necoMAC: Network Coding Aware MAC Protocol for Multirate Wireless Networks

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***Abstract*—In this paper we introduce a network coding aware Medium Access Control (necoMAC) scheme that incorporates many protocols such as NCA-2PSP, 2PSP and NCA-CSMA in order to provide data transmission in higher rates with fewer number of transmissions for multirate wireless networks. We create two golden topologies called golden chain and golden triangle, and calculate their energy consumption, overhead ratio, throughput and fairness for each protocol. We also set up a simulation to further analyze the performance of these protocols with the increasing number of nodes and flows. The simulation results show that the proposed scheme provides higher throughput and less energy consumption compared to the conventional CSMA/CA.**

***Index Terms*—medium access control (MAC), multirate, IEEE 802.11, network coding, multihop wireless network**

I. Introduction

In recent years, a new wireless network called a multihop wireless network (MWN), which does not rely on any fixed infrastructure has been introduced. In this infrastructure, any two nodes can communicate directly if their packets can be correctly decoded under the desired signal-to-interference-plus-noise-ratio is achieved. Otherwise, the packets are relayed from the originating node to the final destination node via one or more intermediate nodes by the hop-by-hop transmission fashion. Such an architecture requires that every node in the network plays the role of a router being able to determine the paths that packets need to follow to reach their destinations [1]. There are several benefits of wireless multihop networks, for example, extending the coverage of a network, improving the connectivity and capability of high data transmission when nodes are close to each other.

Energy consumption is an important issue that needs to be dealt with for a MWN because the nodes in MWN are equipped with the low capacity battery. Authors in [2] carried out a series of experiments to measure the energy consumption of an IEEE 802.11 wireless network interface operating in ad hoc networking environment. Their results showed that fixed overhead costs are very high and improvements in data transmission rates have a fairly limited effect on overall per-packet energy consumption. They explained this is because the MAC protocol and broadcast traffic must use lower transmission rates. Authors in [3] created a 2-hop path selection protocol which can reduce the delay and energy consumption by utilizing the physical layer multirate capability with an introduction of new Ready-To-Relay message to the handshaking procedure of accessing the medium.

In multirate wireless networks, data transmission can be possible in different rates provided by the physical layer hardware. For example, IEEE 802.11a specification supports 8 different data rates ranging from the base rate 6 Mbps to the highest rate 54 Mbps. Data transmission at higher rates can take place under favourable conditions as several environmental factors like channel condition and interference can have a dramatic impact on range and resulting coverage area. The receiver will not be able to decode the receiving message if the signal to interference plus noise ratio is lower than a certain threshold. If two nodes are in a short distance to each other, there is higher chance to transmit in higher rate because of the short link and strong signal quality as shown in Fig. 1.

Moreover, in multihop wireless networks, the routing protocol finds the path between the source and destination depending on the available links and intermediate nodes in the network. Long distance links can reach the destination in few hops, but in some low speed. On the other hand, the short distance links can support the transmission in high rate, but more hops are needed to reach to the destination and the possibility of a node to be involved in relaying the other's data packets becomes high [4]. Therefore, the level of congestion at an intermediate node may become an important issue because of the energy limitation of the node. Relating

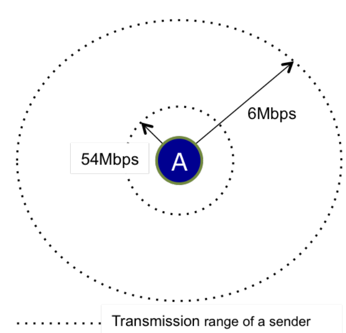


Figure 1. IEEE 802.11a ranges

to these two issues, the energy consumption, overhead ratio and the fairness of the proposed protocols are studied in the present paper by analytical calculation for each golden chain and golden triangle and by setting up the simulation in MATLAB environment to evaluate their performance with regard to the increase in the number of data flows and nodes. This work is based on the work of [1], which focused on the throughput by using the Slepian Wolf coding technique. The difference between their work and ours is that we apply the XOR network coding operation at the relay node that helps relaying the incoming packets in some higher rates if the energy consumption by two-hop transmission is less than that of one-hop direct transmission.

A. Our Contribution

We introduced two topologies of golden chain and golden triangle. The traditional routing which selects the minimum hop paths is updated by creating a golden triangle with the help of a relay between the one-hop transmission range of two nodes. Then the necoMAC scheme detects whether the network coding can be performed on the relay. We created a new message handshake for both 2-hop path selection and network coding based on the 2PSP's handshake procedure. The resulting NCA-2PSP protocol outperforms in terms of energy consumption, latency and throughput.

