Australian Journal of Basic and Applied Sciences, 8(10) July 2014, Pages: 72-80

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

Analysis of impact of Network Topology on Energy Efficient Cooperative Medium Access Control Protocol for Wireless Ad-hoc Network

[1]C. Ellammal and [2]G. Sudha Sadasivam

[1]*C.Ellammal, Anna University, Department of Electronics and Communication Engineering, Dr.NGP Institute of Technology, Coimbatore, TamilNadu, India.*
[2]*G.Sudha Sadasivam, Anna University, Department of Computer Science Engineering, PSG College of Technology, Coimbatore, TamilNadu, India.*

ARTICLE INFO

Article history:
Received 25 April 2014
Received in revised form
8 May 2014
Accepted 20 May 2014
Available online 17 June 2014

Keywords:
Network Lifetime, Network topoly,
Medium Access Contronl, ad-hoc
Network

ABSTRACT

Background: Relay assisted cooperative communication which utilizes nearby terminals to relay the overhearing information has a significant performance gains over the direct communication for wireless Ad-hoc networks. A powerful Medium Access Control (MAC) scheme is needed to support cooperative communication and also to solve the difficulties raised during relaying and cooperative computing. **Objective:** The challenging task in the design of Ad-hoc Network is the extension of network lifetime as all the devices are battery operated. This paper proposes new energy constrained Medium Access Control (MAC) protocol which improves network lifetime as well as maximizes throughput. The impact of various network topologies on the performance of MAC protocol is also discussed. **Results:** The simulation parameters like throughput, network lifetime, energy consumption and end to end delay are taken to compare the performance of proposed protocol with existing IEEE 802.11. The results are analyzed for random, grid and triangle network topologies. **Conclusion:** The simulation results show that the proposed protocol performs well comparing to existing IEEE 802.11 in terms of network lifetime, energy consumption and throughput with little increase in end to end delay.

To Cite This Article: C. Ellammal, G. Sudha Sadasivam, Analysis of impact of Network Topology on Energy Efficient Cooperative Medium Access Control Protocol for Wireless Ad-hoc Network. ***Aust. J. Basic & Appl. Sci.,*** *8(10): 72-80, 2014*

INTRODUCTION

A Mobile Ad hoc Network (MANET) is a wireless network temporarily and spontaneously created by mobile stations without requiring any infrastructure or central control. This feature makes MANETs a very practical and easy to deploy in places where existing infrastructure is not capable enough to allow communication, e.g. in disaster zones, or infeasible to deploy. At the same time it creates huge problems as well. One problem lays in the design of the Medium Access Control (MAC) Protocol which defines how the wireless medium is shared by all nodes. It is possible to design a MAC protocol that can handle the sharing of the medium but at the same time has proved to be one of the most challenging tasks for the researchers. The deployment and rerouting of traffics are flexible in MANETs, but how to efficiently utilize the scarce shared wireless radio channel remains a great challenge in practice. Extensive research efforts have been dedicated to improving the throughput and lifetime of a MANET.

Cooperative communication techniques have been shown to improve network performance by combining the transmission powers of multiple users. While most of the attention has been on improving signal-to-noise ratio in the physical layer, research focus has also been devoted for exploiting cooperative diversity at the MAC layer.

The IEEE 802.11 standard lists five modes for a network interface to operate: transmit, receive, idle, sleep and switch off. While the power consumption values for the first three states do not differs by much, a node can go into a low power sleep state to save energy, though it cannot transmit and receive data in this state. Though taking part in cooperation can help save energy for nodes by reducing idle power consumption, it may not be beneficial for nodes which choose to spend idle time in the sleep state. A high data-rate node which acts as a relay thus spends additional power reducing its overall lifetime, which in turn affects the network lifetime. Thus, a potential relay may decline to cooperate and switch to the sleep state instead. So, design of effective relay assisted energy constrained MAC protocol is a most important task in MANETs.

