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Study of Network Coding-based MAC Schemes for Different Topologies in Wireless Networks

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Abstract This paper presents comparison of network coding-based medium access control (MAC) schemes for many logical network topologies, such as golden chain, golden triangle, multiple access relay channel (MARC), cross and butterfly topologies in wireless networks. Network coding techniques are applied in wireless networks to improve the performance such as throughput and reliability by allowing encoding of incoming packets at intermediate nodes in the network before forwarding to the next hop as in the traditional store-and-forward paradigm. Topology and MAC influence over network coding performance. Depending on topologies, many combination of network coding and MAC schemes are analysed and compared to legacy systems by the performance metrics such as throughput gain, overhead, and energy consumption.

Keywords medium access control protocol, wireless network topology, network coding, throughput

1. INTRODUCTION

In this era of ICT, people are accessing the Internet for their daily food of information relating to different purposes such as political, business, education etc. via a small wireless device in their hands. In the traditional way of wireless communication, all the wireless devices communicate each other by passing through a central access point or a cellular tower. This approach is suitable and well performed for the scenarios where the number of client devices and the demand of quality of service are not as high as today. From the present time to the years to come, it is estimated that the traffic from wireless and mobile devices will become 78% of Internet traffic with only 22% from the wired devices due to the growth in global consumer mobile services such as mobile social networking, mobile gaming and mobile banking [1]. There will be an increased number of devices connected to IP networks and will be 26.3 billion in 2020. This amount of increasing number of devices and services is a huge challenge for the exiting centralised network infrastructure. More research needs to explore the new ways to solve this problem.

One of the possible solutions is to enable the coded communication and cooperation among the nodes to reduce the participation of central infrastructure. If the central infrastructure does not need to participate for every transmissions, it will scale to the increased demands. Use of network coding for communication networks allows combination of incoming data packets at intermediate nodes. The encoded packets carry more information for the receivers of the encoded packets. Depending on the design of encoding schemes, an encoded packet will benefit many receivers to recover the different packets they have lost in the previous transmissions, e.g., coded cooperative data sharing [2]. There are two types of classifications in network coding. They are intra-flow and inter-flow network coding. In intra-flow network coding, the traffics from the same data flow are encoded together, while traffics from more than one incoming data flows are encoded together in inter-flow network coding. Inter-flow network coding technique uses opportunistic listening to produce more innovative encode packets and reduce the redundant transmissions. Different encoding schemes can be designed by using various factors such as packet receiving status of neighbour nodes like in COPE [3] and utilisation of the overheard packets.

In wired networks, network coding is considered as a function of routing protocol and it is implemented at the network layer of the protocol stack. However, in wireless networks, network coding is even considered at the transmission level at link layer protocols. Topology plays an important role for network coding in wireless networks depending on the physical and logical infrastructure of the wireless nodes and opportunity for production of innovative encoded packets. In this paper, we present many ways of logical topology to work with the medium access control protocols and it is enhanced with the help of network coding techniques to save resources such as bandwidth (spectrum) and energy consumption. Depending on the topologies, many combinations of network coding and MAC schemes are analysed and compared to legacy systems by the performance metrics such as throughput gain, overhead, and energy consumption.

The rest of this paper is organised as follows. Review on some related works are presented in Section II. Section III provides different types of logical network topologies and models of MAC schemes for different topologies. Analysis of schemes are discussed in Section 4. Performance evaluations are provided in Section 5. Finally, Section 6 concludes this paper.

2. RELATED WORK

IEEE 802.11 MAC protocol uses a distributed coordination function (DCF) with or without the RTS/CTS handshaking mechanism. In order to avoid a possible collision, in CSMA/CA, a node first senses the medium for an idle channel in Distributed Inter Frame Spacing (DIFS) period before sending any data packet. After DIFS period, the node defers its own transmission by generating a random back off timer and waits. When timer times out and the medium is also free, it broadcasts a Request-To-Send (RTS) control message, specifying a destination and data size. The receiver node responds with a Clear-To-Send (CTS) message if it is free from receiving any other node. The control messages are transmitted after the medium has been free for Short Inter Frame Spacing (SIFS). If the sender node does not receive the CTS message, it may retransmit the RTS message. On receiving the CTS message, the sender sends the DATA and waits for an ACK from the receiver. Every node that hears the RTS/CTS exchange updates its Network Allocation Vector (NAV) value and must refrain from transmitting for that duration.

