Dynamic Slotted Network Coding Protocol

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Abstract: Network Coding (**NC**) is a technique that enhances the performance of wireless networks by increasing the throughput and decreasing the delay. The basic idea is to exploit the mixing of signals that occurs naturally when end nodes transmit at the same time. The main challenge stands for a medium access scheduling allowing synchronized coordination between the nodes involved in that coded transmission. Most of the proposed Medium Access Control (**MAC**) protocols are based either on the **CSMA/CA** or the **TDMA** scheduling. The **CSMA/CA** based protocols suffer from synchronization issues, while the **TDMA** based protocols suffer from the delay due to their static design. This paper introduces a new **NC MAC** protocol called Dynamic Slotted Network Coding Protocol (**DSNCP**) based on a time scheduling to avoid the synchronization issue and uses a new design that makes the data slot assignments dynamic in order to reduce the delay.

Simulation results show a significant performance gain of the proposed **DSNCP** compared to **CSMA/CA** and static **TDMA** protocols in terms of throughput and delay. In some scenarios, the throughput gain of the **DSNCP** could reach **130 %** and **100 %** compared to **TDMA** and **CSMA/CA**, respectively, and the delay gain could reach **80 %** and **40 %** compared to **TDMA** and **CSMA/CA**, respectively.

1 INTRODUCTION

Network Coding (NC) is relatively a recent field of interest which appears for the first time in (Ahlswede et al., 2000). NC is an alternative to the traditional store and forward relaying/routing methods to increase the throughput and efficiency of transmitting data within a network by encoding packets at a relay before forwarding (Fragouli et al., 2006). By this means, the bandwidth allocated to each node can be utilized more efficiently. The underlying idea of NC can be illustrated by the simple scenario called the Two Way Relay Channel (or Network) - TWRC (or TWRN) shown by Figure 1.

In this scenario, we have two nodes S_1 and S_2 exchanging their data via the relay R. Suppose that nodes S_1 and S_2 will exchange packets P_1 and P_2, respectively. When considering a Half-duplex system, where each node has one antenna and can not transmit and receive simultaneously, in the traditional networks (without NC), as shown in Figure 1 (a), node S_1 will send P_1 to the relay R in one time slot, the relay R forwards the received P_1 to the destination node S_2 in the second time slot, in the third time slot, the node S_2 sends P_2 to the relay R and finally, in the fourth time slot the relay R forwards the received data P_2 to the destination node S_1. Hence, the throughput is two packets by four-time slots using the traditional system.

Using the NC technique, as shown Figure 1 (b), node S_1 sends P_1 to the relay R in one time slot, next node S_2 sends P_2 to the relay R in the second time slot. The relay node R applies an encoding function (mainly the exclusive-or (XOR) technique) (Fragouli et al., 2006). Then, in the third time slot, the relay R broadcasts the coded packet $P_1 \oplus P_2$, which can be reverted by XORing the combined packet with one of the original packets at nodes S_1 and S_2. Therefore, the throughput is two packets by three-time slots using the NC technique, and a 33.33% of throughput improvement is achieved.

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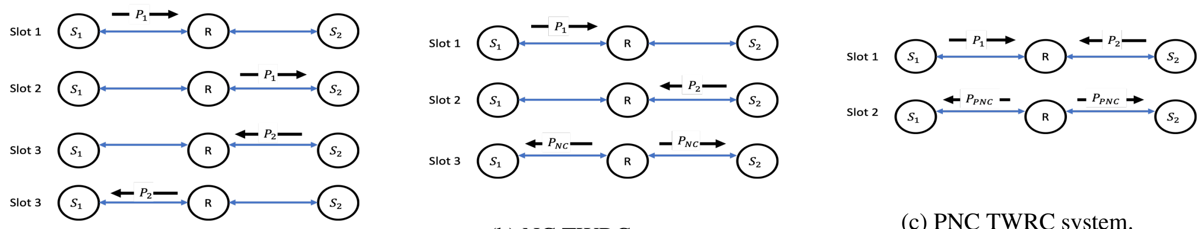


(a) Conventional TWRC system.

(b) NC TWRC system.

(c) PNC TWRC system.

Figure 1: Three relaying schemes on a TWRC system: (a) conventional relaying, (b) NC scheme, (c) PNC scheme. Nodes S_1 and S_2 exchange packets P_1 and P_2 through the relay R. P_{NC} and P_{PNC}, respectively, represent the encoded packet resulting from NC and PNC technique.

A review and a performance analysis of the NC technique are presented in (Zhu et al., 2021).

The Physical-Layer Network Coding technique (PNC), proposed in (Zhang et al., 2006), takes advantage of the natural network coding operation that occurs when electromagnetic waves overlap and extracts the data contained in the interfered signals instead of neglecting or dropping them (Worlanyo, 2016). As shown in Figure 1 (c), the nodes S_1 and S_2 send their data P_1 and P_2 simultaneously in the first time slot. The relay R receives and maps the colluded data into PNC data using, as mentioned before, the XOR mapping technique (Zhang et al., 2006). Then, in the second time slot, the relay broadcasts the encoded data $P_1 \oplus P_2$ to the nodes S_1 and S_2, which retrieves the data of the other one following the same process of the NC technique. As a result, the PNC technique produces a throughput of two packets per two slots with an improvement of 100% and 50% compared to the traditional and NC systems, respectively. In (Liew et al., 2015), network-analytical results were presented to prove the performance of the PNC technique in large networks. Many PHY challenges for PNC have been tackled by prior work (Aissaoui et al., 2021).