Corresponding Author: C. Ellammal, Anna University, Department of Electronics & Communication Engineering, Dr. NGP Institute of Technology, Coimbatore, TamilNadu, India.
Mob: 91-9965578838 E-mail: ellammal.seethapathy@gmail.com

Related Work:

Existing work on cooperation in the MAC layer can be broadly divided into proactive and reactive strategies. Proactive strategies involve making use of relays to improve the transmission quality between stations where the channel condition is low. In case of reactive strategies, intermediate nodes wait for an indication of incorrect reception of data from the receiver, following which they retransmit cached copies of the original data with the objective of reducing the number of retransmissions.

Some existing proactive strategies focuses on multi-rate networks where low rate stations can obtain help from high rate ones. Two such mechanisms were outlined in rDCF (Zhu *et al*., 2006) and Coop MAC (Liu *et al*., 2007) in which the source chooses from a list of relays for cooperation. Liu *et al*. have proposed a CoopMAC to exploit the multirate capability and aimed at mitigating the throughput bottleneck caused by the low rate nodes, so that the throughput can be increased. With the similar goal, Zhu *et al*. have proposed a CMAC protocol for wireless ad-hoc network. However, beneficial cooperation considering signaling overhead is not addressed.

More recently, (Shan *et al*., 2009) proposed a cross-layer design by combining information from the physical layer to achieve cooperation at the MAC layer. As shown in the above mentioned papers, cooperation in multi-rate networks can help overcome the negative effect of low rate stations on the network throughput. However, relaying would imply additional energy consumption for the relay mode. As the transmission duration is shortened for the low rate transmission, the power consumed by the relay node is lower than the power it would have consumed by staying idle for the entire duration of a low rate transmission.

A busy tone based cross layer CMAC protocol [Shan *et al*., 2008) has been designed to use busy tones to help avoiding collisions in the cooperative scenario at the cost of transmitting power, spectrum and implementation complexity. A reactive network coding aware CMAC protocol has been proposed by (Wang *et al*., 2012) in which the relay node can forward the data for the source node, while delivering its own data simultaneously. But the network lifetime is not addressed. A distributed CMAC protocol (Zhai *et al*.,2009) has been proposed to improve the lifetime of wireless sensor networks, but it is based on the assumption that every node can connect to the base station within one hop, which is impractical for most applications. A CMAC protocol for vehicular networks, particularly for gateway downloading scenarios, has been designed by (Zhang *et al*., 2009). A drawback is that it can only be utilized in the scenario that all the vehicles are interested in the same information. Moreover, (Moh *et al.* , 2010) have designed a CMAC protocol named CD-MAC which lets the relay transmits simultaneously with the source using space-time coding technique. Shan *et al*., 2011, have explored a concept of cooperation region, whereby beneficial cooperation can be identified. However, energy consumption is not evaluated for both of them.

The existing CMAC protocols mainly focus on the throughput enhancement while failing to investigate the energy efficiency or network lifetime. While the works on energy efficiency and network lifetime generally fixates on physical layer (Sadek *et al*.,2009) and network layer (Himsoon *et al*.,2007). Net Coop MAC is proposed by (Banerjee *et al*.,2010) for improving network lifetime but is not applicable for ad-hoc network. DEL-CMAC protocol is proposed by (Liu *et al*.,2007) but multiple relays are not considered for improving throughput.

This paper proposes new Energy Constrained Cooperative Medium Access Control (ECC-MAC) protocol which improves network lifetime as well as maximizes throughput. The impact of various network topologies on the performance of MAC protocol is also discussed. Our algorithm seeks to enhance cooperation by identifying the best possible relay while being sensitive to the network lifetime. We show that this can help to obtain a balance between achieving high network throughput and maintaining a high network lifetime.

Analytical Model:

The analytical model is based our previous energy model (C.Ellammal et. al., 2014). Each mobile node in a wireless network is equipped with the Network Interface Card. A node equipped with network interface card can be in any one of the following states and power consumption differs for each state:

- Transmit: Node transmits packet with the transmission power Pt.
- Receive: Node receives packet with receiving power Pr.
- Idle: Node neither send nor receive packet but listens the wireless channel with power P_{idle}
- Sleep: Node enters into sleep state and consumes power P_{sleep}

Energy consumed by a node during particular amount of time is computed as follows:

Energy =Power*Time

Thus, energy consumed during transmission is

Et= Pt*Tt

where,

Tt= Transmission time

Similarly, energy consumed during reception is

Er= Pr*Tr

where,
Tr= Reception time

As mentioned earlier, the energy consumption for a wireless network interface in the active state for the receive and idle modes is not much lower than that consumed in the transmit mode, though the energy consumption in the sleep mode is much lower. We use the power consumption values of the Lucent IEEE 802.11 WaveLAN card which consumes 1.65 W,1.4 W,1.15 W and 0.045 W in the transmit, receive, idle and sleep modes respectively.

