Virtual Wired Transmission scheme using Directional antennas to improve Energy Efficiency in Wireless Mobile Ad-hoc Networks

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***Abstract*—Energy efficiency improvement methods can be applied at different layers of the network architecture for mobile ad-hoc networks. There have been many research efforts on improving the performance parameters at physical, data link, and network layers. The properties of directional antennas have been exploited for better energy efficiency. Some of the properties include simultaneous multiple transmissions, lower interference levels, optimum channel access, and low overhead. This paper proposes a virtual wired transmission scheme with MAC and physical cross layer protocol using directional antennas to improve the performance characteristics of the system. Energy efficiency is the main focus of this paper and results obtained from MATLAB simulations have demonstrated the proposed scheme to be energy efficient.**

***Index Terms*—Directional Antennas, Energy Efficiency, Medium Access Control and Virtual wired transmission.**

I. Introduction

Mobile Ad Hoc networks are networks with no fixed infrastructure or base stations or any wireline backbone network for communication. The mobile nodes use peer-to-peer packet transmissions and multihop routes to communicate with each other. The network topology is continuously changing due to frequent node movements. Routing and contention resolving in such an environment is a challenging task. A lot of research has been done in this field and many solutions have been provided with advanced algorithms for MAC (Medium Access Control) layer, network layer, and improvement of other network parameters such as capacity, interference reduction, energy efficiency, etc.

This paper proposes a MAC protocol based on the use of multiple directional antennas to improve the energy efficiency factor in wireless mobile ad hoc networks. The deployment of directional antenna in mobile networks has proven to be very successful in the improvement of channel capacity. On the other hand, implementation in mobile adhoc networks is quite challenging and complex. The first challenge is that the nodes in ad hoc networks will not have prior knowledge of its neighbor nodes, so it will be difficult to use the directional antenna. This issue is critical in a mobile ad hoc network, due to the limitations over size and cost of the infrastructure. The second challenge is the detection of the channel usage as the neighboring nodes can easily misjudge an ongoing transmission. In this paper, we present a MAC protocol based on a virtual wired transmission scheme to address the above challenges.

The unique nature of directional antenna can reduce several problems in ad hoc networks. When a node is transmitting in a particular direction a neighboring node can simultaneously transmit without interference. This capability improves the overall system capacity. When a node wants to transmit to a neighboring node it transmits only in the required direction, which improves the energy efficiency. Nodes equipped with omnidirectional antennas do not have this capability. Since the spatial channel use of directional antenna is limited, the interference factor also reduces. To support the inherent advantages of directional antennas, several changes are needed in the layered network protocol stack..

Replacing the omni directional antenna not only requires changes in the physical layer, but appropriate modifications need to be performed in the upper layers. The contention avoidance mechanism in the MAC layer has to be modified as the spatial channel used by directional antenna is less and directional information has to be stored. Also the direction of transmission has to be calculated by the MAC protocol, depending upon the final destination, which may modify the network layer also. The antenna system has to be controlled by each layer of the adhoc networking protocol stack appropriately.

This paper proposes a MAC protocol, which could drastically decrease the link breakages, improve throughput, capacity and decrease energy consumption.

The reduction in link breakages ensures that the end-to-end path is a strong communication link similar to that of wired nodes and this concept is termed as virtual wired transmission. It is observed that energy consumption evaluated over the end-to-end path is reduced when the proposed MAC protocol is used.

This paper exploits the use of directional antenna in a new approach, which could benefit a potential military application. It is very essential in battlefield communication that the system be a low power consuming, high capacity, and non-interfering network model. The rest of the paper is as follows. Section II contains the background and related work of the research, Section III contains the proposed model In this section, we also presents the details of the Antenna Model, Network Cross layer Model and Medium access control protocol. Section IV describes the Virtual wired transmission scheme. Section V shows the simulation results and finally in Section VI, we conclude.

II. BACKGROUND AND RELATED WORK

Significant research efforts exist in the literature focusing on improving the network performance characteristics such as capacity, throughput, latency, and interference reduction in mobile ad hoc networks using directional antennas. In [1-2][4-11] MAC protocols have been proposed to solve several problems in ad hoc networks with the use of directional antennas. In [3][4][9] the power consumption problem in wireless networks is addressed. In [5][6][8][10][11], MAC protocols to improve throughput of mobile ad-hoc networks using directional antennas are proposed.

