Cross Layer MAC Protocol for a Peer Conscious Opportunistic Network Coded Cooperation System

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Abstract—This article presents a peer conscious opportunistic network coded cooperation (PC-O-NCC) system that exploits multi-user diversity (MUD) gain in a simple network coded cooperation (NCC) based network. It prioritizes sources with better channel conditions by granting them earlier access than the other competing nodes unlike the prevalent time division multiple access (TDMA) technique used widely in any NCC network. This improves the outage performance of the overall system. To prioritise sources with better channel conditions, a novel timer-based MAC protocol is proposed. The proposed protocol is designed such that it aims to reduce collisions by taking the network load into account along with channel conditions while generating the timer values. It also minimizes the power consumption in performing clear channel assessment (CCA) by sources which is a costly affair for battery-operated devices. The simulation results show that the proposed algorithm improves the outage performance while keeping the latency to a minimum value. The improvement in the outage performance can prove to be important in taking key decisions which becomes crucial in disaster management, drone assisted scenarios or intelligent transportation systems.

Index Terms—Cross layer, MAC protocol, multi-user diversity, network coded cooperation, multi-cast, outage probability

1 Introduction

In the era of wireless communication, data reliability and data throughput are critically important to deal with, with signal fading being their nemesis. A noteworthy solution for better and more reliable communication is to obtain spatial diversity using multiple antennas, designing which is a mammoth task for compact, battery-operated devices. To achieve diversity hassle-free, the concept of cooperative communication (CC) is used [1]. The relay processes the received information and forwards it using protocols like Amplify-and-Forward (AF) and Decode-and-Forward (DF). On the other hand, to attain a higher throughput, the concept of network coding (NC) is used [2]. To revamp the performance further, a network coded cooperation (NCC) based system is used which is an amalgamation of NC and CC. Thus, it reaps the benefits of both NC and CC by having a better throughput along with data reliability [3]. A basic NCC scheme can be elucidated by using multiple source-destination pairs with the destinations working in promiscuous mode aided by a relay to attain diversity as shown in Fig. 1. All the nodes in such scenarios are considered to be following time division multiple access (TDMA) protocol and are within one hop reach of each other. Data from each source is broadcast to the destinations and the relay. Finally, the relay forwards composite data to the destinations. However, this still raises a question on the Quality-of-Service (QoS) being provided as not only do the sources transmit irrespective of the channel conditions but also broadcasting scenarios are inherently unreliable in nature due to the absence of Acknowledgement (ACK) packets. This gives us the opportunity to develop a cross-layer MAC protocol that aims to provide a higher QoS.

Another efficient way to achieve diversity along with high throughput without using a multi-antenna system is the incorporation of multi-user diversity (MUD) gain. This is achieved by scheduling users with a better channel condition to transmit. Normally, Medium Access Control (MAC) algorithms like Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) allow users to transmit whenever they find the channel to be free after a contention. However, this transmission takes place irrespective of the channel conditions thus, leading to re-transmissions in case of failure. Thus, it would be beneficial if the contention took into consideration the random variation of channels as it would provide destinations with the required data at a higher signal-to-noise ratio (SNR). Moreover, the data can be sent at higher data rates thus, improving the throughput of the system. Authors in [4] showed a considerable improvement in throughput of the IEEE 802.11a based system by incorporating MUD gain thus, causing fewer re-transmissions. Although, recent developments are made where different

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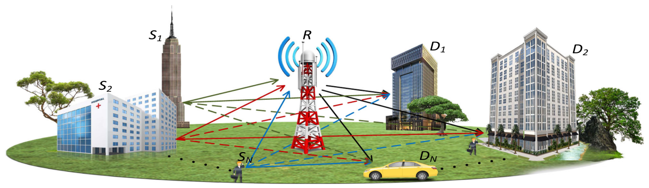

Fig. 1. A generalised scenario of a PC-O-NCC system with N S_i-D_i $\forall\, i \in \{1, \ldots, N\}$ pairs and a dedicated relay R.

transmission rates can be adopted in a multi-casting scenario to attain MUD multi-cast, it is still a quid-pro-quo between delay and throughput [5]. Many MAC protocols have been proposed aiming to exploit MUD gain in a wireless network however, they are unsuitable for a typical NCC based scenario.

In this paper, we propose a novel peer conscious opportunistic network coded cooperation (PC-O-NCC) system. PC-O-NCC aims to incorporate MUD gain in a NCC system by allowing the users with better channel conditions between ith source and relay relative to its average to transmit first. Unlike a normal scenario where sources may transmit at higher rates based on the available CSI and resources, here they choose to transmit at a fixed lower rate. This is because the proposed algorithm ensures a superior channel condition between ith source and relay relative to its average but does not ensure the same between ith source and another destination node overhearing it to attain diversity. By transmitting at a fixed lower rate, every source ensures the proper reception of the overheard data. Thus, it can be said that the transmitting source is conscious of the other peer source-destination pairs and helps them to achieve diversity. The key contributions of this paper can be listed as,

1) We present the notion of peer conscious opportunistic network coded cooperation system which aims to utilise MUD gain to enhance the system performance.
2) A medium-access control (MAC) protocol for multi-user NCC network to achieve MUD gain.
3) An expression taking into account the number of contending sources for timer calculation which proves to be beneficial in terms of latency and resource consumption.
4) An energy-efficient CCA method.
5) We introduce a special Session Initiation Packet (SIP) which marks the beginning of a new session.
6) An energy-efficient sleeping method for all the sources once a source has transmitted its packet.

The rest of the paper is structured as follows: Section 2 focuses on the related work and points out the motivation for the proposed work. Section 3 describes the system model and Section 4 discusses it analytically. In Section 5, various results are compared with the existing models. Section 6 concludes the paper. The notations used in this paper are mentioned in Table 1.

TABLE 1
Notations Used

Symbols	Description
S_i, D_i, R	ith Source, ith Destination and Relay, respectively
x_i	Packet transmitted by ith source
P_X	Transmitting power of node X
$n_X^{(t)}$	Background noise at node X for time slot t
$\sigma^2_{n_X}$	Background noise variance at node X
δ_{ij}	Distance between ith and jth node
β	Path loss exponent
ψ_r	Amplification factor for AF scheme
$\mathcal{Y}_{ab}^{(t_a)}$	Received signal at bth node transmitted by ath node during (t_a)th time slot
ζ	Slot time
Δ	Number of time-slots in which a collision occurred

2 Related Work and Motivation

Substantial research work is conducted on various CC, NC and NCC physical layer (PHY) based models over the years. In recent years, CC has been applied in vehicular scenarios and 5G networks both of which demand robust and highly reliable data [6]. The field of NC too has been researched rigorously [7]. Multiple source-destination pairs are considered along with a single relay node to explore the diversity-multiplexing trade-off and system outage analytically [8]. A basic 5-node full-duplex NCC model is discussed and analysed by authors in [9] which showed superior performance in terms of rate. Authors in [10] analysed a NCC scenario using a drone as the relay. In [11], the authors performed an outage analysis for a drone assisted NCC network. Few other works related to NCC can be found in [12], [13], [14], [15]. NCC in its basic form has also carved its way into the vehicular research domain. Authors analysed a network where multiple vehicles want to distribute their messages to others [16].

Although, CC, NC and NCC PHY models are extensively analysed, relatively few papers deal with MAC layer modelling of a CC based network [17], [18]. A Two Master Nodes Cooperative Network Coding protocol is designed in [19] for Wireless Body Area Networks (WBANs). Authors in [20] designed a TDMA based Cooperative NC MAC scheme for networks based on two way relaying. In [21] authors incorporate and use NC with sufficient re-transmissions to increase the reliability in wireless sensor networks (WSNs). However, MAC protocols for NCC networks still remain an unmapped area. In most cases, the sources are assumed to transmit following the TDMA protocol [10] thus, raising questions on the QoS being provided whereas, others include a relay selection strategy [22]. This leaves a huge gap and motivates us to build a suitable MAC algorithm that aims to increase the QoS of the NCC networks.

On the other hand, broadcasting scenarios are inherently unreliable as the reception of data is not acknowledged. For a reliable transmission, a special multi-cast RTS which helps nodes to send prioritised CTS only if a node has received the data above the targetted data rate is designed in [23] whereas in [24] node receives CTS and ACK only from the listed nodes. Although these methods are effective, they are unsuitable for NCC scenarios. This is because, in the prevalent techniques CTS/ACK are sent from multiple nodes which received the data, thus affecting the throughput of the network. Also, in a typical 802.11 based network, a source after completing a transmission starts contending again which is not the case in a typical NCC scenario. This too gives us an open area to design special packets suitable for networks based on NCC along with a contention-based MAC protocol.

Over the years, the incorporation of MUD gain in a communication system has proven to be beneficial. It is practised to utilise the resources of the system efficiently by allowing the user with a superior channel condition to transmit. The effect of MUD gain is also shown in [4] although, the proposed MAC layer in [4] is unsuitable for a NCC scenario trying to incorporate MUD gain. This is because in a typical NCC network after transmission of data a source has to wait unless the relay does not broadcast the amplified data which is unlike the normal scenario considered in [4]. In [25], the authors incorporate MUD gain in a CC network. The incorporation of MUD gain in a NC based network is discussed in [5]. Timer-based node selection strategies and relay selection strategies are developed in [22] for a CC based network to help nodes contend with each other although they do not consider the network load which might cause a considerable amount of collisions among nodes.