We adopt a design where a node enters the sleep mode upon overhearing an RTS/CTS exchange for a transmission not involving itself, waking up after the specified duration. Earlier papers have raised concerns about the transition time of 250 μs between the doze and awake states. However, considering an 802.11b network, the transmission time for a 2 KB packet at the maximum transmission rate of 11Mbps would take around 1.5ms within which this transition could comfortably be achieved twice, i.e. for the node to enter the doze state and wake up again. Also, given the performance benefits of the sleep mode, we expect future wireless interfaces to have better support for this state with shorter transition times.

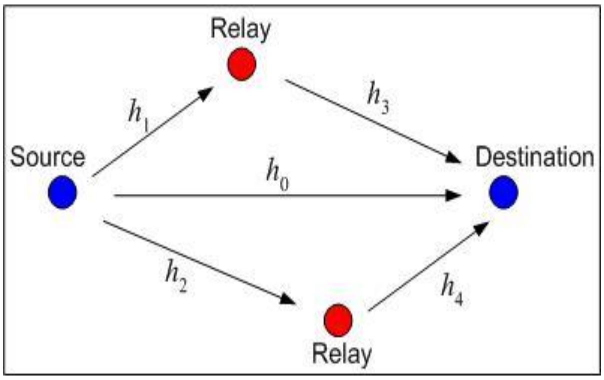

Fig 3.1: Multihop Ad-hoc Network Scenario.

As shown in Figure 3.1, a multi-hop Ad-Hoc network with randomly deployed mobile terminals is considered, where all terminals have the capability to relay. To come up with a reasonable system model, we assume that data connections among terminals are randomly generated and the routes are established by running Ad hoc On-demand Distance Vector (AODV) which is a widely used conventional routing protocol for Ad-hoc network. In the system model, AODV builds the route in a proactive manner by selecting the routing relay terminals firstly. When a route is established, ECC-MAC initiates the cooperation in a hop-by-hop manner by selecting the cooperative relay terminals. In this paper, the source and destination terminals are referred to the terminals at MAC layer and the relay terminal indicate the cooperative relay terminal.

Proposed Energy Efficient Cooperative Medium Access Control protocol:

4. 1 Conventional Distributed Coordination Function:

IEEE 802.11 MAC contains two coordination functions, namely, Point Coordination Function (PCF) and Distributed Coordination Function (DCF), which support the infrastructure configuration and the ad-hoc configuration respectively. PCF depends on a central controller to allocate the channel resource and provide contention-free services, while DCF is a typical contention-based protocol.

The basic operations of the proposed protocol are based on the IEEE 802.11 Distributed Coordination Function (DCF). IEEE 802.11 DCF has been regarded as the basic Media Access Control (MAC) protocol for MANETs. It is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance).

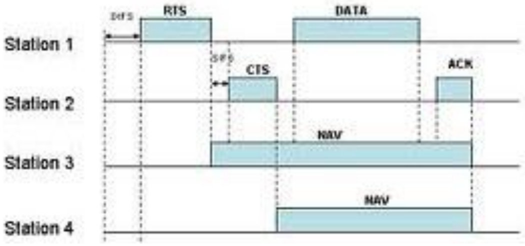

Fig. 4.1: DCF with RTS-CTS handshake.