In wireless networks, the detection of TWRC scenario and the use of the NC or PNC technique is a matter of MAC layer and depends on how wireless terminals access the channel. In time division multiple access (TDMA) or frequency division multiple access (FDMA) based networks, a centralized scheduling is required, which is feasible from a theoretic view but generally difficult to implement in distributed wireless networks in a practical view. Hence, random access mechanisms, such as carrier sense multiple access (CSMA), have been widely adopted in wireless local area networks (WLANs) and wireless ad hoc networks but have higher complexity towards the PNC requirements of synchronization. Therefore, most related works on PNC in the literature assume a TDMA-like MAC layer.

In this paper, we present a new MAC protocol called Dynamic Slotted Network Coding Protocol (DSNCP), designed to efficiently detect the TWRC scenarios (called NC (PNC) opportunities) and apply the NC (PNC) on star topologies (also called PNC atoms) (He and Liew, 2015). We base our design on the well-known TDMA MAC protocol with important modifications that brings dynamic and flexibility for the scheduling policy.

In the following, Section 2 presents the state of art and related issues. Then, the proposed MAC protocol for the NC/PNC technique is presented in detail in the third section. Section 4 evaluates the throughput, delay, and packets loss ratio of the proposed MAC protocol by computer simulation and compares it with that of conventional distributed and centralized MAC protocols, respectively, IEEE 802.11 (Committee et al., 1999) (CSMA/CA) and TDMA MAC protocols, by which we investigate the effectiveness of the proposed DSNCP MAC protocol. Finally, section 5 concludes our work and outlines possible improvements.

2 RELATED WORKS

As discussed before, NC and PNC enhance throughput and reduce the delay. To do so, scheduling techniques and MAC protocols are needed to create the NC/PNC scenarios and schedule the transmissions (Zhang et al., 2006) (Shengli et al., 2007) (Liew et al., 2013). Based on the literature, we divide the existing NC/PNC MAC protocols into three categories: Distributed, Centralized, and Hybrid MAC protocols.

Most of the proposed distributed MAC protocols (Yomo and Maeda, 2011) ,(Argyriou, 2012), (Wang et al., 2013), (Hoang et al., 2015), (Liew et al., 2015), (Hoang, 2020) and (Mao et al., 2016), are based on the IEEE 802.11 (RTS/CTS) Distributed Coordination Function (DCF) standard (Committee et al., 1999).

In (Yomo and Maeda, 2011), authors propose an opportunistic and distributed scheduling based on the DCF RTS/CTS IEEE 802.11 standard where a node *A* sends a RTS frame to node *C* via a relay node *B*. The latter, when receiving the RTS frame of *A*, sends back a CTS frame acknowledging node *A* to transmit and, at the same time, inviting the node *C* to profit from this opportunity and create a TWRC scenario by transmitting its data to node *A* (if it exists) simultaneously. So, the CTS frame works as a control signal for node *A* and node *C* to synchronize their transmissions at symbol level. In this work, the relay cannot differentiate between the ordinary data and the PNC data, so it always applies the same amplify and forward steps, including additional delays for independent RTS/CTS between the relay node and node *C* in the case of ordinary data and always results in an 8-slot traffic pattern. Furthermore, the synchronization of the two source nodes is done by using the CTS message, but in reality, this will be correct only if the two source nodes are already synchronized by the relay node. On another hand, the information on the two-hop route for each packet to follow is obtained by exchanging routing tables among neighboring nodes, which implies additional overhead.

To fix the issues in the work proposed in (Yomo and Maeda, 2011), where the relay node cannot differentiate between the ordinary data and the PNC data. Authors in (Mao et al., 2016) propose that the second node of the TWRC must send an Answer-to-Cooperate (ATC) message to the relay. This ATC message lets the relay know that the next transmission is a PNC transmission.

In (Liew et al., 2015), authors propose a modified version of the work presented in (Yomo and Maeda, 2011). The proposed PNC MAC protocol is developed to work in a system with multiple nodes on the first side of the relay node and just one other node on the other side. Besides the issues of the work in (Yomo and Maeda, 2011), this MAC protocol does not work on a system with multiple nodes on the two sides of the relay node.

Authors in (Argyriou, 2012) propose a PNC MAC protocol for wireless ad hoc local areas networks to dynamically choose the relay nodes among different cooperative relay nodes based on the Channel State Information of the nodes involved in the concurrent transmissions of different communication pairs. The proposed MAC protocol is considered a one-hop ad hoc network with multiple nodes (a fully connected network). As in the work proposed in (Yomo and Maeda, 2011), this work has a synchronization issue where the nodes are already considered synchronized. Furthermore, this work is developed for a one-hop ad hoc network, making it not applicable for multi-hop networks, including the TWRC network.

Unlike the works in (Yomo and Maeda, 2011), and (Argyriou, 2012), where the source nodes initiate the transmissions by sending an RTS message, in the distributed NC/PNC mac protocol proposed in (Wang et al., 2013), the authors adopt a new policy by allowing the relay node to initiate the transmissions by sending an RTS message to the two nodes of the TWRC scenario. To do that, the authors assume that the relay is already known to be the relay node and has real-time knowledge about the neighboring node's stats (full knowledge about the MAC queues). Also, the nodes are aware of the network topology within at least a two-hop range, which are hard assumptions and make the work not really practical in real implementation. Furthermore, the NC/PNC transmissions are always prioritized over ordinary transmissions. Thus, in some cases where NC/PNC opportunities exist, ordinary transmissions could never take place.

To overcome the issue of the real-time knowledge about the neighboring node's assumption, the authors in (He and Liew, 2015) propose a solution to detect the PNC atoms (different scenarios of PNC on star network) in the star topology based on the Point Coordination Function (PCF) mode of the IEEE 802.11 standard. The proposed MAC protocol is divided into two steps: In the first step, the coordination point (the relay) gathers the information from the edge nodes and detects the PNC atoms using the basic polling mechanism of the PCF mode. In the second step, this relay affects each edge node to its data time slot.