Due to the unforeseeable behaviour of wireless channels, direct links between a source and destination may often fail. Cooperation among nodes thus proves to be important in such cases. However, since in any NCC network sources transmit following TDMA protocol, links between source and relay are susceptible to failure too eventually raising a question on the QoS of the system. To the best of the authors' knowledge, none of the existing works takes into account the channel-based contention among multiple sources and exploits the available MUD gain in a multi-user scenario like NCC. This paves the way for us to propose a protocol aiming to minimise power usage and provide diversity along with MUD gain.

3 System Model

In this section, a generalised model of the proposed PC-O-NCC system is explored with multiple sources in contention as shown in Fig. 1. For explaining the cross-layer nature of PC-O-NCC, this section is divided into two parts. PHY modelling and its related assumptions are discussed in Section 3.1. A deeper analysis of the network architecture is conducted in Section 3.2 which includes the modelling of the MAC layer. The latter section sheds light on the device synchronisation and how they participate in the proposed PC-O-NCC network.

3.1 Physical Layer

For analysis purposes, a system model of PC-O-NCC network is illustrated in Fig. 2. It consists of N source-destination ($S_{i\in\{1,\ldots,N\}}$-D_i) pairs and a dedicated relay, R.

To build a robust network, the entire communication process is divided into two phases namely, phase I and phase II. Phase I includes every $S_{i\in\{1,\ldots,N\}}$ multi-casting x_i to respective D_i and R (solid lines) in orthogonal time slots. This is also overheard by $D_{j\neq i, j\in\{1,\ldots,N\}}$ in order to achieve diversity (dotted lines) as shown in Fig. 2a. We refer to phase I as a session throughout the paper. Every S_i determines the time slot for transmission based on the channel state information (CSI) available at the nodes. A brief discussion on the availability of CSI is given in the following sub-section. The model is developed considering non line-of-sight path among nodes. Hence, independent and identically distributed (i.i.d) Rayleigh fading channels are considered. They are denoted by $h_{ab}^{(t_a)}\sim\mathcal{CN}(0,\frac{1}{\sqrt{2}})$ where a, b represent transmitting and receiving nodes, respectively [10] and t_a represents the time slot during which node a transmits where, $a\in\{S,R\}$ and $b\in\{S,R,D\}$. Here, S=$\{S_1,\ldots,S_N\}$ and D=$\{D_1,\ldots,D_N\}$. After a session is complete, phase II commences in which R multi-casts an amplified composite data (*Amp_Comp_Data*) formed by performing superposition coding on the signals received till Nth successful time slot.

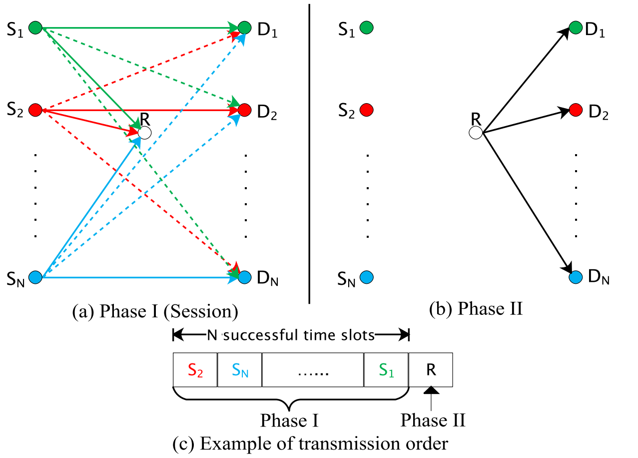

Fig. 2. Illustration of peer conscious opportunistic NCC network.

For mathematical tractability and model simplification, few assumptions are considered throughout the paper. PC-O-NCC is based on multi-casting scenarios. Hence, reception of x_i in every time slot is important for $D_{j\neq i, j\in 1,2,..,N}$ also, to achieve diversity. The coherence time (T_{coh}) is considered to be of same length as a communication block (Successful/Unsuccessful reception of data by R along with exchange of a control packet). Block fading is considered for this work [4]. The channel changes after a coherence time (block) independently, irrespective of the occurrence of a collision or a successful transmission. Hence, the chances of an ever lasting collision perishes when a new coherence window begins. Here, a concern about fairness might arise, that a particular source might continuously access the channel due to better SNR_i. Although, it is not a matter of concern in the proposed PC-O-NCC system since after every successful transmission, the source waits unless the next session begins. Hence, every S_i node gets to transmit once before all the nodes can contend again. A fixed payload size is considered for every source and all the sources are considered to have some packet to transmit at any given time.

3.1.1 Physical Layer Transmission Scheme

To elucidate the functioning of PC-O-NCC in the context of PHY, we consider an example of N S_i-D_i pairs with transmission order as shown in Fig. 2c. Now, let us consider $\mathbf{h}_N^{(\mathbf{t})}$ which contains information about all the channel coefficients between S_i and R for a particular successful time slot[1] $\mathbf{t}$ where $\mathbf{t}\in\{1,\ldots,N\}$ and the lower subscript

1. An ideal collision free case is considered here for better explanation. However, in a later section, the case of collision is also discussed.

represents the number of sources in contention for a particular time slot. Hence, for the first time slot, $\mathbf{h}_N^{(\mathbf{t})}$ can be represented as $\mathbf{h}_N^{(\mathbf{1})} = \{h_{S_1R}^{(1)}, h_{S_2R}^{(1)}, \ldots, h_{S_NR}^{(1)}\}$. To obtain MUD gain, the system is built such that S_i with the best instantaneous SNR ($\mathrm{SNR_i}$) with respect to its average SNR ($\mathrm{SNR_{avg(i)}}$) gets to transmit first. $\mathrm{SNR_i}$ and $\mathrm{SNR_{avg(i)}}$ of the $\mathrm{i^{th}}$ source can be given by

$$\mathrm{SNR_i} = \mathrm{SNR}_{ab} = \frac{P_a \delta_{ab}^{-\beta} \left| h_{ab}^{(t_a)} \right|^2}{\sigma_{n_b}^2},$$

$$\mathrm{SNR_{avg(i)}} = \frac{P_a \delta_{ab}^{-\beta} E\left[\left| h_{ab}^{(t_a)} \right|^2 \right]}{\sigma_{n_b}^2}, \tag{1}$$

where P_a, δ_{ab}, β, $\sigma_{n_b}^2$ and E[.] represent the transmit power of node a, distance between nodes a and b, path loss factor, noise variance at node b and mean of a random variable, respectively. SNR_{ab} denotes SNR $_\mathrm{i}$ at destination b when node a is transmitting. For ease of explanation, the examples considered throughout the paper are based on all the sources having same average SNR ($\mathrm{SNR_{avg}}$). However, our algorithm works equally for sources with different average SNR which is discussed in Section 3.2.1. Now, considering all the parameters to be constant for all the nodes, the channel gain is the only variable available in determining different values of $\mathrm{SNR_i}$. Thus, any S_i with the relatively maximum channel gain among the contending nodes transmits in any given time slot. Going by Fig. 2c, $\max(\mathbf{h}_N^{(\mathbf{1})}) = h_{S_2R}^{(1)}$. Thus, unlike the normal scenario where a pre-scheduled node would have transmitted in the first slot, here the node having the best relative $\mathrm{SNR_i}$ (in this case, S_2) transmits. During the beginning of second time slot, S_2 receives a control frame transmitted by R and goes to sleep for a predetermined time which is discussed later. The remaining N-1 source nodes start the contention for the second time slot based on the new CSI obtained using the control frame which was transmitted by R (discussed further in next sub-section). Thus, the matrix for the second time-slot is $\mathbf{h}_{N-1}^{(\mathbf{2})} = \mathbf{h}_N^{(\mathbf{1})} - \{h_{S_2R}^{(1)}\} = \{h_{S_1R}^{(2)}, h_{S_3R}^{(2)}, \ldots, h_{S_NR}^{(2)}\}$. Following Fig. 2c, for second time slot, $\max(\mathbf{h}_{N-1}^{(\mathbf{2})}) = h_{S_NR}^{(2)}$. Hence, S_N multi-casts its data. This process continues unless N-1 participating nodes transmit their individual packets. After N-1 successful time slots, only 1 source is left behind. Thus, the updated matrix for the N th time slot is given by $\mathbf{h}_1^{(\mathbf{N})} = \{h_{S_1R}^{(N)}\}$. $h_{S_1R}^{(N)}$ being the only element left in updated $\mathbf{h}_1^{(\mathbf{N})}$, is the maximum element. Thus, S_1 transmits in the final time slot. This marks the completion of a session. Following this, R performs superposition coding on the signals it received till Nth successful time slot and multi-casts *Amp_Comp_Data* packet. The incorporation of MUD gain in NCC is possible by prioritising users with relatively higher $\mathrm{SNR_i}$ values using a distributed contention based algorithm. Thus, a novel MAC protocol is proposed in the following sub-section which is suitable for the considered scenario.