The research issue relating to network coding and medium access control is due to the fairness of DCF mechanism in IEEE 802.11 standard [4]. To achieve the highest benefit from network coded packets/frames, they need to be transmitted with a higher priority than the normal packets/frames. This issue becomes very clear when [3] proposed the first practical inter-session network coding approach called COPE for the networks with perfect links. Therefore, performance of network coding opportunity is totally depending on DCF and is limited by DCF.

Huang et al. [5] proposed a combination of network coding with CSMA/CA protocol to enhance the fairness of wireless medium access among stations for a single-relay multi-user wireless networks. They developed optimization of the minimum contention window size according to the number of stations to create appropriate transmission opportunity.

Another modification to improve the MAC protocol is the application of network coding technique in [6], where network coding is integrated into the 802.11 infrastructure by adding a sublayer of network coding functionality between layer 2 and 3 of the standard OSI stack. It combines layer 3 datagrams at access points (APs) and layer 2 broadcasting is performed. With the help of network coding transmission of a complete cycle of control messages and data packet is reduced. However, fairness becomes a problem in accessing the wireless medium due to the inefficiency of DCF in CSMA/CA protocol when the number of clients increase.

Overhead of control messages is also an important issue for the protocol design in combination of network coding and MAC protocol. Many researches have been done in the literature to reduce the overhead and to improve the efficiency of the IEEE 802.11 MAC protocol. Although this handshaking mechanism is useful for avoiding a possible collision in data transmission, the efficiency of the mechanism is poor due to its overhead control messages especially for transmitting a small data packet. COPE tried to reduce the overhead control messages in its transmission cycle. It saves one transmission for ACK message after receiving the coded packet by a source node. This ACK event will be added in the header of next coded packet to acknowledge the packet reception.

3. MODELS OF MAC SCHEMES FOR DIFFERENT LOGICAL TOPOLOGIES

3.1. *Types of Topologies for Network Coding Benefits*

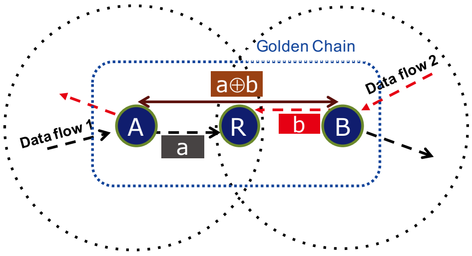
Topology and group formation mechanisms play important roles for the improvement of system performance. There are limitations of network coding opportunity at network layer to achieve the maximum performance because the actual transmissions can only happen when the medium is occupied. Therefore, medium access control influences the network coded transmission. The network coding opportunity also depends on topology where the source, relay and destination form a specific structure in wireless networks.

3.1.1. *Golden Chain and Golden Triangle:* Golden topology means the types of topologies that creates network coding opportunity. The two golden topologies are mainly utilised with the XOR network coding in our work. A golden chain is defined as a chain of three successive nodes with two data flows from opposite directions. Fig. 1(a) shows a golden chain. The two data flows, 1 and 2, forms a golden chain at nodes **A**, **B** and **C**, where **A** and **C** are outside the transmission range of each other.