The rest of the paper is organized as follows. Section II summarizes the background and motivation on CSMA/CA, 2-hop Path Selection Protocol (2PSP) and Network Coding. The proposed necoMAC scheme and the new NCA-2PSP protocol are presented in Section III. In Section IV, we present the calculation and simulation of our work. We evaluate the performance of proposed protocols with various metrics such as throughput, energy, overhead and fairness in different scenarios. Finally, Section V concludes the paper and discusses some future work.

II. Background and Motivation

A. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)

CSMA/CA is the basic media access method of IEEE 802.11 MAC protocol based on the RTS/CTS handshaking mechanism. Before sending data packets, the source first looks for an idle channel in Distributed Interframe Spacing (DIFS) period and generates a random backoff timer. When timer times out, it broadcasts a RTS (request-to-send) control message, specifying a destination and data size. The receiver responds with a CTS (clear-to-send) message. If the source does not receive the CTS, it may retransmit the RTS message. On receiving the CTS, the source sends the DATA and waits for an ACK from the receiver. Any host that hears the RTS/CTS exchange updates their network allocation vector (NAV) value and must refrain from transmitting for the specified duration.

B. 2-hop Path Selection Protocol (2PSP)

A.O. Lim and S. Yoshida developed a 2-hop Path Selection Protocol (2PSP) [3] for a set of nodes, in which data can be sent faster using adaptive rate control capability of IEEE 802.11a/b/g MAC protocol via a relaying concept. Their main objective is to build upon the opportunistic rate adaptation to assist a sender, a relay and a receiver to reach a higher rate data transmission. They also proposed a relay mechanism and a new contention window called a Short Backoff Internal (SBI). A potential node that succeeds as a relay is allowed to send a Ready-To-Relay (RTR) message. The RTR contains the information about a pair of higher transmission rates. These rates are determined by the relay depending on the signal quality of overheard Relay Request to Send (RRTS) and Relay Clear to Send (RCTS) messages from the sender and the receiver respectively. If the sender can decode the relay's message successfully, it sends data with a high data rate selected by the relay. If the sender cannot receive the RTR message, it can send the data according to the standard DCF method. Then the relay node forwards the receiving data with another high data rate to the receiver. Finally, the receiver sends the ACK message to the sender at the base rate.

This 2PSP protocol is designed for a single data flow along the way to the destination. We match the function of this protocol with our concept of golden triangle and we would like to apply the Exclusive OR (XOR) network coding technique into this protocol.

C. Network Coding

Network coding is a coding technique which is applied at an intermediate node to create new packets by combining the data packets received over the incoming links in the network to replace the traditional 'store and forward' paradigm. This technique has benefits such as an increase in throughput and an improvement in the reliability and robustness of the network [5]. There are many existing works that show the benefits of network coding. For example, the work in [6] demonstrated up to 30% throughput gain over the no network coding approach and COPE of [7].

Our interest is to combine the network coding technique into the 2PSP protocol. The higher rate data transmission is achieved by the 2PSP protocol but this is only possible for the payload data, and the overhead for control messages are constant because they are transmitted in base rate. With network coding, the entire one transmission of both overhead control messages and the data can be reduced. Therefore, if we can successfully design a protocol that can exploit the benefits of these two functions, we will be able to save more energy and achieve more throughput improvement.

However, the 2PSP protocol is especially designed for one data flow, and network coding happens when two incoming data flows meet at a node. Some questions such as "How we will combine these two different nature?" and "How will the created protocol perform?" are motivating us to do this research.

III. Proposed necoMAC scheme

In this section, we present a network coding-aware MAC scheme which consists of four different MAC protocols. Firstly we introduce two topologies of a golden chain and golden triangle. Then we describe how network coding can reduce the number of transmissions in a golden chain topology and explain how it can be applied in the 2PSP protocol. Finally, the operation of this scheme is shown with a flow chart.

A. Golden Chain and Golden Triangle

In our work we look for the golden chains and golden triangles inside the network. We define a golden chain as a chain of three successive nodes with two data flows from opposite directions along the path to the destinations. Fig. 2(a) shows a golden chain. The data flow 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.

