(1-\tau_y)$$
$$\sum_{k=1}^{M-3}\binom{M-3}{k}\{\prod_{z=1}^{k}(V_z\tau_z(\beta/2\pi)c(\beta))\prod_{x=k+1}^{M-3}((1-V_k\tau_k(\beta/2\pi)c(\beta))\}$$

The time period the detecting SU defer its transmission for this event is given by T_{E4}^{D}.

Therefore, the probability of only SU signal detection is given by

$$P_{E8}^{D} = P_{ST}^{D} + P_{SSC}^{D} + P_{SDC}^{D} + P_{TFRC}^{D} + P_{TFTC}^{D} \tag{27}$$

3.9 Detection of Both PU and SU Signal (E9)

An arbitrary SU detects both the PU and SU signal when one of the following conditions occurs. An arbitrary SU detects both the SU and PU signals when the PU is present and all the M-1 SUs miss detect the presence of PU and at least one among these SUs transmit in the direction of the detecting SU, or when the PU is present and some of the SUs detect the presence of PU and defer transmission and the remaining SUs miss detect the PU presence and start transmitting to the direction of the detecting SU. The expression for probability of detecting both PU and Su signal simultaneously is derived below.

The probability all the M-1 SUs miss detect the presence of PU and at least one among these SUs transmit in the direction of the detecting SU is given by

$$P^D_{PS} = PH_1(1-p_d)\sum_{k=1}^{M-1}\binom{M-1}{k}\{\prod_{y=1}^{k}(V_y\tau_y(\beta/2\pi)c(\beta))\prod_{x=k+1}^{M-1}(1-V_x\tau_x(\beta/2\pi)c(\beta))\}$$

Therefore, the probability of detecting both SU and PU signal is given by

$$P^D_{E9} = P^D_{PS}$$

$$P^D_{E9} = PH_1(1-p_d)\sum\nolimits_{k=1}^{M-1}\binom{M-1}{k}\{\prod\nolimits_{y=1}^{k}(V_y\tau_y(\beta/2\pi)c(\beta))\prod\nolimits_{x=k+1}^{M-1}(1-V_x\tau_x(\beta/2\pi)c(\beta))\} \tag{28}$$

For this event the detecting node defer its transmission for a period of T^D_{E3}.

4 Throughput for DCR-MAC Protocol

Therefore, the total average throughput of directionally CR MAC protocol can be expressed by

$$U^D = \frac{E[\text{Payload Information transmitted in a slot time}]}{E[\text{length of a slot time}]} \tag{29}$$

$$E[slot]^{Dbas} = P^D_{E6}\delta + P^D_{E7}T^{Dbas}_{E1} + P^D_{ST}T^{Dbas}_{E5} + P^D_{SSC}T^{Dbas}_{C} + P^D_{SDC}T^{Dbas}_{E4} + P^D_{TFRC}T^{Dbas}_{E4} + P^D_{TFTC}T^{Dbas}_{E4} + P^D_{E9}T^{Dbas}_{E3} \tag{30a}$$

$$E[slot]^{Drts} = P^D_{E6}\delta + P^D_{E7}T^{Drts}_{E1} + P^D_{ST}T^{Drts}_{E5} + P^D_{SSC}T^{Drts}_{C} + P^D_{SDC}T^{Drts}_{E4} + P^D_{TFRC}T^{Drts}_{E4} + P^D_{TFTC}T^{Drts}_{E4} + P^D_{E9}T^{Drts}_{E3} \tag{30b}$$

$$E[slot]^{Dmcts} = P^D_{E6}\delta + P^D_{E7}T^{Dmcts}_{E1} + P^D_{ST}T^{Dmcts}_{E5} + P^D_{SSC}T^{Dmcts}_{C} + P^D_{SDC}T^{Dmcts}_{E4} + P^D_{TFRC}T^{Dmcts}_{E4} + P^D_{TFTC}T^{Dmcts}_{E4} + P^D_{E9}T^{Dmcts}_{E3} \tag{30c}$$

$$U^D = L_{avg}P^D_{ST}E[L]/E[slot]^D \tag{31}$$

The maximum throughput of a directional MAC protocol is given by

$$U^D_{max} = L_{max}P^D_{ST}E[L]/E[slot]^D \tag{32}$$

5 Simulation and Discussion

In this section different simulation works are presented to show the performance advantage of directional CR MAC protocol (DCR-MAC) in terms of throughput and packet delay.

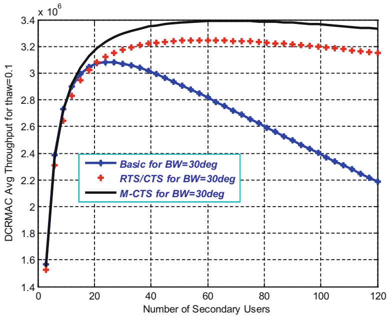
The simulator used is an event driven MATLAB simulator (MATLAB R2013b). We choose MATLAB because it is a powerful simulator to work with analytical and more of physical layer dominated tasks. To perform the simulation we have used the following parameters which are presented in a tabular form below.