3.2 MAC Layer

In this section, the MAC protocol for the PC-O-NCC system is proposed and discussed. The algorithm followed at every participating source node is represented in the form of a flow chart in Fig. 3. The onset of a session is marked by the transmission of SIP by R. This is received by each contending S_i as shown in block 2 of Fig. 3. The SIP conveys information such as initial number of transmissions left for the session to complete (*Tx_left_ini*) and the minimum next target session commencement time ($\mathrm{NTSCT_{min}}$) which is the minimum time required for the next session to begin. $\mathrm{NTSCT_{min}}$ is discussed in details in Section 3.2.3. The proposed frame format of SIP is shown in Fig. 4a. On receiving the SIP, every source sets *Tx_left=Tx_left_ini* where *Tx_left* is the number of transmitters left to transmit successfully for the ongoing session to complete. *Tx_left* is then compared with 1. If it is equal to 1, it simply follows the procedure similar to pure ALOHA since there is only a single device left to transmit for the session to complete. Thus, the node transmits its data packet immediately without waiting or performing clear channel assessment (CCA) as shown in block 3 followed by block 7 of Fig. 3. Otherwise, if $Tx\_left \neq 1$, $\mathrm{SNR_i}$ is calculated at each contending S_i using SIP and a timer T_i is set (block 4, Fig. 3). T_i is discussed in details in Section 3.2.1. Each S_i waits T_i interval and performs CCA for Slot time (ζ) interval. The symbol ζ represents the minimum time required to sense if the channel is busy or not [26]. It plays a pivotal role in saving power for all the devices participating in the PC-O-NCC network which is discussed further in Section 3.2.2. If a source finds the channel energy to be low (CEL) for ζ interval, it transmits the data else it continues to perform CCA unless it receives some control frame (like *ACK* frame or Request to re-transmit

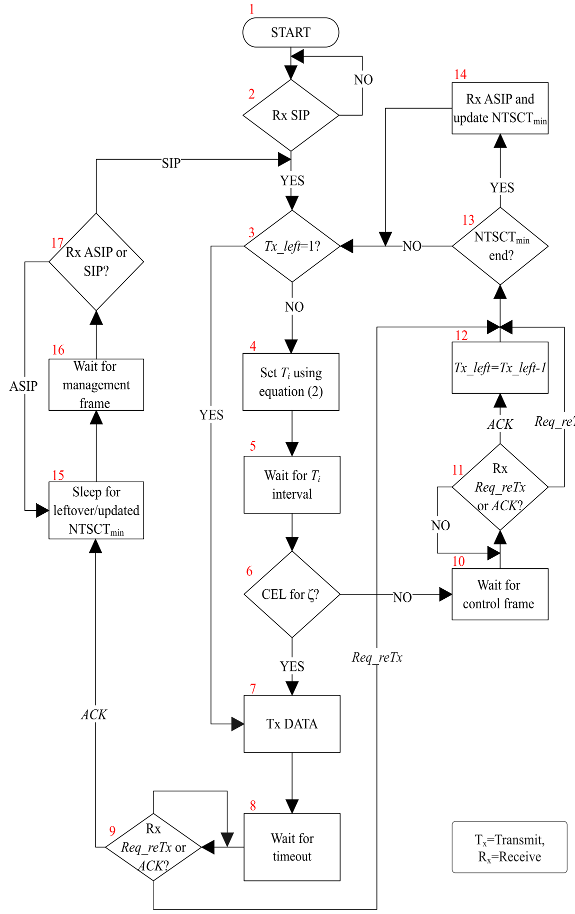

Fig. 3. Flow graph of proposed contention method for PC-O-NCC.

Frame Control	*Tx_left_ini*	$\mathrm{NTSCT_{min}}$	RA	FCS

(a) SIP

Frame Control	RA	*ACK* Flag=1	DA	*ACK* Flag=0	SA	Payload	FCS

(b) *Data*

Frame Control	SA	FCS

(c) *ACK*

Fig. 4. Proposed frame formats.(FCS=frame check sequence).

(Req_reTx) frame) from R. Unlike [23] and [24], in PC-O-NCC, only R sends an ACK to ensure proper reception of data[2]. Thus, to get ACK only from a particular node, we propose a data frame as shown in Fig. 4b. RA, DA and SA refer to relay address, destination address and source address, respectively. It is designed such that the address with adjoining ACK Flag value set to 1, only acknowledges the reception of a message. In this case, R is the only node to acknowledge a received frame from a contending source. ACK from the respective destination is not required, as in a typical NCC network, it is assumed that the data received directly from the respective source is not reliable enough. Frame format of ACK is shown in Fig. 4c. After receiving ACK, the transmitting source for which it was intended goes to sleep for the remaining $\mathrm{NTSCT_{min}}$. Whereas, the other sources decrease the value of *Tx_left* by 1 (block 12 of Fig. 3) and compare it to 1. If *Tx_left*= 1, then the source performs ALOHA as discussed before. If not, it resets the timer to the value based on the new channel conditions obtained from the ACK received as shown in Fig. 3. Just before comparing the value of *Tx_left* to 1, the sources check if the $\mathrm{NTSCT_{min}}$ interval is over or not. If it is over, they wait and receive Assistant Session Initiation Packet (ASIP) frame from R before resuming contention (block 13-14 of Fig. 3) which is explained later in Section 3.2.3.

In case of a collision, the CSI is obtained using the Req_reTx frame. Req_reTx frame has a similar format as ACK with the only difference being the absence of a specific SA in this frame. The reception of Req_reTx frame not only gives S_i the opportunity to gain knowledge of the new CSI in the new coherence window but also conveys the information of a collision which is useful for timer regeneration in the new time slot. The value of *Tx_left* remains the same and all the sources which contended in the previous time-slot, contends again with timers set accordingly with respect to new CSI.

Phase I continues unless all the participating sources have transmitted once successfully. Finally, R combines all the data it received from the sources, amplifies it and broadcasts it to the destinations which is used to extract the second copy of the required data (first one being directly received). Now, as the number of participating sources increase, the chances of collisions increase. Hence, the sources wake up and keep performing CCA even if phase I is not complete. In such cases R broadcasts an Assistant SIP (ASIP) frame which are received by sources and they act accordingly (block 17 followed by block 15 of Fig. 3) as discussed in Section 3.2.3. The frame format of ASIP is similar to that of ACK frame except the fact that it is a management frame and it will contain the updated $\mathrm{NTSCT_{min}}$ time.

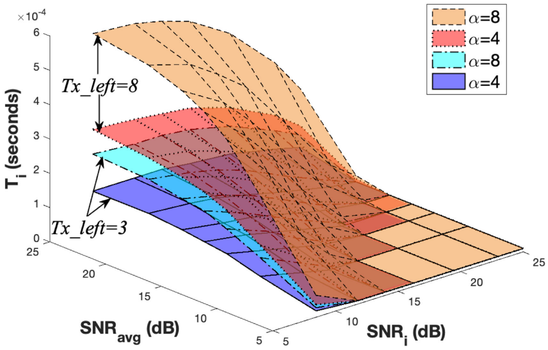

Fig. 5. Illustration of variation of T_i with different values of α and *Tx_left* with respect to $\mathrm{SNR_{avg}}$ and $\mathrm{SNR_i}$.

2. RTS/CTS are not used in the proposed PC-O-NCC scenario as all the nodes are considered to be at one hop distance from each other.

3.2.1 Proposed Timer

In this sub-section, we explain the functioning of the proposed timer along with the effect of making the timer a function of the number of contending sources during any given time-slot. After calculating $\mathrm{SNR_i}$, the sources set their timer by using the following proposed formula given by

$$T_i \quad = \zeta\lceil K(1-F_X(x))\rceil = \zeta\left\lceil Ke^{-\frac{\mathrm{SNR_i}}{\mathrm{SNR_{avg(i)}}}}\right\rceil \tag{2}$$

where K=α**Tx_left* which acts as a limiting factor for T_i whereas α is the parameter to be optimised, $\lceil.\rceil$ is the ceiling function which enforces the value of T_i to the next largest integer and $F_X(x)$ is the cumulative distribution function (cdf) of a random variable X. Here, X and x represent $\mathrm{SNR_i}$ and $\mathrm{SNR_{avg(i)}}$. By taking into account the complementary cdf $(1-F_X(x))$ of the channels, (2) gives the probability with which $\mathrm{SNR_i}$ is above $\mathrm{SNR_{avg(i)}}$. The value of α influences the number of collisions, latency and channel idle time in any time slot. As seen in Fig. 5, the upper bound of the timer changes with α and *Tx_left* which eventually reduces collisions but increases the latency and channel idle time. The optimisation of α and latency is out of scope of this paper. Now, it must be noted that the maximum value of T_i needs to be such that any contending source not being able to access a channel does not fail to receive the ACK or Req_reTx frame which is crucial for the successive time slot. Thus, the maximum value of T_i can be given by, $\max(T_i) \leq T_{Data}$, where T_{Data}=Time taken to transmit x_i. It can also be given by the ratio between Packet size (Payload) and Transmission rate (Data Rate). In this case, R after receiving a data or collided frame needs short inter-frame space (*SIFS*) interval to process it and be ready with an ACK or a Req_reTx frame. Thus, for a minimum value of $\mathrm{SNR_i}$, $\max(T_i)$ can also be given by

$$\zeta * \lceil K\rceil \leq T_{Data}. \Rightarrow \lceil\alpha\rceil \leq \frac{\text{Payload}}{\zeta * \text{Data Rate} * Tx\_left}. \tag{3}$$