In (Hoang et al., 2015), the authors propose a distributed cooperative PNC MAC protocol to support the bidirectional traffic for one-hop random-access networks. The proposed MAC protocol chooses a helper node optimally to play the role of a relay node. As in (Argyriou, 2012), the chosen helper node initiates the PNC transmissions as follows: first, the source node sends an RTS message to the destination node, the latter replays by a CTS message, the source node waits for an amount of time to receive a forwarder-to-send (FTS) frame that indicates if there is a PNC opportunity or not. If there is a PNC opportunity, the two nodes (source and destination) send their data simultaneously to the helper node. Then the helper node forwards the received PNC data to the source and the destination nodes. This work also has synchronization issues, the same as (Argyriou, 2012). To further improve the performance of the system, an improved version of the work proposed in (Hoang et al., 2015) is proposed in (Hoang, 2020) where multiple relaying nodes are chosen instead of one relay node.

For the Centralized MAC solutions, the majority are based on the well known TDMA MAC protocol (Samarasinghe, 2011), (Gao et al., 2014), (Silveira et al., 2016), (De Oliveira et al., 2021) and (Zhou et al., 2018).

In (Samarasinghe, 2011), authors propose an NC TDMA based MAC protocol called GinMAC for collecting data in wireless sensor networks using the NC. GinMAC is proposed to improve throughput, reduce the delay and avoid the problem of overhearing in wireless sensor networks. This work shows good results compared to the traditional TDMA systems without NC, however, since the time slots schedule is pre-allocated statically and the data flows are considered to be known at the time of the deployment, it is not compatible or suitable for real applications where the data flows are dynamic, and the order of transmissions is uncontrollable by the GinMAC protocol, which affects the throughput and the delay of the system.

In (Gao et al., 2014), a real implementation of the TWRC scenario using the NC technique in Software-Defined Radio (SDR) is presented. The authors propose a new MAC protocol based on a static TDMA MAC protocol to construct the TWRC scenarios and use the NC technique. The policy of the proposed MAC protocol is to use buffers in the relay node and store the received packets of the source nodes. When the relay receives packets from one source node, it waits until it receives packets from the other (the waiting time is not specified in this work. The only condition is that The buffer size is sufficiently large enough to achieve an acceptable packet drop rate), encode them into NC packets, and broadcasts them to the source nodes. To avoid the delay problem, it is necessary to assume that the source nodes always have data to send and that the buffers of the relay are not empty; otherwise, the system will suffer from the delay and will be unacceptable. Since this proposed MAC protocol is designed only for three nodes and has delay issues, it is not practical for systems with multiple nodes and dynamic flows.

In (Silveira et al., 2016) and (De Oliveira et al., 2021), authors propose a modified version of the TDMA MAC protocol to use the NC technique in the Power Line Communication systems. The proposed MAC protocols statically schedule the data transmissions to create the TWRC opportunities. The relay detects the TWRC scenario and applies the NC technique based on the received packets. Contrary to the proposal of (Gao et al., 2014), the works in (Silveira et al., 2016), and (De Oliveira et al., 2021) are proposed for multiple TWRC scenarios, i.e a relay node with N source nodes; however, they have the same delay issues since they use a static scheduling method. Thus, they are not practical for real systems.

In (Zhou et al., 2018), a cooperative NC MAC protocol called TW-NCCR based on a static TDMA MAC protocol to construct the TWRC scenarios was presented. Besides the three nodes of the scenario TWRC, the TW-NCCR protocol also uses $helper$ nodes. Those nodes help improve the system's reliability by retransmitting the received data from the two source nodes or the relay. The TW-NCCR's is divided into two parts, 3-time slots for the TWRC scenario and the N time slots for the N helpers. The main drawback of this work is its feasibility only in case of symmetric transmissions as they suppose that the helpers generate zero non-reciprocation packets during the two first time slots. Moreover, authors made hard assumptions of infinite buffer length and error free transmissions.

In (Naves et al., 2019), the authors propose a distributed TDMA based MAC protocol where end nodes exchange RTS/CTS frames prior to data transmission. The relay node then detects PNC opportunities and schedules the data transmissions according to distributed access probabilities and the priority of every node on the queue sizes of its local neighbors. Authors of these works assume that the source and the relay nodes have prior knowledge about the destination nodes where they can decode the PNC data or not, which requires full knowledge about the topology and the state of all the network's nodes in real-time. Those conditions make these protocols hard to be implemented in practical applications.

Based on the drawbacks of the related works, we can point out the main challenges of the NC and PNC MAC protocols as follows:

For the Distributed MAC Protocols: The synchronization of the NC or PNC source nodes and the real-time knowledge about the neighboring node's stats.

For the Centralized MAC Protocols: The delay introduced by a static allocation of time slots in the TDMA MAC protocol particularly in dense networks (Lam, 1977) (Sadek et al., 2007).

For the hybrid MAC Protocols: The real-time knowledge about the neighboring node's stats and the condition of the transmission range to reach all the network's nodes.

This paper proposes a new NC/PNC MAC protocol addressed to Two Way Relay Channel based networks. The proposed solution :

1. uses a slotted scheduling to overcome the imperfect synchronization issue that hinders two or more nodes from transmitting at the same time (Yang et al., 2014).

2. proposes an adaptive and a dynamic slot allocation to overcome the enlarged transmission delay issue.
3. does not require any prior knowledge or exchange concerning the queue state or the routing tables of neighbor nodes and thus reduces the overhead which may result.