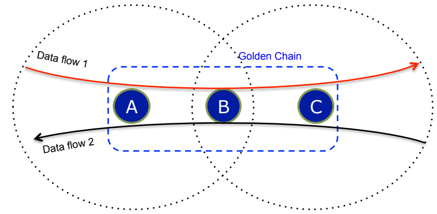
For a golden triangle, A and C are within the 1-hop transmission range of each other. They may have a low-rate link between them. The main property of a golden triangle is the relay node which helps transmission in some higher rates. The difference from a golden chain is that a golden triangle does not necessarily require two data flows. It can happen with one data flow as depicted in Fig. 2(b).

B. Network Coding-aware CSMA (NCA-CSMA)

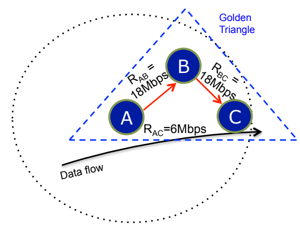
Fig. 3 shows the data transfer in a golden chain. As nodes A and B are within the transmission range of relay node R, A and B cannot transmit their packets to R in the same time slot to avoid the collision. By the conventional CSMA/CA protocol, total number of 4 transmissions are needed to complete a successful data exchange between A and B via the relay R. Exclusive OR (XOR) network coding [8] can be applied at the relay node R to reduce one transmission. With XOR network coding, node R broadcasts the network coded packet $a \bigoplus b$ upon receiving the packets a and b from node A and B in previous time slots respectively. Both A and B can receive the XOR-coded packet in one time slot and can recover the packets b and a by performing the XOR operation of their own packet with the receiving coded packet again. Therefore, data exchange between A and B is completed within 3 transmissions and energy for one transmission can be saved.

C. Network Coding-aware 2PSP Protocol (NCA-2PSP)

We have been motivated to combine the network coding technique into the 2-hop path selection protocol (2PSP) by the existing work of [3] and [7]. 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. We define three new control messages called relay RTS (RRTS), relay CTS (RCTS) and Ready to Relay (RTR) in our work. When a sender wants to send a data packet, it first waits for the DIFS+CW time period before it can transmit the data. After the sender can access the idle channel, it transmits a RRTS message. If the receiver receives the RRTS message correctly, it replies a RCTS message to the sender. A relay node that hears these control messages waits for a random short backoff internal (SBI) period. Within this

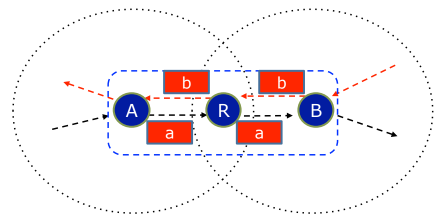


(a)

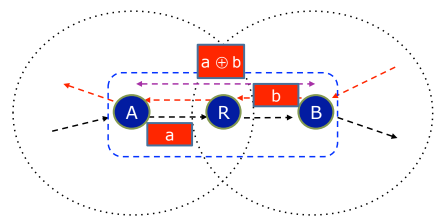


(b)

Figure 2. Two golden topologies (a) Golden chain (b) Golden triangle



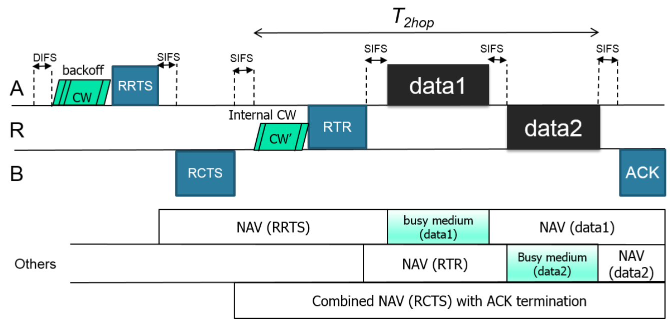
(a)



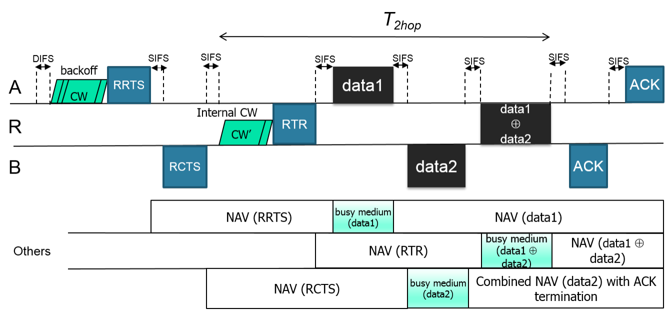
(b)