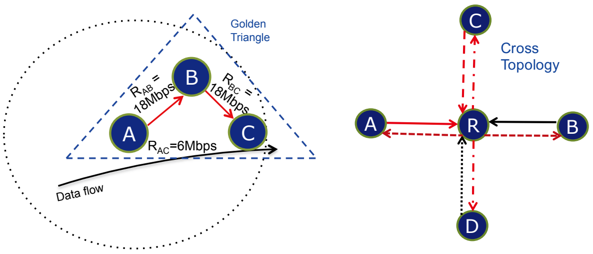
For a golden triangle, **A** and **C** are within the 1-hop transmission range of each other. They may have a low-rate link between them due to the far distance. The main property of a golden triangle is the relay node which helps transmission in some higher rates. The difference from a golden chain is that a golden triangle does not necessarily require two data flows. It can happen with one direction data flow as depicted in Fig. 1(b).

3.1.2. *Cross Topology:* Cross topology is depicted in Fig. 1(c). Two bidirectional data flows from nodes A and B and from nodes C and D intersect at the relay node R. Without coding at the relay, total eight transmissions are needed to exchange pairs of packets between A and B, and C and D. With XOR coding at relay, the relay can encode the two packets from A and Band broadcast to both nodes. The other two nodes also overhear the encoded packet and it can be useful for them if they also want packets from A and B.

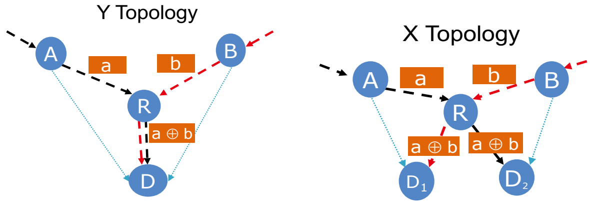
3.1.3. *MARC and Butterfly Topologies:* MARC and butterfly topologies are depicted in Fig. 1(d), and Fig.1(e), respectively. Two data flows from node A and B pass through an intermediate node R to the destinations D1 and D2 in Fig. 1(e) and to a common destination D in Fig. 1(d). Node R can operate network coding function over two incoming flows a and b and transmit the coded packets $a \oplus b$ to



(a) Chain topology



(b) Triangle topology (c) Cross topology



(d) MARC (e) Butterfly topology

Fig. 1: Certain types of topologies that can support network coding opportunity

the destinations. The destination nodes have high chance to overhear the transmissions from the nearest senders without additional transmission cost and copies of those messages are useful for the recovery of original messages.

3.2. *Network Coding-aware CSMA Protocol (NCA-CSMA)*

In the NCA-CSMA, XOR network coding is applied at relay node R. The relay node R broadcasts the network coded packet $a \oplus b$ upon receiving the packets a and b from node A and B in previous time slots respectively. The relay node R notices that there is a network coding opportunity with packets a and b from two counter-directional data flows. Therefore, after successfully receiving *b*, the relay node immediately broadcasts a Ready-To-Broadcast (RTB) message to inform other nodes that it will broadcast a coded packet in next time slot. RTB can also be considered as an ACK to B and we assume that there is no packet loss due to channel errors and buffer overflow. RTB is designed like RTS frame format with two address fields. Both A and B receive the XOR-coded packet in a time slot and can recover the packets b and a by performing XOR operation of their own packet with the receiving coded packet again. The difference between COPE and NCA-CSMA is that a separate ACK for B and a pair of RTS-CTS messages for $a \oplus b$ is used in COPE whereas NCA-CSMA uses RTB to replace these three messages. RD-DCF+NC does not use RTB message for the transmission of coded packet. It directly allocates the channel access with reverse-direction transmission mechanism after receiving *b*.