DCF defines two channel access modes: basic mode and RTS/CTS access mode. Both modes adopt the discrete-time back-off algorithm. In both modes, whenever a node has a packet to transmit, it generates a random back-off counter uniformly from [0,CW-1], where CW represents the size of the contention window. As long as the carrier is sensed idle for period of Distributed Inter Frame Space (DIFS), the node begins to decrement its back-ff counter by one.after that, the back-off counter is reduced by one for each idle slot. If the carrier is busy, the back-off counter is frozen until the next idle slot. When the back-off counter is reduced to zero, the node begins the transmission. The minimum and maximum values of CW, CWmin and CWmax, are determined by the physical layer characteristics. After each unsuccessful transmission, the value of the back-off stage m will be increased by 1 and CW will be doubled until it reaches its maximum value CWmax.

In RTS/CTS mode, two short conversation frames , Request to Send (RTS) and Clear to Send (CTS), are sent prior to the transmission of the data frame as shown in Fig. 4.1. The RTS message contains the expected duration information for the remaining transmission, which includes three Short Inter Frame Space (SIFS) intervals, one CTS message, one data frame and one Acknowledge(ACK) message. If no collision occurs, the destination node replies with a CTS message after an SIFS, which also contains the new expected duration information of the remaining transmission. Other nodes receiving the RTS and CTS message update their Network Allocation Vector (NAV) based on the duration information in RTS and CTS messages. NAV is maintained by each node to indicate when the channel is available and is updated by RTS and CTS messages. All other nodes know when the current transmission will complete according to the updated NAV and avoid transmitting packets during this period.

Proposed MAC Protocol:

Unlike DCF, in the proposed protocol, the RTS packet carries the residual energy of the source and relay request message with corresponding relay address for supporting cooperative communication. After receiving the RTS, the destination sends CTS back after the period of Short Inter Frame Space (SIFS). All the nodes hearing CTS will update their table about the residual energy of the destination which is carried by CTS packet. If the source does not receive CTS within Trts+Tcts+SIFS, a retransmission process will be initiated. Otherwise, after receiving CTS message from destination, the source waits for Willing to Help (WTH) message from relay. All the nodes overhearing both RTS and CTS can act as relay. If a node accepts relay request, it sends WTH message to source. Source selects one potential node as relay. Then, the source sends data packet to relay using first hop data rate and relay forwards it to the destination with second hop data rate. If the destination can decode the combined signals correctly, it sends back an ACK. Otherwise, it just lets the source timeout and retransmits. If the source fails to receive WTH packet, it performs RTS-CTS procedure again for relay request from node next lowest transmission decision factor. Comparing with IEEE 802.11 DCF, the proposed scheme needs extra fields for RTS and CTS packet to carry relay request and residual energy. The RTS, CTS and WTH packets for proposed scheme are given in Figure 4.2.

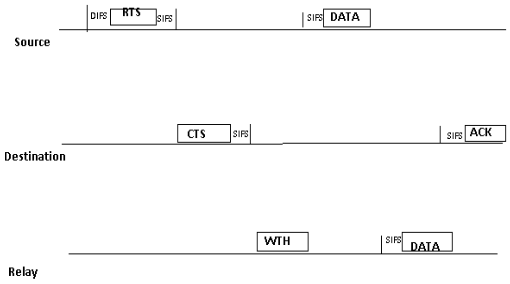

Fig 4.2: Packet Exchanging Process in Proposed System.

Algorithm:

The detailed energy constrained algorithm for the proposed scheme is given below:

Step 1: When packet is ready for transmission, source waits until back off timer expires.
Step 2: Source inserts residual energy of source and relay request message into RTS
Step 3: Source sends RTS to destination
Step 4: Destination sends back CTS with its own residual energy
Step 5: Nodes hearing RTS and CTS can act as relay
Step 6: Possible relay nodes send WTH packet to source with their residual energy, first and second hop data rate
Step 7: Source computes energy factor Qi for all possible relays

$$Q_i = \frac{E_i}{E_{res,i}}$$

E_i – *Initial energy*
$E_{i,res}$ – *residual energy*

Step 8: Source computes throughput factor Si for all possible relays

$$S_i = \frac{t_i}{t_{dir}}$$

t_i – *Transmission time*
t_{dir} – *Direct transmission rate*

Step 9: Source computes transmission decision factor $\boldsymbol{\delta_i}$ *for all possible relays*

$\delta_i = Q_i * S_i$

Step 10: Choose node having lowest δ_i *as relay*
Step 11: Source sends data packet to destination through selected relay

An Example Scenario:

Figure 5.1 shows an example of proposed algorithm. Here, S is the source with a 2 Mbps data rate to the destination D. The source can get help from any of the possible relays A, B, C and E. Each possible relay has various first and second hop data rates as shown in Figure 5.1. For example, node A has first hop data rate of 11 Mbps from source and second hop data rate of 5.5 Mbps to destination. Each node has different residual energies. The residual energies in Joules for node S, A, B,C and E are 4,5,6,1.5 and 2 respectively.