Figure 3. Data exchange in a golden chain (a) CSMA/CA (b) NCA-CSMA

period, the relay node decides whether to help the sender or not by estimating the energy consumption of direct transmission and the transmission with the help of relay. Firstly, the relay node determines a suitable pair of higher data rates based on the signal strength of the receiving RRTS and RCTS messages. Then it calculates the energy consumption with one-hop transmission and that with two-hop transmission. If two-hop transmission saves more energy, the relay broadcasts a Ready to Relay (RTR) message. This message contains the information about the selected rates that the sender and receiver should use when they send their data packets. If the sender cannot hear any response after SBI interval times out, the sender will transmit the data packet according to the standard DCF procedure [9]. If the sender can correctly decode the RTR message, it will transmit its data packet with the new data rate defined in the RTR message. The message handshaking procedure of 2PSP and NCA-2PSP are shown in Fig. 4. NCA-2PSP allows data transmission from the



(a)



(b)

Figure 4. Message handshaking (a) 2PSP (b) NCA-2PSP

receiver B after the sender A sent its data packet in a higher data rate. After the relay node R receives the data packet of receiver B, it creates a XOR-coded packet of a and b and broadcasts the coded packet. As both A and B are within one-hop transmission range of R, both of them can receive the coded packet and can recover the data packet of each other by doing the XOR function of their own packet and the receiving coded packet. After the data packets are successfully decoded, the ACK messages are sent. Neighbor nodes that hear the ACK shall terminate their NAV and are free for medium access. The handshaking finishes when the sender receives the ACK message from the receiver node.

D. Operation of necoMAC Scheme

The necoMAC is a scheme which selects the most beneficial MAC protocol among NCA-2PSP, 2PSP, NCA-CSMA and CSMA/CA protocols. Fig. 5 depicts how this scheme works by a simple flow diagram. Firstly, it investigates whether two opposite flows pass through a certain node on a golden chain or not. If the node detects that two data flows are incoming it from opposite directions, it tries to decide the source nodes are within the transmission range of each other. If they can reach each other with one-hop transmission, the NCA-2PSP protocol tries to find a helper relay node and transmission will be performed with NCA-2PSP protocol. The transmission in NCA-CSMA will be selected when the source nodes are outside the transmission range of each other and they are located on a golden chain. If only one incoming data flow exists at a node, the scheme checks if a golden triangle can be created or not. If the golden triangle can be created with the help of a relay, data transmission in 2PSP is chosen. It will access the medium and send the data with the normal CSMA/CA protocol if both golden triangle and chain do not exist.

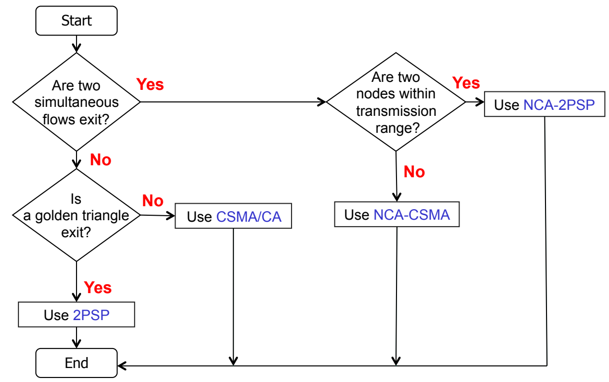


Figure 5. The necoMAC scheme

IV. Numerical Simulations

In this section, we investigate the performance of the proposed necoMAC scheme over the conventional CSMA/CA scheme and 2PSP protocol. We use the IEEE 802.11a hardware specifications for the simulation assuming the multihop wireless network environment. Firstly, nodes are randomly generated in a 160 x 160 m^2 coverage area. Source and destination pairs are randomly selected and data flows are created along the paths produced by the AODV routing protocol. We generate all the nodes and flows, and run the simulation in the MATLAB environment. Then the proposed protocol tries to find the three-node golden chains and golden triangles along the paths to the destination. We do not consider the retransmission in our simulation. We assume that each time slot is long enough for a packet to reach the receiver. We consider the case where golden chains and golden triangles are independent because we assume two transmissions cannot happen within the same time slot if they are in the transmission range of each other except for the case where we apply both for the NCA-2PSP protocol. In each run of simulation, all the nodes, source-destination pairs and corresponding data flows are newly generated. We run the simulation 100 times and simulation results are averaged of 100 times. The simulation parameters are shown in Table I.