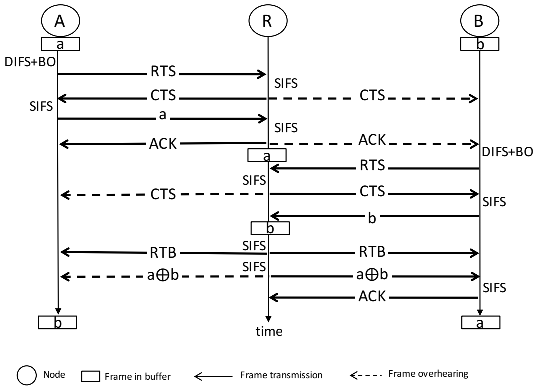
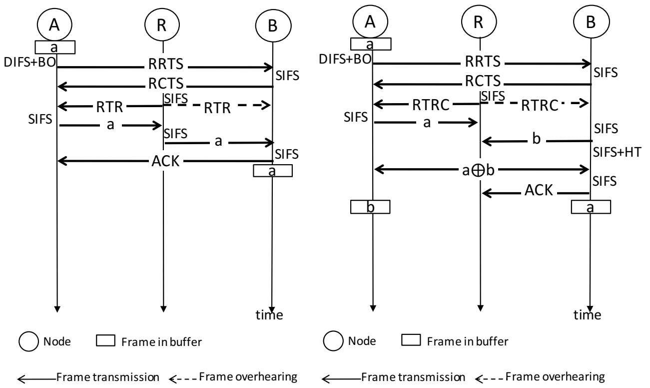


Fig. 2: Message handshaking for data exchange in a golden chain for, CSMA/CA and NCA-CSMA

3.3. *Network Coding-aware 2PSP Protocol (NCA-2PSP)*

The NCA-2PSP protocol works when two nodes on a golden chain possess a helper relay between them and both of them have some data packets to be exchanged. For example, node A and node B in Fig. 3(b) have some packets to transmit to each other and are waiting for some random backoff period. When the timer of node A times out earlier than B, it transmits a Relay-RTS (RRTS) message. If the receiver B receives the RRTS message correctly, it freezes its backoff counter and replies with a Relay-CTS (RCTS) message to the sender.



(a) Message handshaking in 2PSP (b) Message handshaking of NCA-2PSP

Fig. 3: Message handshaking for data exchange in a golden chain for 2PSP and NCA-2PSP

3.4. *COPE (DCF+NC) and RD-DCF with Network Coding*

COPE combines the IEEE 802.11 DCF with the XOR network coding technique. The MAC operation of COPE is according to the DCF of IEEE 802.11. The relay node needs to compete the channel access with the other nodes to transmit the coded packet. The performance of NC is depending on the DCF and network coding opportunity in COPE is limited by the DCF. COPE tried to reduce the overhead control messages in its transmission cycle. It saves one transmission for the ACK message after receiving the coded packet by a source node. This ACK event will be added in the header of next coded packet to acknowledge the packet reception.

A coding-aware MAC scheme with network coding is introduced [7]. This scheme enables the reverse direction (RD) communication between the relay node and any other station. Upon successful reception of a data packet the relay station can transmit a coded packet whose destination is the source of the received packet. The relay station can reduce the channel contention and the coded packet can be sent right after a packet is received. The value of the duration field in the transmitted data packet is extended to cover the channel access for the duration of transmission in reverse direction. Therefore, the throughput, delay and energy saving can be improved. Only when the channel condition is poor, this RD transmission will lead to the retransmission of both the forward and reverse data because the reverse transmission is used as an implicit ACK and the packet loss probability is higher for a data packet than for an ACK packet.

4. ANALYSIS OF THROUGHPUT, ENERGY CONSUMPTION AND OVERHEAD OF PROTOCOLS

Latency is the sum of transmission delay and propagation delay, $M/R{+}D$ seconds. where transmission delay is the time to put M-bit message "on the channel". *M*-bit is divided by data rate, *R* (bits/sec). Propagation delay, D, is the time for bits to propagate across the channel and it is calculated by dividing the length of packet in bits by speed of signals, *c*, which is the speed of light and equals to $3 * 10^8$ m/s. We consider 1500 bytes for length of a packet, and therefore, it is constant for every protocol. Delay for one transmission between two nodes is calculated by (1). The values shown in Table II are calculated as a sample with *N* = 2 data packets for each model. For the analysis purpose, we use the highest data rates to compute the maximum and minimum values for each metric.