Mineo Takai *et.al.* [1] proposed a new Directional Virtual Carrier Sensing (DVCS) mechanism that is implemented in the MAC layer. The basic idea is to use the directional antenna to increase the network capacity by alleviating the interference in shared channel. The following three capabilities are added to the IEEE 802.11 MAC Protocol for directional communication with DVCS: Caching of Angle of Arrival (AOA), Beam locking and unlocking, and the use of DNAV's (Directional Network Allocation Vectors). Each node caches the AOA when it hears from a neighboring node whether the signal is for itself or not. When a RTS is received from a neighbor it adjusts its beam pattern to maximize the receiving power and locks the CTS transmission in that direction. Similar to network allocation vectors in IEEE 802.11(a/b/g), directional network allocation vectors are used to cover a direction.

Unlike many algorithms using directional transmission and omni-directional reception the MAC layer algorithm proposed by Zhang [2][3] uses both directional transmission and reception. The protocol proposed in [2] offers four significant advantages: (1) It assumes directional transmission/reception, (2) It is distributed, thus relies on local information only, (3) It allocates slots to different links dynamically based on demand, (4) Power control is easily carried out during neighbor discovery, reservation, and data transmission period with very little overhead. In [2], a TDMA algorithm, neighbor discovery algorithm, directional transmission, and reception algorithm are proposed. Time is basically divided into three slots for neighbor discovery, reservation and data transmission. For every need of transmission timed slots are allotted for each of the steps neighbor discovery, reservation and transmission in an order. Both neighbor discovery and reservation algorithms proposed are three way handshake mechanisms. By transmitting the transmission power in the packet [3] the energy capabilities of the algorithm have also been exploited.

The power and energy metrics are discussed by Suresh Singh *et.al*. and a power aware MAC protocol PAMAS is introduced [4]. PAMAS provides the metrics to be followed in traditional routing protocol to achieve energy awareness in networks, thus achieving energy efficiency. Safwat *et.al*. [9] proposed a cross layer model with MAC information being passed to network layer to achieve energy efficiency. Two methods Energy Constrained Path Selection (ECPS) and Energy-Efficient Load Assignment (E2LA) are discussed which could be applied depending on the network conditions. E2LA assigns the load depending on the energy distribution of the network whereas ECPS follows the path having low energy cost.

A reservation based MAC protocol is proposed in [5] using directional antennas. The reservation based MAC protocol demonstrates increased throughput performance for directional antennas over omnidirectional antennas. Nasipuri *et.al*. [6] proposed another MAC protocol evaluating the throughput performance based on the contention avoidance capability of the protocol. Channel reservation is based upon the directional antenna information and knowledge of neighboring nodes. The RTS and CTS frames are sent over all the unblocked beams, which ensures that the neighbors have the knowledge of the ongoing reservation, leading to no interference in that channel. Romit Roy Choudhury *et.al*. [11] proposed two Directional MAC (DMAC) protocol schemes. One scheme uses only directional RTS (DRTS) packets while the second uses both Omnidirectional RTS as well as Directional RTS packets. The simulation results show that the DMAC schemes perform better than the IEEE 802.11 MAC. A real time testbed utilizing directional antennas in ad-Hoc networks (UDAAN)[8] with a complete system solution has been proposed by Ramanathan et.al.

It is clear from the above research efforts that directional antennas provide better performance characteristics than omni antenna. Several other performance parameters have also been addressed in the papers using directional antennas. The energy consumption problem has been dealt well in [3] but the paper still lacks performance when compared to virtual wired transmission concept proposed in the current paper. The current paper introduces the concept of virtual wired transmission and proposes a MAC protocol using a directional antenna model.

III. THE PROPOSED MODEL

A. Antenna Model

In this section, a theoretical antenna model is attributed to each node in the network model. Multiple directional antennas are used so that all the directional antennas can constitute an omni directional antenna. It is assumed that the radiation pattern of the directional antenna has a major lobe for beamforming and has no side lobes having a significant power level. The wireless nodes are equipped with multiple limited steerable directional antennas and variable transmitting power control.