Our simulation can be categorised into two. In the first simulation, we investigate the impact of increasing data flows on protocol performance. The number of nodes is fixed at 100. The number of data flows is varied from 10 flows to 60 flows in steps of 10 flows. In the second simulation, we focus on the influence of the number of nodes on the performance of the protocols. The number of data flows is fixed at 30 flows. The number of nodes is varied from 100 nodes to 600 nodes in increment of 100. In our simulation, the transmission rates are approximated according to the distance between two nodes based on the transmission ranges as described in Table I by referencing the Cisco Systems' definition [10].

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Hardware specification	IEEE 802.11a OFDM
Simulation environment	MATLAB 2014b
Routing protocol	AODV
MAC protocol	CSMA/CA, 2PSP, NCA-CSMA, NCA-2PSP
Network coverage area	160 × 160 m^2
Transmission power	100 mW
Transmission range	50, 45, 39, 33, 26, 19, 15, 13 m
Transmission rate	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Antenna type	Omni Antenna
RTS, RRTS size	20 bytes
CTS, ACK size	14 bytes
RCTS, RTR size	15 bytes
MAC header	34 bytes
Slot time	9 μs
Preamble time	16 μs
Signal time	4 μs
SYM time	4 μs
DIFS	34 μs
SIFS	16 μs
Number of running times	100

A. Comparison of Throughput

Fig. 6 and 7 show how throughput varies with the number of nodes and the number of data flows, respectively. Throughput is defined as the amount of payload data that can be received at the destinations for all the unicast data flows transmitted by the sources. The necoMAC scheme outperforms both 2PSP and CSMA/CA protocols significantly as the number of nodes increases. The necoMAC scheme can increase the throughput by about 22.8% for 100 nodes compared to the CSMA/CA protocol. The percentage is gradually increased to about 57.2% for 600 nodes. The throughput improvement is approximately equal to 45.3%. This shows that the NCA-2PSP protocol can find more relay nodes that will help the transmissions in high rate and network coding operation can further reduce the number of transmissions, which leads to the improvement in throughput when the number of nodes increases. From Fig. 7, we obtain the behaviour of throughput decrement as the number of data flows increase. The reason for this behaviour is because of the high latency when data flows increase. High latency means low throughput. When the number of flows in the network increase, there is high possibility of contending the media access channel by many nodes for sending the data, which leads to the delay and affects the throughput performance. Our proposed scheme shows high throughput than the CSMA/CA scheme and 2PSP protocol for all the flow numbers. An average amount of 23.7% throughput improvement is achieved with 100 nodes in the network. The network coding and relaying in high rate leads to less number of transmissions and less total transmission time than the others. Fig. 8 depicts the latency value versus the number of data flows. The necoMAC scheme can gain an average of 20% delay reduction over the CSMA/CA protocol.