Thus, the values of α can be set accordingly with respect to *Tx_left*, Payload and Data Rate. Here, the value of α is pre-

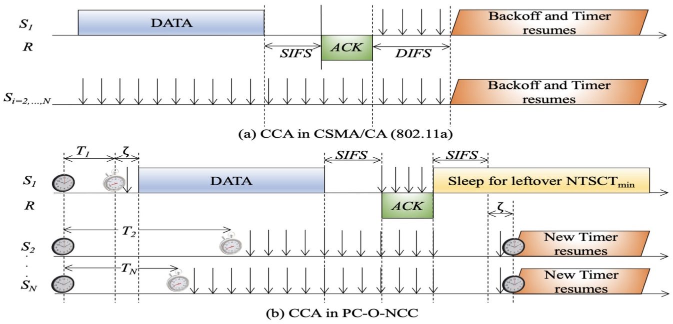

Fig. 6. CCA comparison of the two protocols.

fixed and considered to be the same throughout a session for all the nodes. For the least possible collisions, (3) must satisfy the equality. The dependence of K on *Tx_left* reflects not only on the decreased number of collisions to a certain extent but also keeps the latency under check throughout the session by changing the upper bound of T_i for a new time-slot after every successful transmission.

A bit more insight can be obtained into the working of the timer from Fig. 5. It must be noted that even though the examples in this paper are based on a model with same average SNR, the algorithm works equally for devices in contention with different SNR_{avg}. To illustrate this, two examples are considered. First, we consider an example with sources having different average SNR followed by an example with same average SNR. Let us consider N=3 S_i-D_i pairs with $\text{SNR}_{\text{avg}(1)} = 5$ dB, $\text{SNR}_{\text{avg}(2)} = 15$ dB and $\text{SNR}_{\text{avg}(3)} = 10$ dB and each having SNR_{i}=10 dB, respectively for $i \in \{1, 2, 3\}$. Even though all the channels are having the same SNR_{i} values, T_1 consists the lowest value followed by T_3 and T_2. This can also be observed in Fig. 5 for *Tx_left*=3, α=8. Thus, S_2 wins the contention as S_2-R link is the best performing channel in this scenario.

Similarly, for the second example with same average SNR for all the 3 sources, let us consider SNR_{avg}=20 dB and SNR_{i}=5, 15 and 25 dB, respectively for $i \in \{1, 2, 3\}$. It can be clearly seen in Fig. 5, that S_3 and S_1 consist of minimum and maximum timer values, respectively. Thus, the proposed timer always prioritises the source having the best SNR_{i} with respect to its average.

3.2.2 Proposed Clear Channel Assessment Mechanism

In general, performing CCA is a very costly affair in terms of power usage. Conventionally, in a 802.11 network setup, every device randomly selects a value between some preset limits. Then, it waits and decreases the value and performs CCA subsequently. This continues unless the value decreases to 0. In the mean time, if it finds the channel to be busy, it freezes the variable and keeps on checking the channel unless the channel is free for distributed coordination function inter-frame space ($DIFS$)(=$SIFS$+2ζ) interval [26]. This is illustrated in Fig. 6a. As can be seen, say source S_1 won the contention and sends data. The other sources keep on performing CCA unless it finds the channel to be free for $DIFS$ interval. However, in a PC-O-NCC network, the knowledge about channel energy is sufficient for each source to wait for the succeeding time slot to contend to transmit. Hence, if T_i at each source S_i is kept atleast ζ apart, it would be sufficient enough to let the device know about any ongoing transmission when they start performing CCA. If while performing CCA, CEL for ζ interval, x_i is transmitted. Otherwise, as discussed before, it continues to check the channel until it either receives ACK or Req_reTx frame. This is also illustrated in Fig. 6b where it has been shown that S_1 has won the contention and successfully performed CCA. On the other hand, the other sources complete their individual timers but once it starts performing CCA, they find the channel to be busy and thus, waits for a control frame to renew their timers based on the new channel conditions.

It should be noted that the introduction of a distributed algorithm to incorporate MUD gain comes at the cost of NC losing its own benefit of higher throughput from NCC. This is due to contention that inevitably causes collisions. This is avoided to a considerable extent by making (2) a function of network load and α. In a basic NCC case, diversity is obtained at the end of N+1 time slots but the reliability of data is low since the transmitting node transmits data in its pre-determined time slot irrespective of the channel conditions. In the proposed PC-O-NCC, diversity is achieved after N+Δ+1 time slots where Δ is the number of time slots during which a collision occurred in a particular session. The value of Δ is dependent on the value of the parameter K in (2) which acts as a trade-off factor to the number of time slots used in a session. Using (2), the S_i with relatively higher SNR_{i} than its average is allocated lesser T_i value. To the best of authors' knowledge, there is no expression available in the prevailing literature for timer calculation that takes into account the factors like ζ, α, *Tx_left* and $\frac{\text{SNR}_{\text{i}}}{\text{SNR}_{\text{avg(i)}}}$. However, the usage of a ratio between SNR_{i} and a lower threshold SNR can be seen in [27] without taking the other factors into account.

Since an opportunistic contention based algorithm is used for deploying a distributed system, collisions are bound to happen. Although efforts have been made to reduce the number of collisions by designing the timer such that collisions decrease to a considerable extent but it is inadequate to avoid collisions radically. Although for network scenarios with longer T_{coh}, the usage of an increased value of K with every collision along with a parameter c as mentioned in [4] can prove to be another efficient method to reduce successive collisions within the same T_{coh}.

3.2.3 Minimum Session Duration

In a PC-O-NCC network, a node S_i can only transmit once during a session and has to be dormant unless the next session starts. In order to save energy, S_i can go to sleep for a pre-determined time unless the new session starts. Thus, $\text{NTSCT}_{\text{min}}$ can be given by

$$\begin{aligned}\text{NTSCT}_{\text{min}} = &\underbrace{(1\zeta + T_{Data} + 2SIFS + T_{ACK})(Tx\_left - 1)}_{>1 \text{ Tx left (Contention)}} \\ &+ \underbrace{2SIFS + T_{Data} + T_{ACK}}_{=1 \text{ Tx left (ALOHA)}} + \underbrace{SIFS + T_{Amp\_Comp\_Data}}_{\text{R multi-casting}} \end{aligned} \tag{4}$$

where T_{ACK} and $T_{Amp\_Comp\_Data}$ are the time taken to transmit ACK and Amp_Comp_Data by R, respectively. The

TABLE 2
Varying $\text{NTSCT}_{\min}$ Interval

Tx_left	Leftover $\text{NTSCT}_{\min}$ value
3	250μsec+3*T_{Data}+$T_{Amp\_Comp\_Data}$
2	169μsec+2*T_{Data}+$T_{Amp\_Comp\_Data}$
1	88μsec+T_{Data}+$T_{Amp\_Comp\_Data}$
0	16μsec+$T_{Amp\_Comp\_Data}$

expression in (4) is divided into three parts mainly. The first two parts add up to the minimum time required to complete a session. The former being the minimal contention period when more than one sources are contending whereas the latter refers to the time taken to transmit data when only one source is left. The third part refers to the time taken to transmit the composite data by R. $\text{NTSCT}_{\min}$ can be optimised based on environment. Since, all the packets sent by the sources are of same length and R transmits $T_{Amp\_Comp\_Data}$ at the basic rate available, $T_{Amp\_Comp\_Data}$=T_{Data}. Now, as the minimum value of NTSCT is discussed, an ideal case is considered where T_i=1ζ for the winner for every time slot. Initially, $\text{NTSCT}_{\min}$ is set using the information provided through SIP. The decreasing value of $\text{NTSCT}_{\min}$ is illustrated in Table 2 for N=3 S_i-D_i pairs. Since, N=3, *Tx_left* is set to 3 and every node sets their $\text{NTSCT}_{\min}$ as provided by R. After every successful transmission, the source which won the contention for that time slot goes to sleep for the leftover $\text{NTSCT}_{\min}$ as shown in Table 2. It can be observed that after every successful transmission, the contention winner goes to sleep for a lesser amount of time so that they wake up by the time R transmits the next SIP for the new session.