In what follows, we present our proposed new MAC protocol for the NC and the PNC techniques.

3 DYNAMIC SLOTTED NC PROTOCOL

The use of NC/PNC techniques in large and dense wireless multi-hop networks may result on some design complexity that can lead to quite difficult performance analysis.

Therefore, to elucidate the applicability of our protocol, we adopt, in a progressive approach, a network division into small building blocks called atoms and represented by the star topology in figure 2 (He and Liew, 2015).

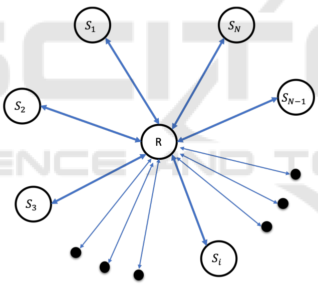


Figure 2: Star network topology.

In those atoms, we have N edge nodes $(S_1, S_2, S_3, ..., S_i, ..., S_N)$ exchanging their data via a central node called the relay node R. Such topology can be useful in Satellite Networks, Access Point networks, Sensor Networks and Radio Access Network...

In order to improve the performance of the system by using the NC (PNC) technique, we only have to profit from the possible NC (PNC) scenarios in each atom. In this work, we focus on the TWRC scenario since its the simplest and the most frequent scenario in the NC (PNC) domain. Remember that to profit from the NC (PNC) technique, a MAC protocol is needed to schedule the NC (PNC) transmissions and to construct the NC (PNC) scenarios. Therefore, this section presents a new proposed MAC protocol called Dynamic Slotted Network Coding Protocol (DSNCP) which is proposed for the atom level or the star topology's systems.

The basic idea of our proposal is to develop a transmission scheduling in an opportunistic perspective so as to detect and prioritize network coding scenarios and, hence, improve the data throughput and minimize the resulting delay.

In order to convey a basic understanding of the protocol, basic assumptions and the fundamental protocol elements are explained:

1. internal clocks of all edge nodes are synchronized to the relay node, not in absolute terms (i.e., so that all stations share the same time) but such that all nodes know exactly when a new time slot or mini-slot starts and when it will end. The development of an explicit synchronization scheme is beyond the scope of this paper but we suggest existent proposals such as (Van den Bossche et al., 2011; Huang et al., 2012; Chen et al., 2013; Liew et al., 2015; Kramarev, 2016; You et al., 2016; Kramarev et al., 2016; Hotescu et al., 2017).
2. the neighboring information is already given either using hello messages (Krco and Dupcinov, 2003) or authentication and association techniques (Roshan and Leary, 2004; Ganz and Wongthavarawat, 1999; Athanasiou et al., 2007).
3. edge nodes have half-duplex links with the relay node do not have links with each other.
4. all data packets have the same size so that nodes will need the same duration or number of time slots to transmit their data.
5. all the time-slots packets adhere to a fixed maximum size (which translates to a fixed transmission duration less or equal to the time slot).
6. for design simplicity, we assume that the error-correcting codes (Kwon and Shin, 2021) are used to correct the corrupted packets so that acknowledgments are no longer needed.

We consider a modified version of the TDMA protocol where time is divided into slots of unit length as presented in Figure 3.

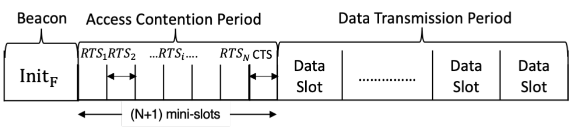


Figure 3: DSNCP Frame.

Each slot is divided into two parts: An access Contention Period used for allocating resources and a Transmission Period for data communications.

3.1 Access Contention Period (ACP)

The access contention period is further divided into $(N+1)$ mini-slots as shown in Figure 3, where N is the number of relay's neighbors (edge nodes). These mini-slots are designed so as to support the traditional RTS/CTS handshake for the allocation of the following data transmission period. Such a mechanism will help the relay node to detect NC/PNC opportunities and make a better management of the data transmissions.

Prior to each Access Contention Period, the relay sends a super-frame $Init_F$ to trigger a new period. This super-frame includes the type of the message ($Init_F$) which is in the frame control, the number of mini-slots (NB_{MS}), the allocation of each edge node to its mini-slot (AF_{MS}) and the Frame Check Sequence (FCS) as shown in Figure 4 (a).

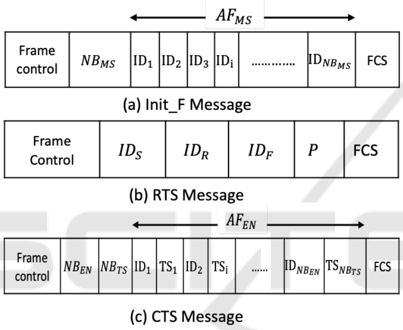


Figure 4: DSNCP Control Messages.

The starting time of the mini-slot (MS_i) allocated to the edge node N_i could be computed using the formula below:

$$MS_i = t_0 + \sum_{j=1}^{i-1} (MST_j)(\ 1 \leq i \leq NB_{MS}) \qquad (1)$$

Where MS_i is the start time of the i^{th} mini-slot, t_0 is the starting time of the mini-slots phase, and MS_j is the duration of the j^{th} mini-slot.

We have modified the RTS/CTS mechanism to take into account the particularities of NC/PNC as follows:

In a given contention mini-slot, an edge node wanting to send data sends first a Request To Send frame (RTS) to the relay node. The RTS message, as shown in Figure 4 (b), besides the type of the message (contained in the Frame Control field) and the FCS, contains Four fields: the node identifier (ID_S), the priority (P) of the data to send, the relay node identifier (ID_R) and the final destination identifier (ID_F).