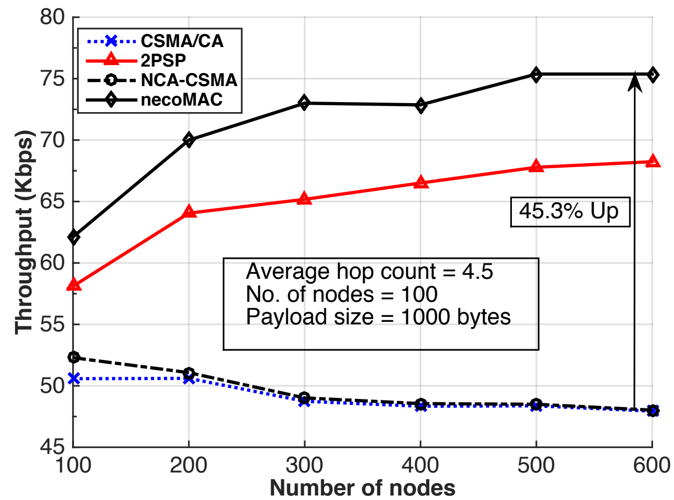


Figure 6. Throughput as a function of nodes increase

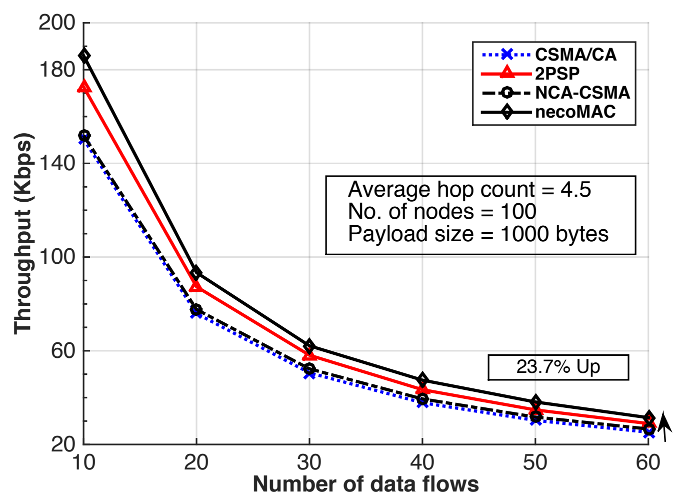


Figure 7. Throughput as a function of flows increase

B. Comparison of Energy Consumption

Fig. 9 and 10 show that the necoMAC scheme consumes less energy than the other protocols. The energy consumption is the energy of the control messages and the successfully transmitted data packets. The total energy consumption increases as the number of data flows increases and there is a dramatic decrease with the increase in the number of nodes inside the network. The amount of energy saving is, in average, about 20.5% for the case of increasing flows while it is about 29.1% when the number of nodes increases up to 600. The reason for this dramatic decrease is, with the fixed number of 30 flows, increasing number of nodes create more and more opportunity to find a relay node between the sender and receiver, which enables the data transmission in high rates and

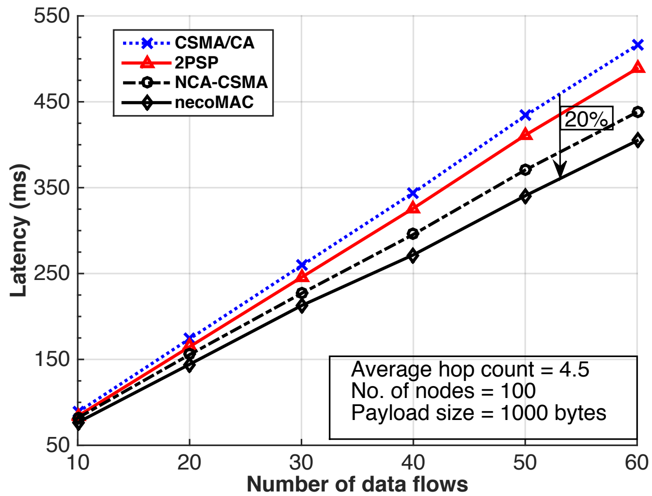


Figure 8. Latency as a function of flows increase

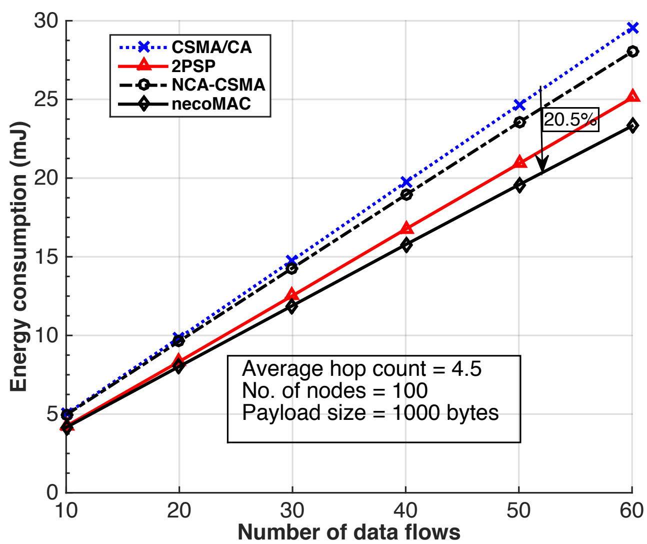


Figure 9. Energy consumption as a function of flows increase

less energy consumption. In our work we choose a relay based on the energy consumption rather than the rate by comparing two consumption, one with direct transmission and another with two-hop transmission. This is differ from the work of [3], where a candidate relay is selected only based on the achievable higher rate that the relay can transmit.