Since the minimum value of NTSCT is considered, in a practical scenario, nodes are bound to be awake before the transmission of the next SIP. This might happen either due to variable values of T_i or due to collisions or both. In such cases, if the medium is found to be free by R and transmissions are still left to complete phase I, whereas $\text{NTSCT}_{\min}$ is over, R multi-casts ASIP instead of SIP. ASIP notifies the awaken as well as the contending nodes about the minimum amount of delay in time for the transmission of the next SIP. Using ASIP, all the nodes set the value of $\text{NTSCT}_{\min}$ to the updated value as notified by ASIP. The nodes which have already sent their packets for the ongoing session, goes to sleep for the updated $\text{NTSCT}_{\min}$ interval whereas the others reset their T_i using ASIP and start to contend. This is illustrated in block 14 followed by block 3 of Fig. 3. On the other hand, if the channel is busy, R transmits an ASIP/SIP as soon as it finds the channel to be free after the ongoing transmission is over. ASIP is transmitted if phase I is still going on whereas SIP is transmitted otherwise after phase II is over. If $\text{NTSCT}_{\min}$ interval is over and the channel is found to be busy by any S_i which have already participated in a session, it keeps on checking the channel unless it receives a management frame (SIP/ASIP) from R.

4 Analytical Edifice for PC-O-NCC

In this section, we delve into the analytical portion of the proposed scheme. Initially, we analyse a case with 3 S-D pairs for ease of explanation. Later, we generalise the model for N such pairs followed by a SNR based opportunistic metric which gives us a better insight into the proposed algorithm.

4.1 Framework for Three Source-Destination Pairs

To understand the network, Fig. 7 depicts the case where we have $S_{i\in\{1,2,3\}}$-D_i pairs with a dedicated R. The onset of the session is marked by the transmission of SIP by R in Fig. 7. As discussed before, each S_i receives the SIP, initialises *Tx_left*=3 and sets their T_i using (2). Let SNR_i be such that T_1=5ζ, T_2=2ζ and T_3=4ζ. As illustrated in Fig. 7, each S_i waits for respective T_i interval before performing CCA. Node S_2 having the lowest timer value, performs CCA after waiting for T_2 interval and completes it successfully. Thus, the channel gets allocated to S_2 for the first time slot. On the other hand, nodes S_1 and S_3 start performing CCA after T_1 and T_3 interval but could not find the CEL for ζ interval. The signals received at any receiving node $Q \in \{R, D_{i\in\{1,\ldots,N\}}\}$ at the end of the first time slot can be written as

$$\mathcal{Y}^{(1)}_{S_2Q} = \sqrt{P_{S_2}\delta^{-\beta}_{S_2Q}}h^{(1)}_{S_2Q}x_2 + n^{(1)}_{Q}, \tag{5}$$

where $\mathcal{Y}^{(t_a)}_{ab}$, x_a and $n^{(t_a)}_b$ represent the signal received at node b when node a transmits, packet transmitted by a and Additive White Gaussian Noise (AWGN) with $n^{(t_a)}_b \in (0,\sigma^2)$ at node b, respectively during the time slot when node a won the contention. After receiving the data, R acknowledges S_2 by transmitting ACK. On receiving ACK, S_2 goes to sleep for the remaining $\text{NTSCT}_{\min}$ as illustrated in Fig. 7. Whereas, S_1 and S_3 overhear ACK, calculates SNR_i, reduces *Tx_left* by 1 and use it to reset their timers according to the new channel conditions. Say, T_1=4ζ and T_3=2ζ respectively as illustrated in Fig. 7. Node S_3 having the least timer,

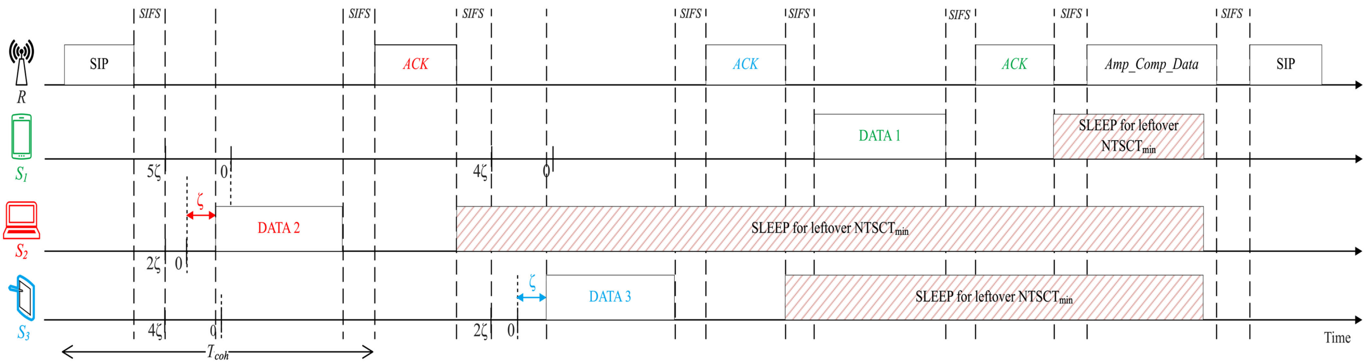

Fig. 7. Operation of the proposed scheme in time domain.

successfully performs CCA after T_3 interval and transmits x_3. Hence, by the end of the second time slot, the signals received at Q are

$$\mathcal{Y}_{S_3Q}^{(2)} = \sqrt{P_{S_3}\delta_{S_3Q}^{-\beta}}h_{S_3Q}^{(2)}x_3 + n_Q^{(2)}, \tag{6}$$

After receiving the data in the second time-slot, R transmits ACK. Node S_3 on receiving it goes to sleep for the leftover NTSCT$_{\min}$. Node S_1 on the other hand, on receiving ACK decreases *Tx_left* by 1 and compares if *Tx_left*=1 which it finds to be affirmative and the procedure of ALOHA is followed. Thus, signals received at Q may be written as,

$$\mathcal{Y}_{S_1Q}^{(3)} = \sqrt{P_{S_1}\delta_{S_1Q}^{-\beta}}h_{S_1Q}^{(3)}x_1 + n_Q^{(3)}, \tag{7}$$

After the third time slot, R transmits ACK and then multicasts *Amp_Comp_Data* as shown in Figs. 2b and 7.

Now, let us consider D_1 to be the node of interest here. Composite signal received at D_1 by the end of the fourth time slot can be given as

$$\mathcal{Y}_{RD_1}^{(4)} = \psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}\sum_{i=1}^{3}\mathcal{Y}_{S_iR}^{(t_{S_i})} + n_{D_1}^{(4)}, \tag{8}$$

where ψ_r is the amplification factor given by [10]

$$\psi_r^2 = \frac{P_R}{\sum_{i=1}^{3} P_{S_i}\delta_{S_iR}^{-\beta}|h_{S_iR}^{(t_{S_i})}|^2 + 3\sigma_{n_R}^2}. \tag{9}$$

Putting Q=R in (5) and (6), (8) can be rewritten as,

$$\begin{aligned}\mathcal{Y}_{RD_1}^{(4)} &= \psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}\Bigg\{\sqrt{P_{S_2}\delta_{S_2R}^{-\beta}}h_{S_2R}^{(1)}x_2 \\ &\quad + n_R^{(1)} + \sqrt{P_{S_3}\delta_{S_3R}^{-\beta}}h_{S_3R}^{(2)}x_3 + n_R^{(2)} + \mathcal{Y}_{S_1R}^{(3)}\Bigg\} + n_{D_1}^{(4)}.\end{aligned} \tag{10}$$

Putting Q=D_1 in (5) and (6), and subtracting its weighted value from (10), the second copy of the desired signal can be obtained as $\hat{\mathcal{Y}}_{RD_1} = \mathcal{Y}_{RD_1}^{(4)} - \omega_1\mathcal{Y}_{S_2D_1}^{(1)} - \omega_2\mathcal{Y}_{S_3D_1}^{(2)}$ where,

$$\omega_{i\in\{1,2\}} = \frac{\psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}\sqrt{\delta_{S_iR}^{-\beta}}h_{S_iR}^{(t_{S_i})}}{\sqrt{\delta_{S_iD_1}^{-\beta}}h_{S_iD_1}^{(t_{S_i})}}.$$

Putting ω_1 and ω_2 in $\hat{\mathcal{Y}}_{RD_1}$, we get

$$\begin{aligned}\hat{\mathcal{Y}}_{RD_1} &= \psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}\mathcal{Y}_{S_1R}^{(3)} + n_{D_1}^{(4)} + \psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}n_R^{(1)} \\ &\quad + \psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}n_R^{(2)} - \omega_1 n_{D_1}^{(1)} - \omega_2 n_{D_1}^{(2)}.\end{aligned} \tag{11}$$

The second copy of x_1 is reconstructed at D_1 using the packets overheard from S_2 and S_3. The first copy of x_1 being obtained directly at D_1 from S_1 at the end of third time slot. Thus, a diversity of order 2 is achieved in a PC-O-NCC based network. Finally, the second copy obtained at D_1 can also be written as, $\hat{\mathcal{Y}}_{RD_1} = \psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}\mathcal{Y}_{S_1R}^{(3)} + \tilde{n}_{D_1}$, where $\tilde{n}_{D_1}$ can be termed as ANC noise at D_1 [28]. Thus, ANC noise at D_1 is given by,

$$\begin{aligned}\tilde{n}_{D_1} &= n_{D_1}^{(4)} + \psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}n_R^{(1)} + \psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}n_R^{(2)} \\ &\quad - \omega_1 n_{D_1}^{(1)} - \omega_2 n_{D_1}^{(2)}.\end{aligned}$$