When the relay receives all the RTS frames and based on the adopted technique or system (NC or PNC), it sends a NC or PNC Clear To Send frame (CTS) in the $(N+1)^{th}$ mini-slot to the sender nodes allowing them to send their data in the following Data Transmission period.

This CTS frame, as shown in Figure 4 (c), contains: the type of the CTS message (CTS_{NC}/CTS_{PNC}) (in the Frame Control field), the number of edge nodes will send their data (NB_{EN}) in this frame, the number of time slots in the Data Transmission Period (NB_{TS}), the order of transmission of each sender (the allocation of each node to its time slot) (AF_{EN})and the FCS. In the AF_{EN} section, each node's ID will be followed by his data slot number TS_i.

Based on the received RTS frames, the relay can easily detect and extract the TWRC scenarios versus the ordinary scenarios and adapts the data transmission period allocation for that purpose.

In fact, for nodes forming an NC opportunity, the relay provides three time slots: One for the first node's packet, one for the second node's packet and the latter for the relay to send the coded resulting packet. The order is made with respect to the data priority so that the first transmitting node is the one having the highest data priority. Whereas, for the PNC opportunity, the relay provides two time slots: One for the first and the second node's packet and the latter for the relay to send the coded PNC resulting packet.

On the other hand, the relay provides two-time slots for each ordinary scenario so that the first time slot is allocated for the ordinary node to send its data, and the second is allocated for the relay to deliver the ordinary data to the corresponding destination.

By sending the CTS frame, the Access Competition Period ends, and the Data Transmission Period begins. We present details of this period's functioning in the next section.

3.2 Data Transmission Period (DTP)

In this phase, edge nodes will transmit their data to the relay node, which will forward the received data to each destination. After receiving the CTS frame, each node could compute its starting time slot using the formula below:

$$S_i = t_0 + \sum_{j=1}^{i-1} (DS_j)(\ 1 \leq i \leq NB_{MS}) \qquad (2)$$

Where S_i is the start time of the i^{th} data slot, t_0 is the starting time of the DTP, and DS_j is the duration of the j^{th} data slot.

For further data packets, the edge nodes will wait until they receive a new $Init_F$ super frame to initialize a new DSNCP period.

The DSNCP flow graphs of the edge nodes and the relay node respectively summarize the different steps of the proposed solution and are presented by Figure 5 and Figure 6.

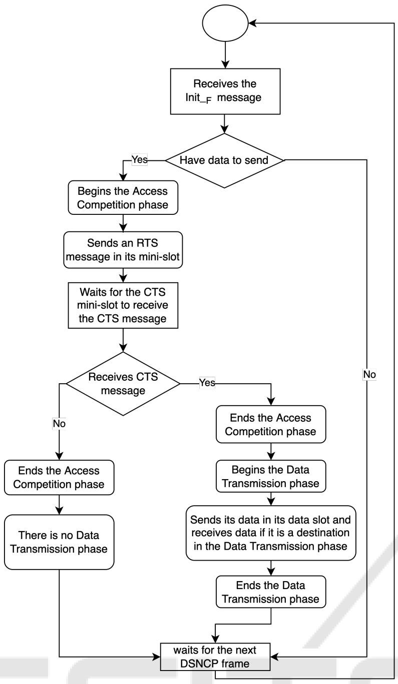


Figure 5: DSNCP flow graph for the edge nodes.

3.3 Illustrative Example

To illustrate the process of the proposed solution, we refer to the example in Figure 7 in which five edge nodes are exchanging data via a relay node. First, the relay sends a message $Init_F$ to initialize a new period. Based on the received $Init_F$, each edge node that wants to send data sends first an RTS message on its mini-slot using equation 1.

Based on the received RTS frames, the relay node detects data flows that can be combined on a NC/PNC opportunity and ordinary ones. As mentioned in the table 7 (b), the first NC/PNC scenario is formed by transmissions of nodes N_1 and N_5 referred as $NCT(N_1, N_5)$, the second scenario in formed by transmissions of nodes N_2 and N_4 referred as $NCT(N_2, N_4)$. The flow of node N_3 will be relayed as an ordinary traffic and referred as $OT(N_3)$.

Then, the Data Transmission Period will be divided into eight data time slots using the NC (six time slots using the PNC) and scheduled with respect to the priority of nodes involved in each transmission. In this example, the priority of the NCT(N_1,N_5) is the $\max(P_1, P_5) = 1$, the priority of the NCT(N_2,N_4) is the $\max(P_2, P_4) = 2$ and the priority of the OT(N_3)

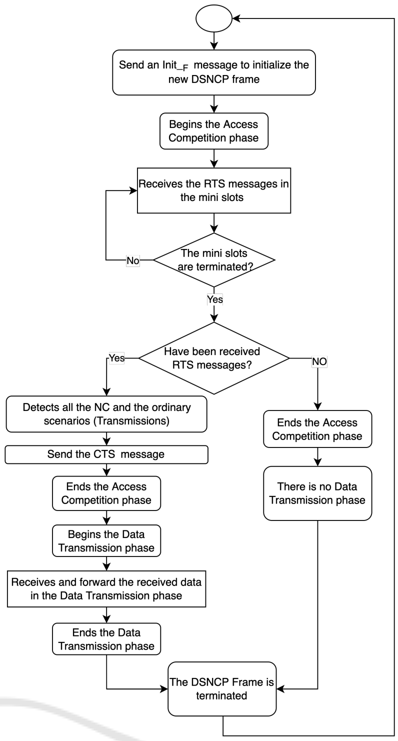
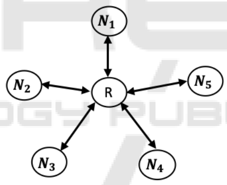


Figure 6: DSNCP flow graph for the relay node.