Table 2. DCR-MAC protocol simulation parameters

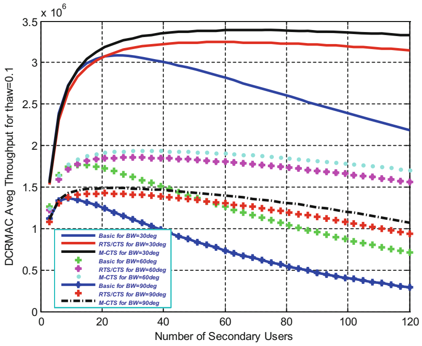
Simulation parameters used	
Channel bit rate	1 Mbit/sec
Slot time	20 µsec
Spectrum sensing time	0.5 ms
SIFS	10 µsec
DIFS	50 µsec
Initial contention window size (W)	32
Maximum backoff stage (m)	5
PHY header	192 bits
MAC header	272 bits
Packet payload	8000 bits
DPTS	112 bits + PHY Header
DRTS	160 bits + PHY Header
DCTS	112 bits + PHY Header
DACK	112 bits + PHY Header

The throughput performance of DCR-MAC protocol for the three accessing mechanisms namely Basic, RTS/CTS, and M-CTS are presented in Fig. 5 and Fig. 6 below. For our simulations the throughput is measured in bit per second. The simulations are carried out based on the simulation parameters given in Table 2. Besides, the following parameters are used in the simulations, probability of false alarm (Pf = 0.01), probability of detection (Pd = 0.9), and probability of vacant channel availability (PH0 = 0.9) unless otherwise.

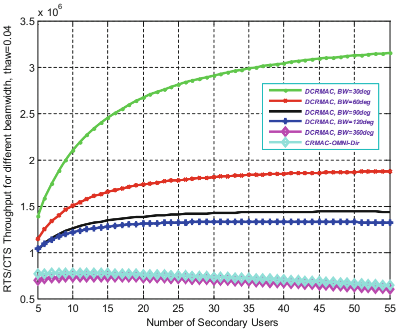
Simulation in Fig. 5(a) shows the throughput performance of the three access mechanisms. The simulation is carried out for transmission probability of 0.1, and beamwidth of 300. We used a multiple antenna to produce the required beamwidth (radiation pattern). The simulation result shows that the M-CTS access mechanism outperforms the remaining two access methods. As the number of SUs increases the average throughput of the three access mechanisms increases linearly and equally for almost number of users less than fifteen which was true for the conventional wireless communication system, but as the number of SUs keeps increasing the performance of the three access mechanisms becomes different. The performance of the Basic access mechanism keeps increasing with the increase of number of SUs only up to twenty SUs then the performance starts to decline. For the remaining two access mechanisms the performance increases with the increasing number of SUs but with the slow rate. The performance of RTS/CTS mechanism becomes almost constant after forty SUs and starts to decline after nearly sixty SUs. The performance of M-CTS access mechanism keeps increasing up to sixty SUs and becomes constant and starts to decrease its performance after eighty five SUs. As compared to the omni-directional CR-MAC protocol proposed in the previous chapter, all the three prosed directional CR-MAC protocols outperform the throughput performance by nearly four folds, this is due to the concurrent transmission capability of directional communication. The performance gain of the newly proposed access mechanism, M-CTS, brings an additional throughput gain of nearly 0.8 Mbits/sec.



a) Average throughput Vs number of SUs for Basic, RTS/CTS, and M-CTS access Mechanisms



b) Average throughput comparison for Basic, RTS/CTS, and M-CTS access Mechanisms for different Beamwidth Vs number of SUs



c) Average throughput comparison for different beamwidth Vs CRMAC-OMNI-Dir based on RTS/CTS access mechanism

Fig. 5. Impact of number of SUs on the performance DCR-MAC throughput

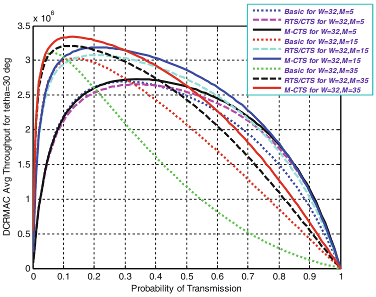
Simulation in Fig. 5(b) shows as the size of the antenna beam becomes wider and wider, the average throughput performance of the DCR-MAC protocol continuous decreasing. This is because as the antenna beamwidth increase the average number of concurrent transmissions decreases, in a single link much of the area will be covered which means much of the SUs will defer their transmission, and as a result it reduces the spectrum utilization efficiency and reduce the average throughput of the protocol. Therefore, narrower beamforming antenna is very fundamental.