It should be noted that, $E[n_{D_1}]$=$E[n_R]$=$E[\tilde{n}_{D_1}]$=0. Thus, the variance of $\tilde{n}_{D_1}$ can be represented by,

$$\begin{aligned}\tilde{\sigma}_{\tilde{n}_{D_1}}^2 &= \sigma_{n_{D_1}}^2 + 2\left(\psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}\right)^2\sigma_{n_R}^2 + \left(\psi_r\sqrt{\delta_{RD_1}^{-\beta}}h_{RD_1}^{(4)}\right)^2 \\ &\quad \sigma_{n_{D_1}}^2\left(\left(\frac{\sqrt{\delta_{S_2R}^{-\beta}}h_{S_2R}^{(1)}}{\sqrt{\delta_{S_2D_1}^{-\beta}}h_{S_2D_1}^{(1)}}\right)^2 + \left(\frac{\sqrt{\delta_{S_3R}^{-\beta}}h_{S_3R}^{(2)}}{\sqrt{\delta_{S_3D_1}^{-\beta}}h_{S_3D_1}^{(2)}}\right)^2\right).\end{aligned} \tag{12}$$

4.2 Description for N Source-Destination Pairs

This subsection extends the analysis to the general case of N S_i-D_i pairs. We also discuss two separate algorithms, Algorithm 1 and 2 working at S_i and R, respectively. The proposed PC-O-NCC model provides us a diversity of order 2. The first copy of data being received directly while the second copy needs to be reconstructed using overheard data and the data received through R. Suppose for a particular time slot, channel gets allocated to node S_k. Let D_i be the node of interest here. Thus, the first copy of x_k at D_i can be represented by $\mathcal{Y}_{S_kD_i}^{(t_{S_k})} = \sqrt{P_{S_k}\delta_{S_kD_i}^{-\beta}}h_{S_kD_i}^{(t_{S_k})}x_k + n_{D_i}^{(t_{S_k})}$, where $i,k \in \{1,\ldots,N\}$. To obtain the required diversity, the second copy can be obtained at D_i by subtracting necessary overheard data as shown in previous sub-section. Thus, after retrieval, (11) can be generalised as, $\hat{\mathcal{Y}}_{RD_i} = \psi_{r(N)}\sqrt{\delta_{RD_i}^{-\beta}}h_{RD_i}^{(N+1)}\mathcal{Y}_{S_kR}^{(t_{S_k})} + \tilde{n}_{D_i}$ where,

$$\mathcal{Y}_{S_kR}^{(t_{S_k})} = \sqrt{P_{S_k}\delta_{S_kR}^{-\beta}}h_{S_kR}^{(t_{S_k})}x_k + n_{D_i}^{(t_{S_k})}, \tag{13}$$

$$\psi_{r(N)} = \sqrt{\frac{P_R}{N\sigma_{n_R}^2 + \sum_{k=1}^{N} P_{S_k}\delta_{S_kR}^{-\beta}|h_{S_kR}^{(t_{S_k})}|^2}}, \tag{14}$$

$$\tilde{n}_{D_i} = n_{D_i}^{(N+1)} + \sum_{\substack{j=1\\ j\neq i}}^{N}\psi_{r(N)}\sqrt{\delta_{RD_i}^{-\beta}}h_{RD_i}^{(N+1)}n_R^{(t_{S_k})} - \sum_{\substack{j=1\\ j\neq i}}^{N}\omega_j n_{D_i}^{(t_{S_k})}. \tag{15}$$

ω_j is the weighting factor given by

$$\omega_j = \frac{\psi_r\sqrt{\delta_{RD_i}^{-\beta}}h_{RD_i}^{(N+1)}\sqrt{\delta_{S_jR}^{-\beta}}h_{S_jR}^{(t_{S_j})}}{\sqrt{\delta_{S_jD_i}^{-\beta}}h_{S_jD_i}^{(t_{S_j})}}. \tag{16}$$

From (15), generalised form of (12) at D_i can be given by

$$\begin{aligned}\tilde{\sigma}_{\tilde{n}_{D_i}}^2 &= \sigma_{n_{D_i}}^2 + (N-1)\left(\psi_{r(N)}\sqrt{\delta_{RD_i}^{-\beta}}h_{RD_i}^{(N+1)}\right)^2\sigma_{n_R}^2 \\ &\quad + \sum_{\substack{j=1\\ j\neq i}}^{N}\omega_j^2\sigma_{n_{D_i}}^2.\end{aligned} \tag{17}$$

An insight into the impact of ANC noise is obtained from (17) which clearly increases with the number of devices participating in a session. The SNR of the two copies of data can be given by $\mathrm{SNR}_{\mathrm{Direct}}$ and $\mathrm{SNR}_{\mathrm{Indirect}}$. $\mathrm{SNR}_{\mathrm{Direct}}$ is the SNR of x_i received directly from S_i which can be given by (1) and $\mathrm{SNR}_{\mathrm{Indirect}}$ is the SNR of the copy received through R. Thus, it can be given by,

$$\mathrm{SNR}_{\mathrm{Indirect}} = \frac{\mathrm{SNR}_{S_iR}\mathrm{SNR}_{RD_i}}{\mathrm{SNR}_{RD_i} + \frac{\tilde{\sigma}^2_{\tilde{n}_{D_i}}}{\sigma^2_{n_{D_i}}}\left(N + \sum_{i=1}^{N}\mathrm{SNR}_{S_iR}\right)}. \tag{18}$$

Algorithm 1. Proposed Method for Channel Contention and Occupation

Input: *Tx_left_ini*, $\mathrm{NTSCT}_{\mathrm{min}}$, α for T_i calculation.
Output: Channel contention and occupation followed by sleep interval till the next session.
1: Rx SIP, set *Tx_left*=*Tx_left_ini* and store $\mathrm{NTSCT}_{\mathrm{min}}$.
2: **if** *Tx_left =1* **then**
3: Go to **Step 9**.
4: **else**
5: **Initialize/Update**: Set T_i using (2) by calculating SNR_i from the received frame (ACK / Req_reTx).
6: **end**
7: Wait for T_i interval and perform CCA.
8: **if** *CEL for ζ interval* **then**
9: Tx x_i and set Timer to Rx ACK.
10: **if** Rx ACK **then**
11: S_i goes to sleep for leftover/updated $\mathrm{NTSCT}_{\mathrm{min}}$.
12: Keep performing CCA unless Rx ASIP or SIP.
13: **if** *Rx ASIP* **then**
14: Update $\mathrm{NTSCT}_{\mathrm{min}}$ and go to **Step 11**.
15: **else**
16: Go to **Step 1**.
17: **end**
18: **else**
19: **if** $NTSCT_{min}$ $over$ **then**
20: Rx ASIP and update $\mathrm{NTSCT}_{\mathrm{min}}$ value.
21: Go to **Step 2**.
22: **else**
23: Go to **Step 2**.
24: **end**
25: **end**
26: **else**
27: Keep performing CCA and Rx ACK / Req_reTx.
28: **if** Rx ACK **then**
29: **Update** *Tx_left*=*Tx_left*-1.
30: **if** $NTSCT_{min}$ $over$ **then**
31: Rx ASIP and update $\mathrm{NTSCT}_{\mathrm{min}}$ value.
32: Go to **Step 2**.
33: **else**
34: Go to **Step 2**.
35: **end**
36: **else**
37: **if** $NTSCT_{min}$ $over$ **then**
38: Rx ASIP and update $\mathrm{NTSCT}_{\mathrm{min}}$ value.
39: Go to **Step 2**.
40: **else**
41: Go to **Step 2**.
42: **end**
43: **end**
44: **end**
Result Completion of successful channel occupation by S_i.

The specific channel allocation algorithm for any participating node is shown in the proposed Algorithm 1 whereas Algorithm 2 shows the steps being followed at R throughout phases I and II. Let $S^{(1)}$=$\{S_1,\ldots,S_N\}$ and D=$\{D_1,\ldots,D_N\}$. The set $S^{(t)}$ represents all the contending nodes for any time slot $t \in \{1,\ldots,r,\ldots,N\}$ and the length of $S^{(t)}$ represents *Tx_left*. As discussed before, the contention begins once the sources receive the SIP and store the necessary values (Algorithm 1: line 1). Following this, the sources compare the value of *Tx_left*. If it is equal to 1, it directly transmits the data and waits for ACK (Algorithm 1: lines 2,3 and 9). Otherwise, a timer is set based on the packet received (Algorithm 1: line 5). Once the timer ends, it starts performing CCA (Algorithm 1: line 7). If CEL for ζ interval, data is transmitted and it waits to receive ACK or Req_reTx (Algorithm 1: line 9). If ACK is received, the source goes to sleep for leftover $\mathrm{NTSCT}_{\mathrm{min}}$ interval. Once it is done, it wakes up and keeps performing CCA unless it receives ASIP or SIP. On the other hand, if Req_reTx is received, it resumes contention by going back to line 2 of Algorithm 1. However, if CEL is not found to be affirmative for ζ interval, the sources keep performing CCA unless it receives ACK or Req_reTx (Algorithm 1: line 27) followed by lines 28-43.