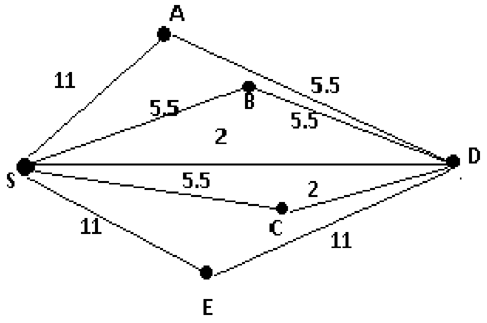

Fig. 5.1: Illustration of proposed strategy

When a source has data packet, it computes transmission decision factor $\boldsymbol{\delta_i}$ of each neighboring node. Source chooses node with lowest transmission factor as relay. The proposed algorithm can be thought of as applying a dual filter to the choice of relay by choosing a node on the basis of both the throughput improvement as well as energy constraints. In case of direct transmission, the source always transmits at the direct transmission rate which results in the same energy consumption irrespective of the residual energy.

In case of proposed algorithm, the source actively chooses the mode of transmission which is affected least due to relaying. Thus, if a particular node is low on residual energy, the source would look for a different option which results in lower effective loss of energy.

RESULTS AND DISCUSSION

Simulation Environment:

We simulate the performance of 802.11 and the proposed algorithm using discrete event simulator written in C. For the network setup, nodes are placed randomly in a square region of side 200 metre as shown in Fig. 4. We assume that all nodes start with identical battery capacities. A fixed payload size (L) of 1024 bytes is considered. All stations operate under saturation conditions and always have a packet ready to send. The simulation settings and parameters are listed in Table 1. Each node supports one of possible data rates: 11Mbps, 5Mbps,2 Mbps and 1Mbps. RTS and CTS packets are transmitted with a rate of 1Mbps and data packets are transmitted with variable rate.

Table 1: Simulation Parameters.

RTS	32 bytes
CTS	20 bytes
ACK	14 bytes
WTH	18 bytes
PHY header	192 bits
MAC header	272 bits
Packet Payload	1024 bytes
Unit time	0.1ms
Initial Energy	10 J
Noise power	-60dBm
Transmitting Power	10dBm

Simulation Topologies:

The performance of proposed protocol is evaluated for various topologies like grid topology as shown in Fig. 6.1 , triangle topology as shown in Fig. 6.2 and random topology as shown in Fig.6.3

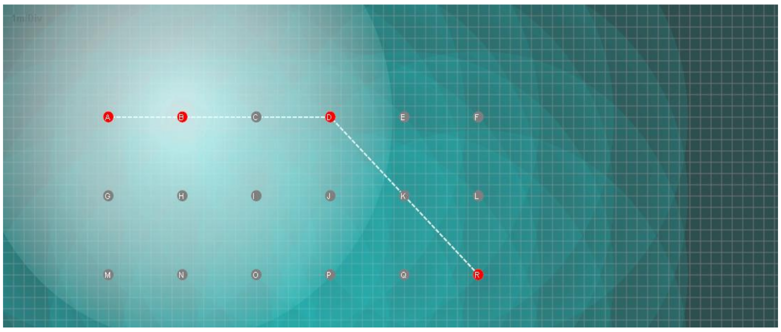

Fig. 6.1: A snapshot of Grid Topology.