(a) The network's topology

RTS message	ID_S	ID_{FD}	P
RTS_1	N_1	N_5	0
RTS_2	N_2	N_4	1
RTS_3	N_3	N_5	5
RTS_4	N_4	N_2	2
RTS_5	N_5	N_1	1

(b) The received RTS messages

			AF_{EN}										
CTS_{NC}	NB_{EN} 5	NB_{TS} 8	N_1	6	N_2	3	N_3	1	N_4	4	N_5	7	FCS

(c) The received NC CTS message

			AF_{EN}										
CTS_{PNC}	NB_{EN} 5	NB_{TS} 6	N_1	5	N_2	3	N_3	1	N_4	3	N_5	5	FCS

(D) The received PNC CTS message

Figure 7: Illustrative example.

is $P_3 = 5$. Hence the order of the transmissions is as follows: the OT(N_3) first, the NCT(N_2,N_4) second, and finally, the NCT(N_1,N_5). When dealing with an NC transmission, the node's priority has no impact on the two packets of the NC transmission since the relay node will effectively deliver the coded frames to each destination node at the same third-time slot, but such priority is useful for the relay to schedule transmission times. However, those priorities are very important for the order of the different NCT and OT transmissions, since the higher the priority, the lower the order of the NCT and OT transmissions, and the lower the delay is.

Hence, after receiving the RTS frames and identifying all the NC/PNC opportunities, the relay node broadcasts a CTS frame allowing concerned nodes to send their data frames in their allocated time slots. As shown in Figure 7 (c/d), this CTS frame contains: the type of the message CTS_{NC}/CTS_{PNC}, the number of edge nodes will send their data (NB_{EN}) in this frame, the number of time slots (NB_{TS}) in DTP, the allocation of each edge node to its data time slot (AF_{EN}) and the FCS.

Based on the information contained on the CTS frame, we can resume the scheduling details of the NC DTP and PNC DTP as shown in Table 1 and 2, respectively.

Table 1: Scheduling of the NC Data Transmission Period.

The node's ID	1	2	3	4	5	R
Time Slot	6	3	1	4	7	(2,5,8)

Table 2: Scheduling of the PNC Data Transmission Period.

The node's ID	1	2	3	4	5	R
Time Slot	5	3	1	3	5	(2,4,6)

Figures 8 and Figure 9, respectively, summarize the NC and the PNC scheduling of the example 7 made by the DSNCP solution.

4 IMPLEMENTATION AND RESULTS

This section presents the results of a simulation-based performance evaluation of DSNCP and compares the obtained results with a CSMA/CA and TDMA implementation. For the well-known CSMA/CA and TDMA MAC protocols, the NC opportunities are detected by the relay depending on the queue of the received data. If the relay detects an NC opportunity, it encodes the two packets involved in this opportunity and sends the encoded packet as an NC packet. We first describe the simulation environment, the performance metrics, and finally, we present and interpret the obtained results.

Using NS-3 we implemented the $CSMA/CA_{NC}$, $TDMA_{NC}$ and $DSNCP_{NC}$ protocol. The system's configurations are presented in Table 3.

The performances of the proposed DSNCP are evaluated using three metrics: the throughput, the delay, and the packet loss rate, as these metrics are closely impacted by the network coding paradigm.

The average throughput is measured in Kbits per second and considers the average of the received bits by all the edge nodes during the simulation period. The formula for computing the throughput is:

Table 3: Parameters used for the implementation.

Layer	Parameter	Value
Application	- Results obtained - Simulation time - Distance between each edge node and the relay	The average of 30 simulations 200 seconds 300 meters
Network	- routing protocol	Static
Data Link	- Time Slot - Mini-slot's time - Packet's size - NC mapping technique	0.8 millisecond 20 microsecond 1024 bytes XOR
Physical	- Physical standard - Propagation loss model	DsssRate11Mbps FriisPropagationLossModel

$$Throughput = \left(\frac{\sum_{i=1}^{N} RCVDATA_i}{N}\right) \tag{3}$$

Where $RCVDATA_i$ is the amount of the received data by the edge node i, and N is the number of edge nodes.

The average end-to-end delay represents the total time to deliver a packet and includes all possible delays caused by buffering, queuing at the interface queue, re-transmission delay at the MAC layer, propagation, and transfer time. It is expressed in milliseconds and is measured by the formula below:

$$Delay = \frac{\sum_{j=1}^{P} (DT_j - CT_j)}{P_k} \tag{4}$$

Where $(DT_j - CT_j)$ is the end-to-end delay of packet j, which is the duration between the creation time of the packet j by the sender (CT_j) and its delivery time by the final destination (DT_j), and P_k is the number of all the received packets by all the edge nodes.

Finally, the third metric is the packet's loss rate (PLR), which represents the ratio of successfully received packets (SRP) from all transmitted data packets (TDP). Since in our simulation we assume a perfect physical layer, where packets cannot be lost due to the physical medium, we consider that all lost packets are dropped by the MAC or the NC queues. The formula for computing the PLR is:

$$PLR\ \% = \frac{(SRP * 100)}{TDP} \tag{5}$$

Simulation results are given, respectively, by Figure 10 when varying the network density i.e the number of edge nodes (we used topologies of 2,4,6,8,12,16 and 20 nodes) and Figure 11 when varying the traffic load i.e the number of packets sent by each edge node (we used a traffic pattern of 1000, 2000, 3000, 4000, 5000 and 6000 packets/node, and whatever the traffic load, the production of the packets is regular).