Algorithm 2. Proposed Relaying Protocol for Coded Data

Input: *Tx_left_ini*.
Output: Successful data reception over N+Δ time-slots followed by transmission of *Amp_Comp_Data*.
1: Calculate value of $\mathrm{NTSCT}_{\mathrm{min}}$ and Tx SIP.
2: Set *Tx_left*=*Tx_left_ini*.
3: Keep performing CCA and Rx Data frame.
4: **if** *Data received appropriately* **then**
5: Tx ACK and update *Tx_left*=*Tx_left*-1.
6: **else**
7: Tx Req_reTx.
8: **end**
9: **if** *Tx_left*=0 **then**
10: Superpose all the stored data and amplify it using (14) and Tx Amp_Comp_Data.
11: Go to **Step 1**.
12: **else**
13: **if** $NTSCT_{min}$ $over$ **then**
14: Update $\mathrm{NTSCT}_{\mathrm{min}}$ using (4) and Tx ASIP.
15: Go to **Step 3**.
16: **else**
17: Go to **Step 3**.
18: **end**
19: **end**
Result Algorithm at R for phases I and II.

Algorithm 2 works at R throughout phases I and II. Just after the set-up phase, R calculates *Tx_left_ini* and $\mathrm{NTSCT}_{\mathrm{min}}$, embeds them in SIP and transmits it (Algorithm 2: line 1). Following this, it keeps performing CCA unless it receives a data frame (Algorithm 2: line 3). If it is decodable, it stores it and transmits ACK followed by the decrement of *Tx_left* value by 1 (Algorithm 2: lines 4-5) else it transmits Req_reTx (Algorithm 2: line 7). If phase I has ended, then R transmits *Amp_Comp_Data* (Algorithm 2: line 10). Otherwise, if previous $\mathrm{NTSCT}_{\mathrm{min}}$ is over, R calculates new $\mathrm{NTSCT}_{\mathrm{min}}$ and

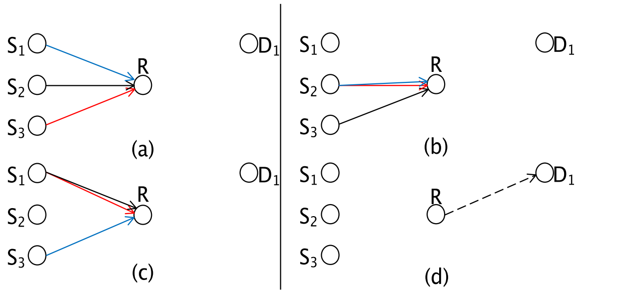

Fig. 8. Example of data transmission in phase I for N=3 ((a), (b), (c)) followed by transmission of Amp_Comp_Data by R in phase II (dashed line) (d) for PC-O-NCC (black line), CSMA/CA (red line) and TDMA (blue line).

TABLE 3
Simulation Parameters

Parameters	Value
Number of sources (N)	1-10
Transmitting power (P_{S_i}, P_R)	(1-10) mW
Noise power	10^{-10}W
Path loss exponent (β)	3
$\delta_{S_iR}, \delta_{RD_i}$	(10-80) meters
Slot time (ζ)	9μsec
$SIFS$	16μsec
Transmission rate	3 Mbps
Payload size (L_{Data})	1500 bytes
ACK frame size (L_{ACK})	12 bytes

transmits ASIP (Algorithm 2: line 14). The complexity of the Algorithms 1 and 2 are $\mathcal{O}(N+1)$ and $\mathcal{O}(2N)$, respectively.

4.3 SNR Based Opportunistic Metric

To show the effectiveness of the proposed scheme, in this sub-section, we compare the proposed PC-O-NCC scheme with the prevalent TDMA and CSMA/CA schemes based on a SNR based opportunistic metric. This metric takes into account the least weighted (maximum SNR_{S_iR}) path of the composite data which is received at D_i in order to achieve diversity. The cost of a path during any time-slot can be given by, $d_{ab}^{SNR} = \frac{1}{1-e^{-\frac{\text{SNR}_\text{i}}{\text{SNR}_\text{avg}}}}$. Thus, the total cost of the composite data being received at any destination D_i can be given by, $C = d_{RD_i}^{SNR} + \sum_{i=1}^{N} d_{S_iR}^{SNR}$.

To illustrate the dependence, let us consider Fig. 8 where N=3 and D_1 is the destination of interest. Let all the S_i have the same SNR_avg=10 with $\text{SNR}_\text{i}^{(1)} = [8.98, 19.34, 11.27]$, respectively for the first time slot. As can be seen in Fig. 8a, for a network using simple TDMA, S_1 transmits whereas for a network based on PC-O-NCC and CSMA/CA, S_2 and S_3 transmits, respectively. The individual costs for the first time slot can be given by 1.686, 1.169 and 1.479, respectively. For the second time slot represented in Fig. 8b, let the $\text{SNR}_\text{i}^{(2)}$ be [12.78, 20.63, 16.79], the respective costs of which can be given by 1.385, 1.1454 and 1.171. Similarly, for the third time slot, the costs for the respective users would be 1.178, 2.208 and 1.299 for $\text{SNR}_\text{i}^{(3)} = [18.87, 6.03, 14.67]$, respectively. Thus, the total cost for different algorithms used for $d_{RD_i}^{SNR}$=1.2 are 4.718, 5.0024 and 5.3304, respectively for PC-O-NCC, CSMA/CA and TDMA. From the above example it can be observed that, PC-O-NCC opts for the lesser weighted path. Although, unlike the above example, the metric does not always ensure short term fairness but it definitely proves to be advantageous in the longer run.

5 Results

In this section, the performance of PC-O-NCC system is compared with schemes used in [3], [19], [26], [29], [30] based systems using MATLAB. Authors in [3] considered a typical NCC system with TDMA as the protocol being used for transmission of data. In [19], authors designed a network where there are two master nodes and diversity of order 2 will be achieved only if master node 2 was unable to receive the required data correctly and it broadcasts a negative acknowledgment ($NACK$) packet. Protocol in [26] uses a CSMA/CA based model. The network considered in [29] consists of nodes which can book their time-slots by sending time slot resource request (TREQ) packets whereas for the network in [30] the authors consider a dynamic model where the scheme automatically changes the contention time and reserve the time slots for transmission, based on the number of participating nodes. A model similar to the system model in [28] is used with appropriate changes made to the systems considered for comparison to keep the fairness intact. Outage probability, latency, throughput, packet delivery ratio (PDR) and energy consumption are investigated at the destination of interest, D_1. Parameters used during simulation are listed in Table 3.

A model similar to the outage analysis model discussed in [8] is considered for analysis purpose. It is assumed that the direct copy of transmitted signal x_i received from S_i at D_i is not reliable enough to take critical decisions. This emphasizes the requirement of an additional copy of the data, which is reconstructed with the help of R. Maximal Ratio Combining is applied at destination nodes. A destination node is said to be in outage if the effective SNR at that node is less than a threshold (T) where Effective SNR = $\text{SNR}_\text{Direct}+\text{SNR}_\text{Indirect}$.

Fig. 9 presents the outage comparison of PC-O-NCC with respect to T with other relevant MAC schemes like TDMA [3], Two Master Nodes-Cooperative Network Coding (TMN-CNC) [19], CSMA/CA [26], RES-TDMA [29] and MAC protocol based on traffic prediction (TPF-MAC) [30]. It may be noted that as the value of T increases, the outage performance worsens for all the network models. However, the proposed PC-O-NCC scheme shows a superior outage performance than the other models. The superiority in outage is solely due to the MUD gain achieved from the

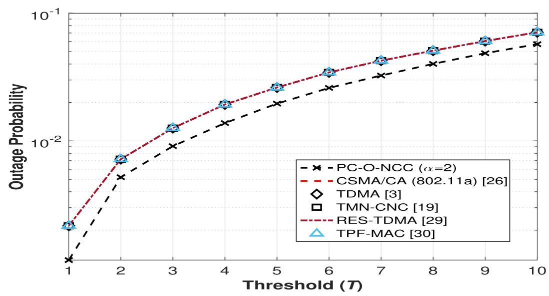

Fig. 9. Outage comparison of PC-O-NCC with few other MAC protocols for N=3 and SNR_avg=20dB.

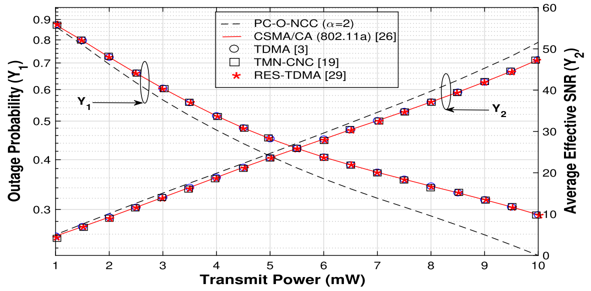

Fig. 10. Outage probability (Y_1) and average effective SNR (Y_2) with respect to transmitted power for N=3.