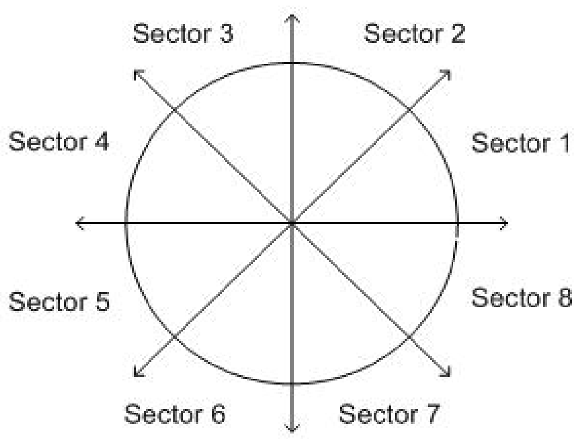


Fig. 1 illustrates a node having eight directional antennas

Fig. 1 illustrates a node having eight directional antennas where space is divided into eight sectors each of angular width 45 degrees. Apart from the spatial division it is also important to assume that each directional antenna has variable range of transmission that can be controlled by the MAC layer. For example, if a node is far away from the transmitting node then the transmitting node increases its antenna range and if the node is close to the transmitting node then the antenna range is decreased by lowering the power, thereby reducing the energy consumption. It is also to be noted that limited steerable antennas are used so that maximum energy gain could be achieved during beamforming and beamlocking. When a node moves in a circular path around a transmitting node it is bound to change its transmitting directional antenna as the node moves from sector to sector. But the high signal level can be maintained by steering the beam to a limited angle until it can hand over the transmission to the adjacent antenna with high signal level as well.

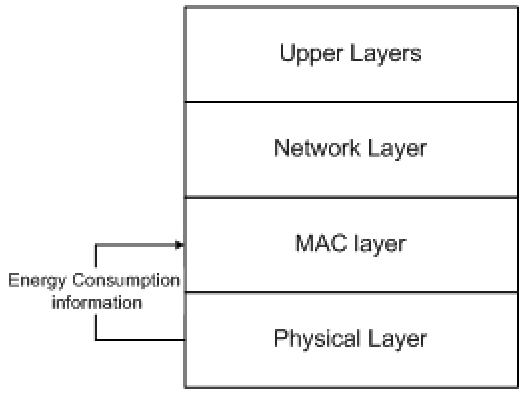


Fig. 2 The proposed Cross layer Model showing the proposal of sending energy consumption information from physical to MAC layer.

B. Network Cross Layer Model

In this section, we describe the cross layer model involving the MAC and physical layers. The proposed cross layer model considers improving the energy efficiency by sending energy consumption information from PHY layer to MAC layer. Energy consumption is determined by the received power at the receiving antenna, which is included in the packet and sent to the MAC layer. Using the energy information the MAC layer judges and identifies the strongest link, which has the least probability to leave the range of the transmitting node. The strongest link indicates a link with the least energy consumed and least influenced by contention. The MAC layer has to choose the path depending on the energy consumption of the links. Thus, the MAC layer proposes the transmission power of the directional antennas of each node. Since the MAC layer chooses the strongest link, it not only establishes a strong link (which is generally the link nearest to the destination node) but also causes a reduction in the channel space usage. When the spatial usage is very low there is less influence or interference due to the neighboring nodes. The capacity of the system is bound to improve as simultaneous transmissions or receptions can be possible if the receiving or transmitting circuitry supports the facility. Fig. 2 shows an illustration of the proposed cross layer model. In the proposed model, the PHY layer sends the frame and the energy consumption information to the MAC layer.

C. Medium Access Control protocol

In this section, we present the details of the proposed MAC layer protocol. The nodes in the network initially do not have any information of its neighboring nodes.

However, a node communicates with its neighbor only when it is involved in sending or receiving information. So, it is important to have a identification number for each node, i.e. Network Identification Number (NIN) and a Antenna Identification Number (AIN). The main functionalities of a MAC protocol are as follows: neighbor discovery, channel reservation, and data transmission.