C. Comparison of Overhead Ratio

Fig. 11 and 12 shows the overhead ratio as a function of number of data flows and as a function of number of nodes, respectively. The overhead ratio is defined as the ratio of the total number of control messages transmitted (in bytes) and the total number of control messages plus the total number of data bytes received. It can be seen that the overhead ratio of the proposed scheme is higher than the 2PSP and CSMA/CA protocols for both parameters of the X-axis. The graph for necoMAC of Fig.11 is fluctuating between 0.19 and 0.2 with

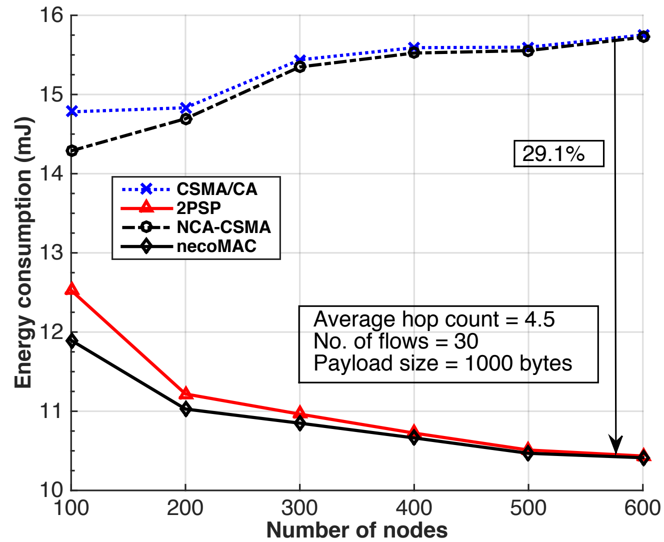


Figure 10. Energy consumption as a function of nodes increase

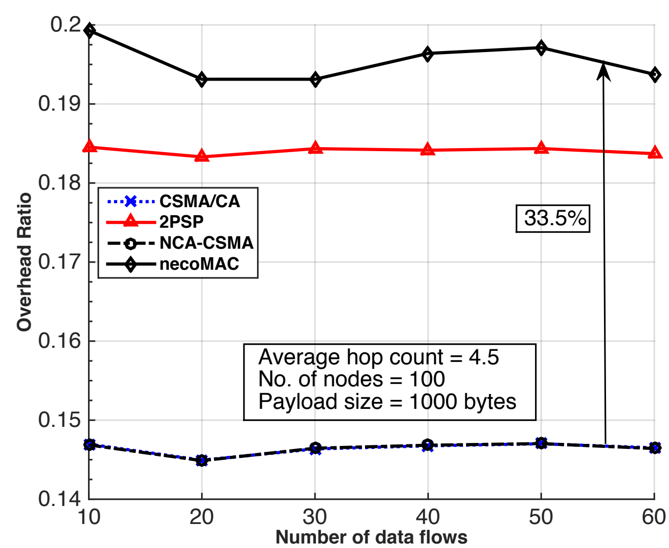


Figure 11. Overhead ratio as a function of flows increase

the increase in the number of data flows until 60. The graphs for 2PSP and CSMA/CA protocols are nearly constant at 0.185 and 0.146 respectively. With the constant payload size, the only reason for the fluctuation of the graph is because of the changes in the control messages depending on the transmission in coding and without coding. However, the graph tends to increase with the number of nodes increase as the transmissions via relay cost more control overheads with more opportunity of finding a relay between a sender and a receiver. The overhead ratio increases to about 65.2% when the number of nodes increases whereas it is only about 33.5% difference compared with the CSMA/CA for the increase in data flows.

D. Comparison of Fairness

We also studied the fairness of our MAC protocols using the Jain's fairness index [11]. Jain's fairness index is used to