$$\begin{aligned} Delay =& T_{DIFS} + 3T_{SIFS} + T_{BO} + T_{RTS} + T_{CTS} \\ & + T_{DATA} + T_{ACK} \end{aligned} \tag{1}$$

Throughput is defined as the number of bits contained in a payload data, MSDU divided by the time required to transmit the data packet that includes the payload data.

$$Throughput = \frac{\textit{MSDU (bits)}}{\text{Delay}} \tag{2}$$

Energy consumption is the total energy consumed for the transmission of control messages and data packets. The energy consumption for one transmission between two nodes is multiplication of transmission power and time taken from (1) for each specific protocol. Due to the space limit, we omit the equations for each. The energy consumption of a pair of data exchange between two nodes in a golden chain is calculated by multiplying the transmission power and the delay for each CSMA/CA, NCA-CSMA, 2PSP and NCA-2PSP protocol. We assume all nodes transmit at the same transmit power and only busy time is considered. The overhead ratio, *OR*, is defined as the ratio of the total number of control messages (in bytes) and the total number of control messages plus the total number of payload bytes to transmit a data packet.

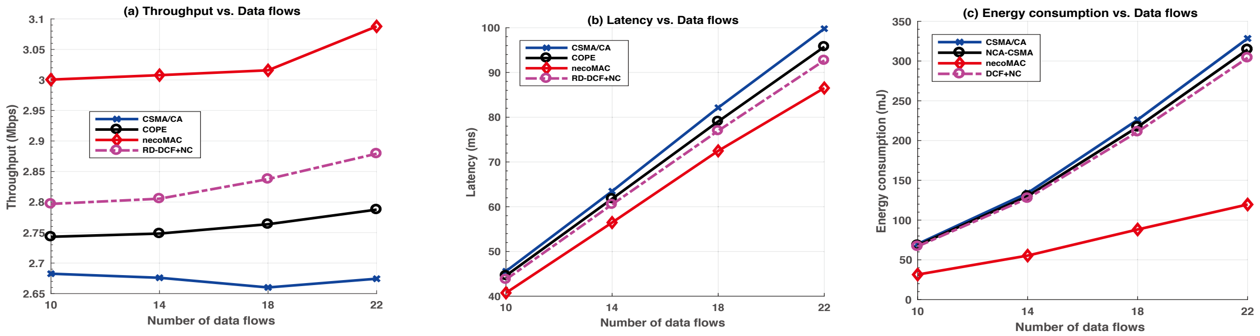
TABLE I: Parameters of PHY and MAC Layers for 802.11a

Parameter	**Value**
Transmission power	100 mW
RTS, RRTS size	20 bytes
CTS, ACK size	14 bytes
RCTS, RTR size	15 bytes
RTB size	21 bytes
MAC header	30 bytes
MAC header1	28 bytes
MAC header2	24 bytes
FCS size	4 bytes
XOR header	40 bytes
Slot time	9 s
Preamble time	16×10^{-6}s
Signal time	4×10^{-6}s
SYM time	4×10^{-6}s
DIFS	34×10^{-6}s
SIFS	9×10^{-6}s
L_{Tail}	6 bits
$L_{Service}$	16 bits
Average Backoff time (BO)	67.5×10^{-6}s
Holding time T_h	10×10^{-6}s