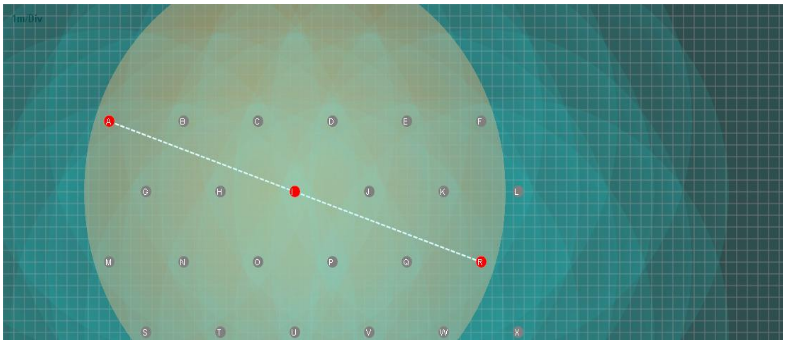

Fig. 6.2: A snapshot of Triangle Topology.

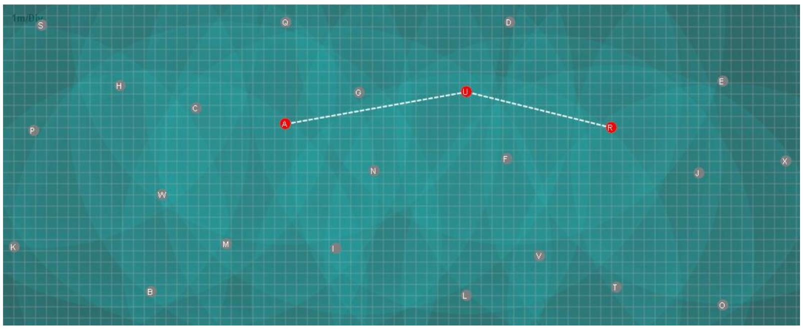

Fig. 6.3: A snapshot of Random Topology.

Performance Evaluation Metrics:

The evaluation metrics used are network lifetime, energy consumption, throughput and delay.

Network Lifetime:

The lifetime is defined as the duration from the network initialization to the time that the first terminal runs out of power.

Energy Consumption:

The total energy consumption is the summation of the transmitting (including both transmit amplifier and circuitry) and receiving energy cost at the source, destination and relay.

Throughput:

The throughput metric measures how well the network can constantly provide data to the sink. The throughput is the number of packet arriving at the destination per seconds.

End to end delay:

This is the ratio of the interval between the first and second packet to total packet delivery.

Simulation Results:

Fig. 6.4 shows the comparison of network lifetime of proposed ECC-MAC protocol over existing 802.11 protocol for grid, random and triangle topologies. The result shows ECC-MAC performs well than 802.11 protocol for all topologies.

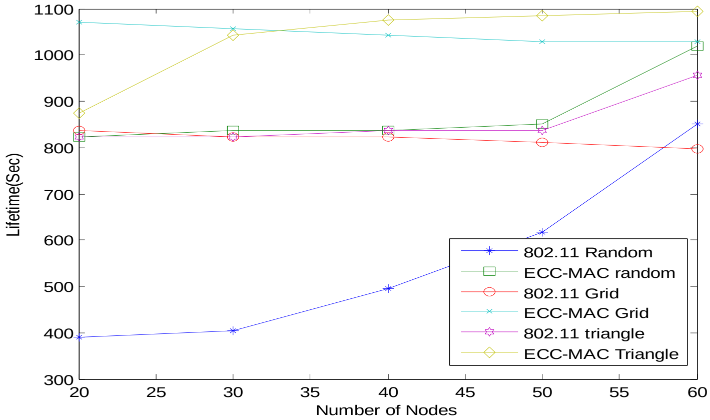

Fig. 6.4: Network Lifetime versus Number of nodes.

The network lifetime of ECC-MAC improves well for grid topology comparing to other topologies as shown in Fig. 6.5.

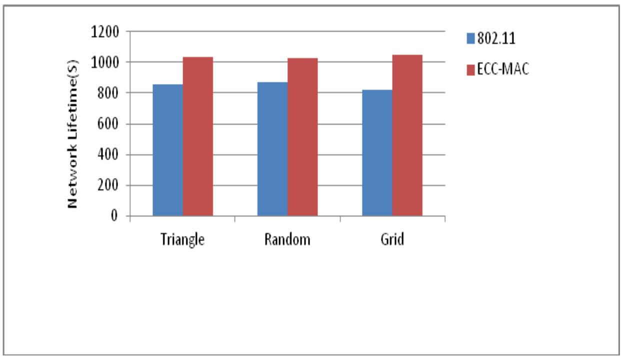

Fig. 6.5: Comparison of Network Lifetime for various topologies.