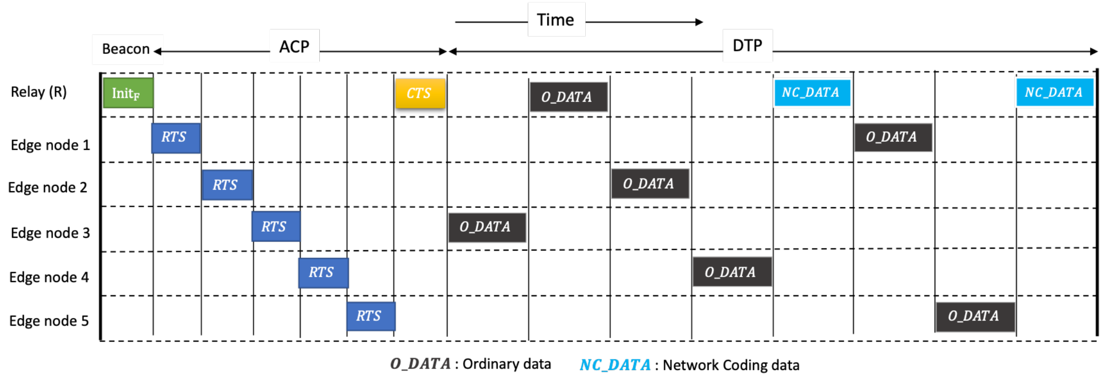


Figure 8: The NC DSNCP scheduling of the example presented in Figure 7.

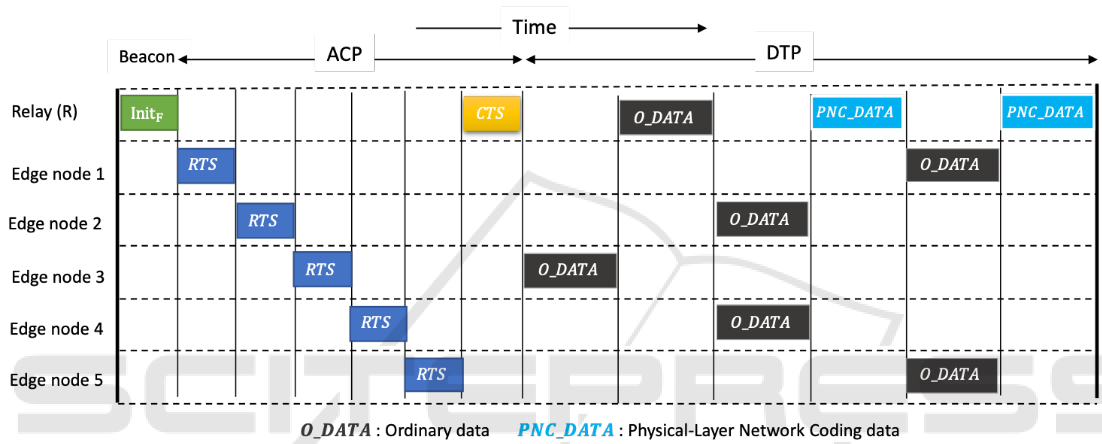


Figure 9: The PNC DSNCP frame of the example presented in Figure 7.

For the throughput, figures 10 (a) and 11 (a) show that the DSNCP always outperforms the CSMA/CA and the TDMA MAC protocols regardless of the nodes number and the traffic load. It maintains a good throughput longer because of its opportunistic nature and its capacity to detect, beforehand, all the possible NC opportunities for all the data flows compared to the CSMA/CA and TDMA MAC protocols.

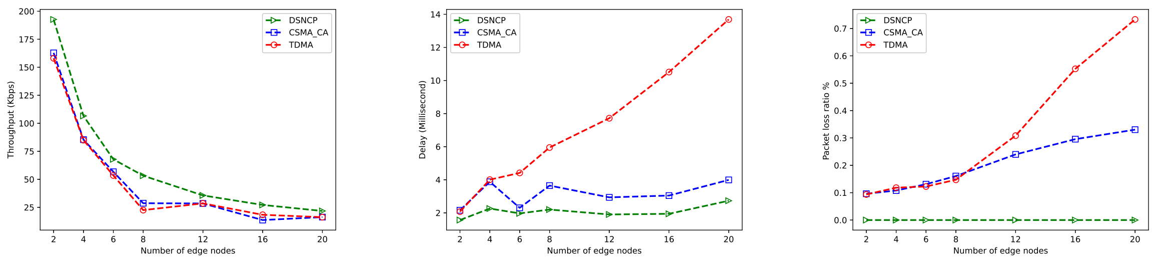
Furthermore, compared to CSMA/CA protocol where medium access is made in a completely random manner and compared to TDMA standard where time slots are allocated to edge nodes in a static way and therefore, the detection of NC opportunities is rare and sometimes impossible, the centralized and the dynamic aspects of our protocol DSNCP made the medium access control easy and the scheduling of data flows adaptive and efficient.

Moreover, the throughput is highly affected by the forwarding MAC queue of the relay (the MAC queue of the received packets from the edge nodes to forward by the relay) and the NC queue, which is used to store the NC packets for the relay and the sent packets, which used to decode the NC packets for the edge nodes. Compared to our protocol, where the maximum required size of the forwarding MAC queue or the NC queue is 2 (for the two packets of the two edge nodes involved in the TWRC scenario).

Figure 10 (a) also shows that the throughput decreases gradually with the number of edge nodes. This decrease is due to the processing delays and losses caused by queue saturation at the relay node, which increases with the affluence of new data packets.