5. SIMULATION AND DISCUSSION

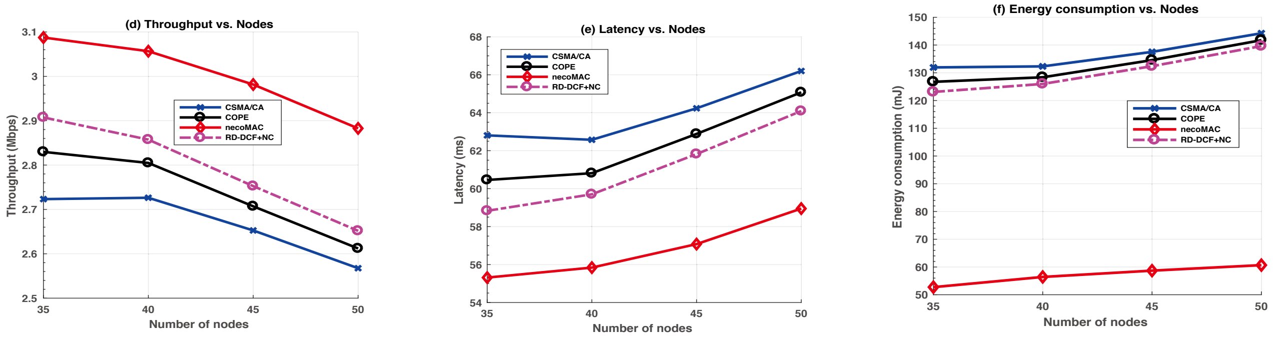
In this section, we investigate the performance of the protocols over the conventional CSMA/CA scheme. We assume that coding and decoding using XOR operation consume negligible time and energy. We do not use fragmentation for the simulation. All nodes have one pair of (data rate, control rate) among (6,6), (9,6), (12,12), (18,12), (24,24), (36,24), (48,24), and (54,24). Simulation scenario are categorized into two. In the first scenario, we investigate the impact of increasing number of data flows on protocol performance with the fixed number of nodes 40. The number of data flows is varied from 10 to 22 flows in steps of 4 flows. In the second scenario, we focus on the influence of the number of nodes on the performance of the protocols. The number of data flows is fixed at 14 flows. The number of nodes is varied from 35 nodes to 50 nodes in increment of 5.

We create the simulation program in MATLAB environment and generate all nodes and flows uniformly distributed in a 1000 x 1000 m^2 coverage area. Source and destination



(a) Throughput vs. Data flows (b) Latency vs. Data flows (c) Energy Consumption vs. Data flows

Fig. 4: Throughput, latency and energy consumption of the necoMAC, CSMA/CA, COPE and RD-DCF+NC protocols as a function of increasing number of data flows in golden chain and golden triangle topological networks



(a) Throughput vs. Nodes (b) Latency vs. Nodes (c) Energy Consumption vs. Nodes

Fig. 5: Throughput, latency and energy consumption of the necoMAC, CSMA/CA, COPE and RD-DCF+NC protocols as a function of increasing number of nodes in golden chain and golden triangle topological networks

pairs are randomly selected with the setting of maximum and minimum hop count 4 and 2 respectively because our models are 2 hops. All data flows are equal in size 1500 bytes and one unicast data flow for each path. In each run of simulation, all nodes, source-destination pairs and corresponding data flows are newly generated. We run simulation over 500 times and simulation results are averaged. The results of necoMAC incorporates NCA-2PSP, NCA-CSMA, 2PSP and CSMA/CA protocols. The scheme decides a suitable protocol to transfer the data packets depending on the opportunity of network coding and golden topologies.

5.1. *Throughput*

Fig. 4(a) and Fig. 5(d) respectively show the throughput per flow values of CSMA/CA, necoMAC, COPE and RD-DCF+NC protocols with the increase in the number of data flows and nodes. The throughput per flow increases with the increasing number of data flows for all protocols except CSMA/CA and it decreases with the increasing number of nodes for all protocols. The reason for this behaviour is because of the high opportunity of network coding and golden chain with many data flows in a fixed 40 nodes network. For CSMA/CA, although data flows increase, it does not improve the throughput due to its DCF fairness. On the other hand, throughput decreases with the increasing number of nodes for all protocols. This is because only existing many nodes has no great effect without the active data flows. The number of flows is fixed at 14 for this experiment. For that value, throughput improves until 35 nodes and gradually decreases when the number of nodes increases. With some network coding opportunity and golden chain, other protocols have higher throughput than the CSMA/CA in spite of the similar trend. The necoMAC is the best among the four because it includes 2-hop path selection mechanism in the scheme which provides advantage of utilising relay-based transmissions in the network with many nodes. As the number of nodes increases in the network, the opportunity of finding a helper relay is higher. In both cases, necoMAC has 11% higher throughput per flow than the CSMA/CA protocol and 9% than COPE. There is a tradeoff between the increasing number of flows and nodes.