Fig. 6.6 shows the comparison of energy consumption of proposed ECC-MAC protocol over existing 802.11 protocol for grid, random and triangle topologies. The result shows ECC-MAC performs well than 802.11 protocol for all topologies. The network configured in triangle topology consumes less power than other topologies.

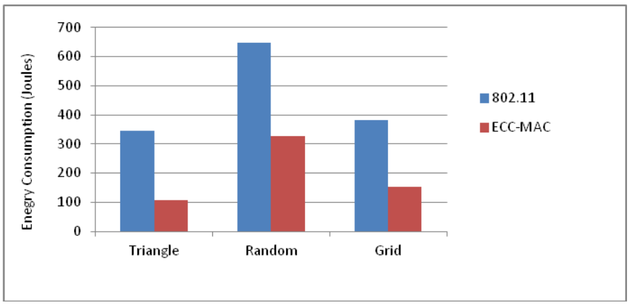

Fig. 6.6: Comparison of Energy consumption for various topologies.

Fig. 6.7 shows the comparison of throughput of proposed ECC-MAC protocol over existing 802.11 protocol for grid, random and triangle topologies. The result shows ECC-MAC performs well than 802.11 protocol for all topologies. The network configured in triangle topology has better through put comparing to other topologies.

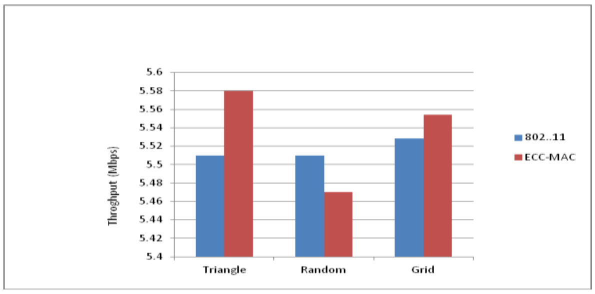

Fig. 6.7: Comparison of Throughput for various topologies.

Fig. 6.8 shows the comparison of end to end delay of proposed ECC-MAC protocol over existing 802.11 protocol for grid, random and triangle topologies. The result shows the delay increases for ECC-MAC comparing to 802.11 protocol for all topologies. This result is expected since the additional control frame overhead is required to coordinate the cooperative transmission. Besides, the back off used for choosing the best relay and the enlarged interference range by relaying also affect the delay negatively.

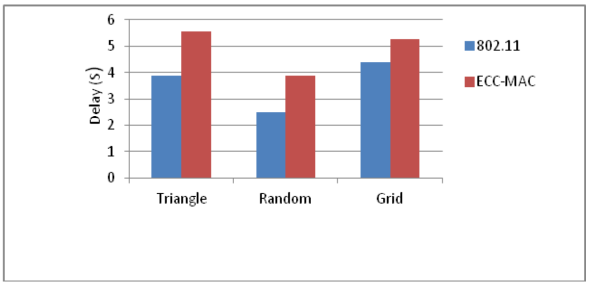

Fig. 6.8: Comparison of Delay for various topologies.

Conclusion:

In this paper, we proposed the design of a energy constrained cooperative MAC protocol protocol based on a cooperation framework which seeks to optimize the tradeoff between network throughput and network lifetime. The impact of various network topologies on the performance of MAC protocol is also discussed. The results are analyzed for random, grid and triangle network topologies. The simulation results show that the proposed protocol performs well comparing to existing IEEE 802.11 in terms of network lifetime, energy consumption and throughput with little increase in end to end delay.

As part of our future work, we will investigate our ECC-MAC for multirelay cooperation for larger scale network size and with high mobility. Also, we foresee a more suitable scenario for multi-relay cooperation in 802.11a/g networks which support a larger set of data rates than 802.11b.

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