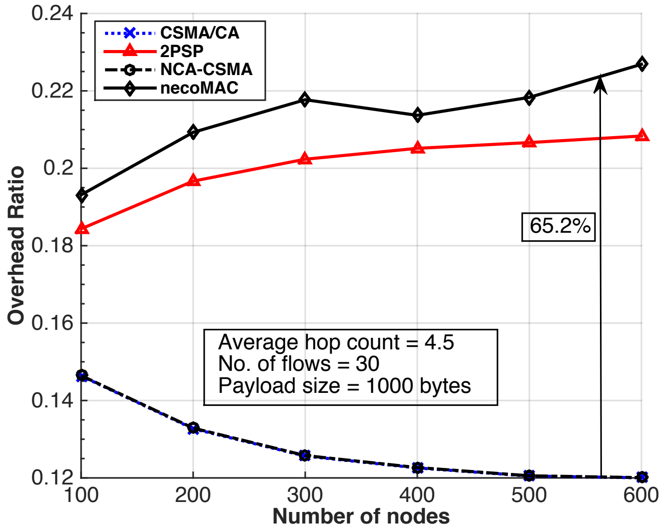


Figure 12. Overhead ratio as a function of nodes increase

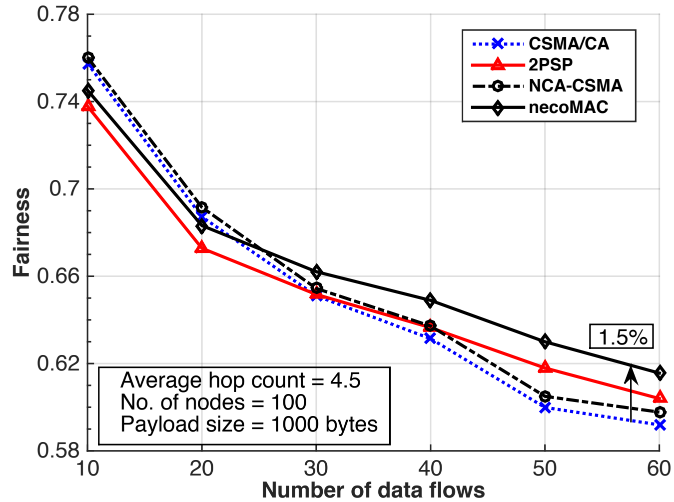


Figure 13. Fairness as a function of flows increase

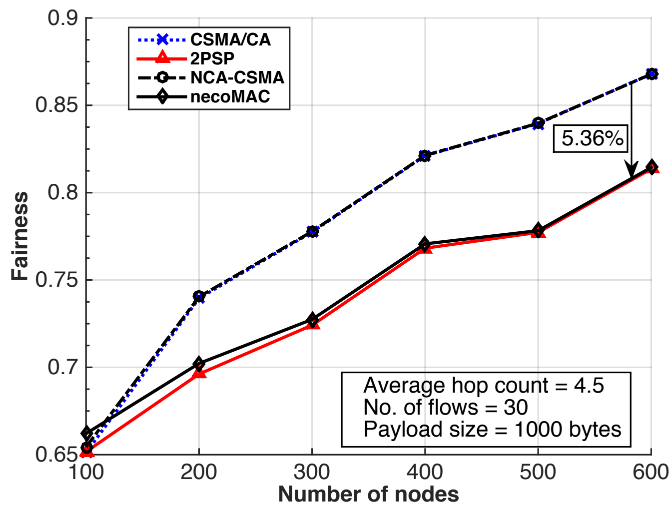


Figure 14. Fairness as a function of nodes increase

measure fairness by calculating the variability of throughput at each node on the way of data flows. Larger values of Jain's index indicate better fairness and the index value 1 means the equal share of channel among the nodes. We calculate the local throughput of each node for all the data flows passing through the nodes and compute the fairness of that instant time period. Fig. 13 shows the fairness performance with 100 nodes and the increase in the number of data flows. We observe that all the protocols perform higher fairness while the number of flows is 10, and the fairness gradually decreases as the number of flows increases. Our proposed protocol shows a better fairness index than the CSMA/CA and NCA-CSMA by about 1.5% difference when the flows number is 60. Fig. 14 shows increasing the number of nodes has high impact to the fairness among the nodes.The fairness for CSMA/CA and the proposed one is around 0.65 in 100 nodes network while their figures increase to 0.87 and 0.81 in 600 nodes network, respectively. We observe that the possibility of a node to be involved in relaying the other's data packets becomes high.

V. Conclusion

We have studied the network coding-aware CSMA which is applied at three-node golden chains and network coding-aware 2PSP that works for golden triangles with multirate transmission capability. We created a network coding aware medium access control scheme which incorporates NCA-CSMA, NCA-2PSP, 2PSP and CSMA/CA protocols. We evaluated the performance of the necoMAC scheme compared to the conventional CSMA/CA scheme with throughput and energy consumption. We also studied other important metrics such as overhead ratio and fairness among the nodes so that we can evaluate the performance of our necoMAC scheme. The simulation results reveal that more than 20% of energy is saved and 20–40% of throughput is improved by the proposed scheme. However, there is a tradeoff with the overhead ratio as the overhead ratio of the NCA-2PSP is bigger than the other protocols. Our future direction will be the creation of more network coding opportunity at the place where golden triangles and golden chains appear as neighbours. The present work considers only one relay node involving in the relaying of the data packets. Our future work needs to consider selecting the best relay among many candidate relay nodes when we increase the number of nodes in the network. This may save more energy and create more coding opportunity with the tradeoff of increasing the overhead control messages.

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