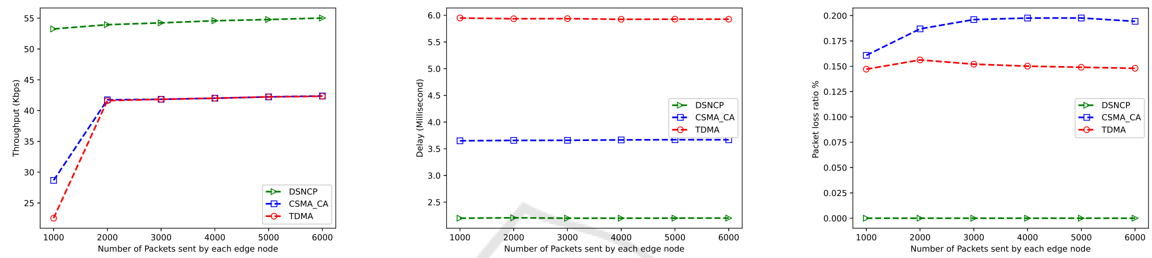
We also note, from that figure 10 (a), that, for relatively dense topologies (more than 12 nodes), the CSMA/CA protocol slightly loses its efficiency in terms of throughput compared to the TDMA protocol because of the losses associated with medium access and interference problems when dealing with several nodes which are avoided in deterministic and slotted access.

From figure 11 (a), we can see that all the protocols are stable over time which is due to the regular production of the data packets. Whenever the amount of data is transmitted, the DSNCP outperforms in terms of throughput. Also, we can see that CSMA/CA



(a) Throughput. (b) Delay. (c) Packet's Loss.

Figure 10: The performance results depending on the network density.



(a) Throughput. (b) Delay. (c) Packet's Loss.

Figure 11: The performance results depending on the traffic load.

and TDMA protocols give almost the same throughput in the same topology over time. Also, there is a jump in the beginning for TDMA and CSMA/CA because of the small traffic load where there are a few NC opportunities. Therefore the throughput will be low compared with a high traffic load where there are more NC opportunities.

For the delay results, depicted in figures 10 (b) and 11 (b), we can clearly observe the notable gain made by DSNCP compared to other protocols. In fact, since the NC decision in CSMA/CA and TDMA protocols are based solely on data packets already received by the relay node, this gives an advantage to our opportunistic solution to detect more opportunities, to reduce the time slots needed for each TWRC scenario and thus to achieve better overall performance, particularly in terms of delivery delay.

From Figure 10 (b), if the number of edge nodes increases, the delay of the DSNCP and CSMA/CA is either constant or increased by a tiny percentage, compared to the TDMA protocol, which gives the worst delay and increases exponentially with the number of edge nodes.

The results in 10 (b) also show that, for all MAC protocols, the end to end delay increases with the size of the network, because, in general, increasing the number of nodes in the network results in a further traffic load and thus, the delays caused by buffering delays and queues at the relay node contribute significantly to the end to end delay.

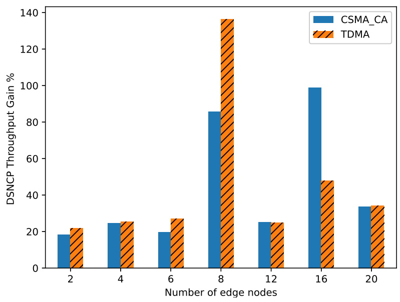
This increase is particularly significant with the TDMA protocol, which could be explained by the static time slot allocation and the presence of time slots allocated uselessly to nodes that do not have data to transmit.

Figure 12 shows the gain of the DSNCP compared to CSMA/CA and TDMA protocols in terms of, respectively, throughput and end-to-end delay.

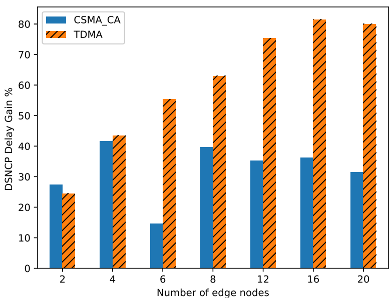
Figures 10 (c) and 11 (c) present the packet loss ratio depending on the network density and the traffic load, respectively. Since the DSNCP is based on a prior handshake mechanism and the received packets are directly followed in the next time slot by the relay, it is generally rare to drop packets due to the fullness of MAC queues or timeout. Hence, when, in addition, considering a perfect physical medium, the packet's loss ratio of the DSNCP is naturally very low.

From results in figure 10 (c), we can conclude that, since TDMA is static, the more the number of edge nodes is, the more the received packets are, which can lead to a fast saturation of queues and packet timeout. Losses in CSMA/CA context are generally caused by collisions at the access contention period.

From all the results, we conclude the performance and the stability of the DSNCP over the CSMA/CA and the TDMA MAC protocols in terms of throughput, delay, and packet loss rate.



(a)



(b)

Figure 12: The DSNCP's Delay and Throughput gains compared to TDMA and CSMA/CA protocols.

5 CONCLUSION

In this paper, a dynamic slotted MAC protocol (DSNCP) based on the well-known TDMA standard has been proposed. DSNCP is designed to opportunistically support network coding TWRC scenarios with a prior adapted handshake mechanism. The proposed DSNCP introduces mini-time-slots in which the relay node detects the TWRC opportunities and schedules these transmissions in an efficient dynamic way. By simulation under different network density and traffic load patterns, we have demonstrated that the DSNCP can substantially enhance the throughput and the delay compared to the IEEE 802.11 CSMA/CA and TDMA based MAC protocols.

An ongoing experimentation of our solution is performed on a real testbed based on Software Defined Radio technique which would validate this primary work and studies its feasibility in real large wireless networks.

In future work, we also intend to propose a distributed and restriction-free medium access scheduling making the DSNC solution more adapted for larger wireless networks.

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