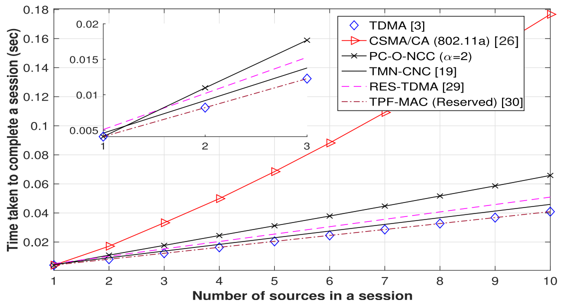

Fig. 11. Amount of time taken to complete a session with respect to increasing number of sources in a session.

proposed algorithm. Since, the other MAC algorithms are not transmitting based on $\mathrm{SNR_i}$, they show similar performances due to the absence of MUD gain.

The outage probability (Y_1) along with effective SNR (Y_2) with respect to transmit power is illustrated in Fig. 10. It can be observed that as the transmit power increases, the effective SNR increases for all the considered cases. Although, PC-O-NCC gets an edge in terms of effective SNR due to the increasing effect of MUD gain with respect to transmit power. Thus, it also shows a better outage performance which improves with the increasing transmit power. In cases of lower transmit power, the performance of all the schemes are close, however the outage performance of PC-O-NCC increases significantly as the transmit power increases.

Fig. 11 compares the latency (delay) of the proposed PC-O-NCC for α=2 with the other considered MAC algorithms as shown before with respect to increasing number of contending sources in a session (N). Here, latency is the average total time taken to complete a session. TDMA along with TPF-MAC (Reserved) show a similar performance and outperforms the others as both include the announcement of transmitting schedule followed by transmission of data in their respective time-slots thus, causing no collisions. The performance of TMN-CNC is slightly worse than TPF-MAC as it includes the exchange of Negative Acknowledgement ($NACK$) frames to ask for cooperation. This is followed by the performance of RES-TDMA where time-slots for transmissions are booked using the time-slot resource request (TREQ/TRER) packets. PC-O-NCC performs better when compared CSMA/CA. Although with increasing number of contending devices in a session the performance of both PC-O-NCC and CSMA/CA worsens due to increased collision probability, PC-O-NCC has a linearly degrading performance whereas CSMA/CA has a non-linear one. The

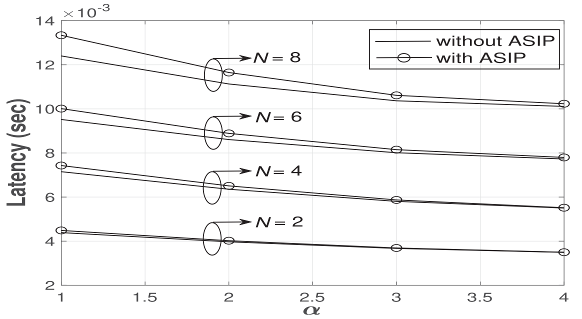

Fig. 12. Latency comparison with respect to α for different values of N for the cases where ASIP is not being used and being used, respectively.

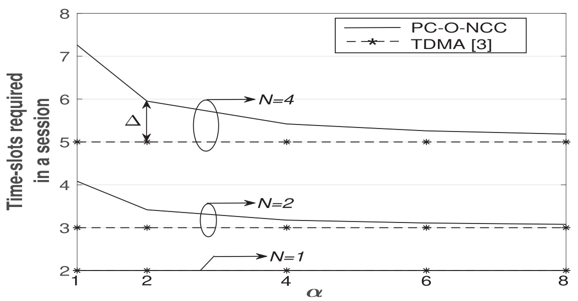

Fig. 13. Requirement of time slots to complete both Phase I and Phase II with respect to α.

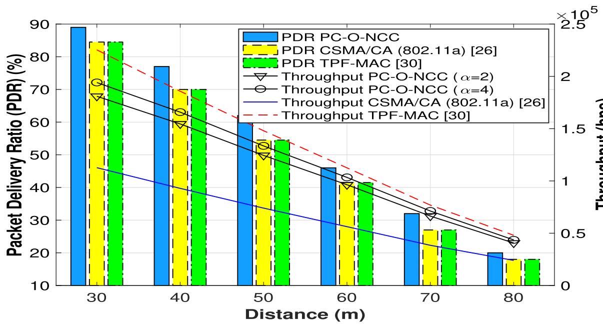

Fig. 14. Packet Delivery Ratio (PDR)(Y_1) and Throughput (Y_2) comparison with respect to distance.

reason for the linear degradation of performance is the allocation of T_i in (2) which is based on factors like α and Tx_left. This not only reduces the number of collisions but also keeps the upper bound same even after a collision whereas the upper bound in CSMA/CA increases thus, causing a non-linear increase in latency for CSMA/CA.

In Fig. 12 we compare the latency of the proposed PC-O-NCC scheme with respect to different values of α and N. We have mainly compared two cases in this figure where in one case we use the concept of ASIP and in the other we do not use ASIP. It can be seen that as the value of α increases, the latency decreases as the number of collisions decrease (discussed in the paper). However, when ASIP is being used, there is a slight shift in latency to the higher side. For lesser values of N and α, the lesser number of ASIP are being exchanged. However, as the value of N increases, for lesser values of α there are more collisions. Thus, more ASIP needs to be exchanged and this decreases with increasing values of α.

Fig. 13 shows that the number of collisions decrease with increasing value of α, thus, decreasing the probability of an

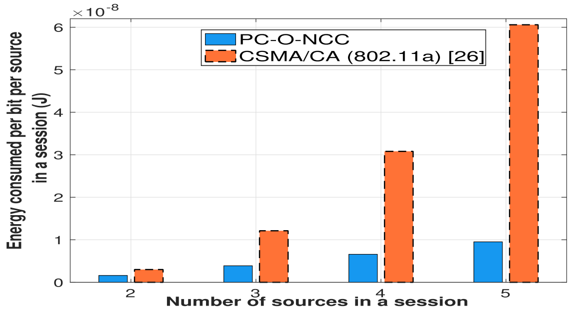

Fig. 15. Per bit energy consumption by any particular source with respect to increasing number of sources in a session. (P_{S_i}=1.5 mW and power consumed to perform CCA=1 mW).

extra time-slot for a particular value of N. Although the probability of collision increases with increasing value of N.

In Fig. 14, we compare PDR and Throughput with respect to distance (δ_{S_iR}=δ_{RD_i}). For comparison, we have considered TPF-MAC and CSMA/CA along with PC-O-NCC. The PDR of all the considered schemes fall with an increase in distance. However, the proposed PC-O-NCC scheme shows a superior performance than TPF-MAC (Reserved) and CSMA/CA because of the incorporation of MUD gain. However, the superiority of MUD gain comes at the cost of an increased session time which affects the throughput of PC-O-NCC to some extent. TPF-MAC shows a superior performance in terms of throughput. This is because as discussed before, in TPF-MAC based on the participating nodes, the number of reserved slots are increased in order to facilitate a collision free transmission. On the other hand, CSMA/CA shows the worst performance because of a high number of collisions as the participating nodes are unaware of the number of participants. Now, as discussed before, the performance of PC-O-NCC depends on the value of α. In Fig. 14 we have shown the throughput for α=2 and 4. α=4 shows a better throughput performance because even though the contention time increases it is negligible with respect to the time consumed due to a collision.

Fig. 15 compares the per bit energy consumption by a source in a session for a PC-O-NCC with α=2 and a CSMA/CA network. Two primary sources of energy consumption in a network are transmission of data and CCA. It is observed that PC-O-NCC outperforms CSMA/CA in terms of energy conservation not only due to fewer collisions because of varying bounds with respect to α and Tx_left, but also due to the factor ζ in (2). As explained in Section 3.2, unlike CSMA/CA, PC-O-NCC performs CCA only once when T_i=0. Until that it sleeps which is considered to be 10% of the power used to perform CCA. Thus, with increasing number of sources in a session, the average energy consumption increases for both PC-O-NCC and CSMA/CA although, the difference between their performance increases too due to increased latency and more power consumption to perform CCA in a CSMA/CA based network.

6 Conclusion

This paper proposes a peer conscious opportunistic network coded cooperation system that exploits MUD gain in a NCC network comprising of multiple source-destination pairs and a relay. Extensive simulations show an improved outage performance of PC-O-NCC when compared to other relevant MAC schemes. However, the MUD gain achieved comes at the cost of a longer session time when compared to TDMA which is primarily due to the contention time and the collisions caused. Although taking network load into account proves to be beneficial in terms of latency. Thus, it becomes a trade-off between the value of α and the latency. Moreover, PC-O-NCC also conserves energy when compared to CSMA/CA by using the proposed CCA method.

Some of the typical applications include drone assisted disaster management scenario, Vehicle to Everything (V2X) scenario. Although this work primarily explores the effects of MUD gain in a NCC network using a SNR based timer, analysis can be easily extended towards more complex methods to decide the transmission priority. This work can be further investigated to find the optimal values of α and $\text{NTSCT}_{\min}$ and the effect of MUD gain on ANC noise.

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