Simulation in Fig. 5(c) shows a simulation carried out for RTS/CTS access mechanism for DCR-MAC and CRMAC (OMNI-Directional) for constant probability of transmission and different antenna beamwidth for the case of DCR-MAC protocol. In the simulation it is shown that the average throughput performance of DCR-MAC protocol with a radiation beamwidth of 3600 becomes almost the same as to the throughput performance of CRMAC which operates in omni directional mode. Generally, increasing the number of SUs improves the performance of average throughput of DCR-MAC protocol in a much meaning full way than the CRMAC protocol.

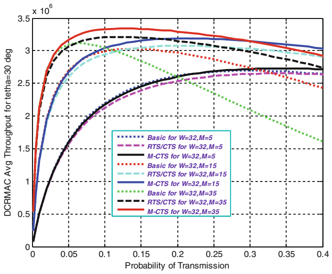
The simulation in Fig. 6 presents the impact of probability of transmission on the performance of average throughput of DCR-MAC protocol. In Fig. 6(a) the simulation shows that DCR-MAC protocol results better average throughput for lower probability of transmission particularly as the number of SUs becomes larger and larger. As the number of SUs and the probability of packet transmission becomes larger, greater number of the SUs attempt transmission and there will be a higher probability of collision which degrades the average throughput of the DCR-MAC protocol. Whereas, as the number of SUs becomes smaller and smaller and the average throughput decline very faster as the probability of transmission increases because due to high probability of transmission the probability of collision increases which results lower spectrum utilization efficiency. Figure 6(b) shows that the average throughput of DCR-MAC protocol for a beamwidth of 300 become maximum around 0.1 probability of transmission for the three access mechanisms especially as the number of SUs becomes large. The graph shows the chopped section of the simulation.

Simulation in Fig. 6(c) shows the throughput performance comparison between DCR-MAC and CRMAC protocols for RTS/CTS access mechanisms which holds true for both basic and M-CTS access mechanisms. The maximum average throughput of DCR-MAC protocol for a beamwidth of 300 is at least three times higher than the maximum throughput of CRMAC protocol. As the number of SUs becomes smaller the CRMAC protocol shows better performance gain (in terms of throughput) in relative to the DCR-MAC protocol this is due to poor spectrum utilization efficiency.

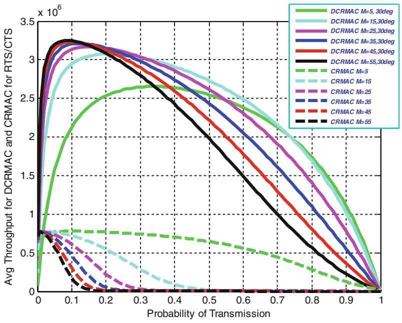
Simulation in Fig. 6(d) compare the throughput of a single link DCR-MAC protocol and the throughput of CRMAC protocols for different number of SUs and different values of probability of transmission. Until now the performance of DCR-MAC and CRMAC has been compared in terms of average throughput. As can be observed from the simulation, a node may enjoy the maximum throughput in CRMAC protocol than in DCR-MAC protocol. This is because the link in directional communication could fail due to hidden communication to the transmitter or receiver which decreases the maximum throughput but DCR-MAC shows remarkable performance for all probability of transmission in relative to CRMAC.



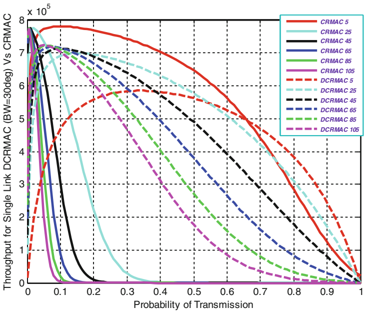
a) Throughput performance comparison of DCR-MAC protocol for different number of SUs Vs probability of transmission



b) Throughput performance comparison of DCR-MAC protocol for different number of SUs Vs probability of transmission to clearly observe the optimum average throughput for beamwidth of 30^0.



c) Throughput performance comparison of DCR-MAC and CRMAC protocols for different number of SUs Vs probability of transmission for beamwidth of 30^0.



d) Single link throughput performance comparison of DCR-MAC and CRMAC protocols for different number of SUs Vs probability of transmission for the RTS/CTS access mechanism.

Fig. 6. Impact of probability of transmission on the throughput of DCR-MAC protocol.

6 Conclusion

In this paper, we have designed MAC protocols for CRN in general and to CRWMN in particular using multiple antenna systems. DCR-MAC protocol is a random access MAC protocols proposed for CRWMNs using multiple antenna systems. In the design of DCR-MAC protocol, directional communication is the corner stone of our finding. Assuming directional communication we have proposed a directional random access MAC protocol using the three access mechanisms. In relative to the omni-directional CR MAC protocols, all the directional CR MAC protocols show better performance. Especially, the newly proposed DCR-MAC protocol which uses the M-CTS access mechanism shows a motivating performance improvement in terms of average throughput and average packet delay.

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