TABLE II: Theoretical values of proposed protocols and the legacy systems for MSDU length 1500 bytes and data rate 54Mbps in golden chain and triangle topologies

Protocol	**Topology**	**Throughput(Mbps)**	**Overhead Ratio**	**Energy($\times 10^{-6}$J)**
CSMA/CA		13.029	0.2073	92.1
NCA-CSMA	Chain	19.983	0.06	60.1
2PSP	Triangle	15.905	0.0794	75.5
NCA-2PSP	Chain + Triangle	23.335	0.0466	51.4
COPE	Chain	17.272	0.0625	69.5
RD-DCF+NC	Cross	20.236	0.0502	59.3

5.2. *Latency*

Fig. 4(b) and Fig. 5(e) depict the latency value versus the number of data flows and the number of nodes, respectively. The necoMAC can gain an average of 11% delay reduction over the CSMA/CA protocol for each case. The value of latency becomes high when the number of data flows increase in the network with 40 nodes. For necoMAC, latency is 40 ms for 10 data flows and 86 ms for 22 flows. The necoMAC is 7% less latency than RD-DCF+NC and 8% less than COPE. For the network with increasing nodes, high latency means low throughput for constant payload size and flows size.

5.3. *Energy Consumption*

Fig. 4(c) and Fig. 5(f) show the energy consumption of protocols under evaluation. The total energy consumption increases as the number of data flows and nodes in the network increases according to the increase in latency for both cases. However, the necoMAC consumes significantly less energy than the other protocols. The amount of energy saving is, in average, about 60% for the case of increasing flows and about 58% when the number of nodes increases. The reason for this decrease is, with the fixed number of 14 flows, increasing number of nodes create more opportunities to find a relay node between the sender and receiver. This enables the data transmission in high rate and in shorter duration of transmission, which leads to less energy consumption. Other protocols do not include the 2-hop path selection mechanism and take longer time to transmit a packet to the receiver compared to the necoMAC scheme.

5.4. *Overhead Ratio (OR)*

The results of overhead ratio are for the exchange of a pair of data packets in a chain topology and are taken from Fig. II. The value of one means that the size of the control messages is equal to the size of the control messages plus data payload. It should be desirable to transfer a certain amount of payload data with smaller amount of control packets. It can be seen that the overhead ratio of the proposed NCA-2PSP protocol for payload size 1500 bytes is 0.0466, which is the smallest among the compared systems. Another proposed protocol, NCA-CSMA possess an overhead ratio of 0.06, which is a little higher than the RD-DCF+NC with 0.0502 and a little smaller than COPE (0.0625). CSMA/CA protocol has the highest value of overhead ratio with the amount 0.2073 and 2PSP is the second highest with 0.0794. These two protocols are the only ones that do not have network coding mechanism in their protocol designs. The observation from these values describes that the protocols that can utilize the network coding opportunity can save time slots and some amount of control packet transmissions. This leads to the overall reduction in overhead for the completion of data exchange in a golden chain topology. The NCA-2PSP has 77.5% improvement than the CSMA/CA protocol and 7% than the state of the art.

6. CONCLUSION

In this paper, we presented comparison of network coding-based medium access control (MAC) schemes for many logical network topologies, especially golden chain, golden triangle, cross or star topologies in wireless networks. Topology and MAC have influence over network coding performance. Depending on the topologies, many possible combination of network coding and MAC schemes can be designed to improve the throughput gain, overhead, and energy consumption. Increasing the data flows creates more opportunity for topology and network coding while increasing the number of nodes provides more chance to find a relay node which is also helpful for topology and network coding opportunity between source and destination nodes.

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