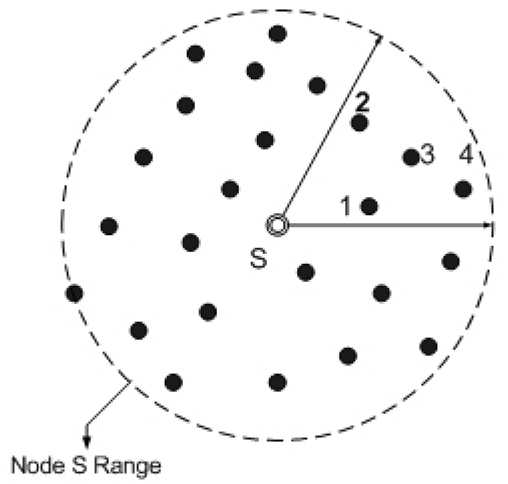


Fig. 3 An example network to show the order of mode selection (transmission or reception) during neighbor discovery process.

The neighbor discovery procedure is one of the key aspects when directional antennas are used since the direction information of neighboring nodes has to be stored. This protocol varies from other protocols as neighbor discovery is done only when there is a need for transmission. The conventional three-way handshake mechanism is used with energy information transmitted in the control packets during the neighbor discovery procedure. The nodes participating in the handshake mechanism mutually obtain the transmitting power to be used for transmitting packets to each other.

An important aspect before discussing the neighbor discovery procedure is to know the mode selection of the nodes. Nodes could either be in transmitting mode, receiving mode, or idle mode. When many neighboring nodes receive an advertising packet from a transmitting node, all the receiving nodes cannot transmit the advertising packets at once since the packets will collide. The solution for this is to wait for some duration of time (Time to wait) depending upon the received power at the antenna. For example in Fig. 3 if four nodes receive a advertising packet then the time to wait for discovering their neighbors will depend upon the received power for each node. Following is the order in which the nodes will transmit: Node1, Node2, Node3, and Node 4. Contention is resolved by avoiding the collision among the neighbors during neighbor discovery procedure by a hierarchical process. The hierarchical process of neighbor discovery process helps the nodes to be in complementary modes of transmitting and receiving during communication. The neighbor discovery procedure is as follows:

- MAC layer of the transmitting node first senses if the channel is idle.
- Hand-shake step1: A node (Node 1) intending to transmit sends an advertising control packet in all directions with its NIN and AIN.
- Hand-Shake step2: When a neighboring node (Node 2) receives the control packet, it sends back the acknowledging control packet which contains NIN and AIN of node 2 and the energy received at receiver antenna E_{R1}, back to node 1.
- The sender's antenna receives the acknowledgement which sends the energy information E_{R1} in the packet to the MAC layer. The physical layer calculates the received energy of the acknowledgement packet E_{R2} and sends it to the MAC layer.
- MAC layer of node 1 then calculates the recommended energy of transmission to the node 2.
- Hand-Shake step3: Node 1 sends another packet with E_{R2} to node 2.
- MAC layer of node 2 then calculates the recommended energy for transmission to node 1.

However, it has to be added to the procedure that if the current transmitting node is an intermediate node (one which did not initiate the discovery process), it calculates Time to wait (T_{wait}) depending on the received power and starts discovery after T_{wait}.

The next step of the MAC layer is to make channel reservations. Channel reservation implies that there will be no interference between the communication of two nodes during the reservation time. This requires that the neighboring nodes be aware of the ongoing communication so that it does not transmit any message in that direction during that time. It is also reliable to monitor the energy by sending the energy information periodically during the reservation time. The procedure for making reservation is a three-way handshake process based on a similar process in the neighbor discovery procedure. The channel reservation procedure works as follows:

- The channel is first sensed and if it is idle node 1 sends a reservation request packet with the reservation time, NIN and AIN included in the packet
- Node 2 receives the packet and either accepts or rejects the reservation request. If it accepts the reservation request it sends back an ACK accepting the request with the E_{R1}, NIN and AIN attached.
- Node 1 then calculates the recommended power to transmit and sends back another ACK back to node 2 with E_{R2} included in the packet and sends another announcement packet to all its neighbors with its AIN, NIN, reservation time and energy of

transmission (E_{T1}) to all its neighbors announcing the transmission.

- Node 2 receives the confirmation from node 1 and it also transmits to all its neighbors the reservation time, NIN to all its neighbors so that its neighbors are aware of the communication.

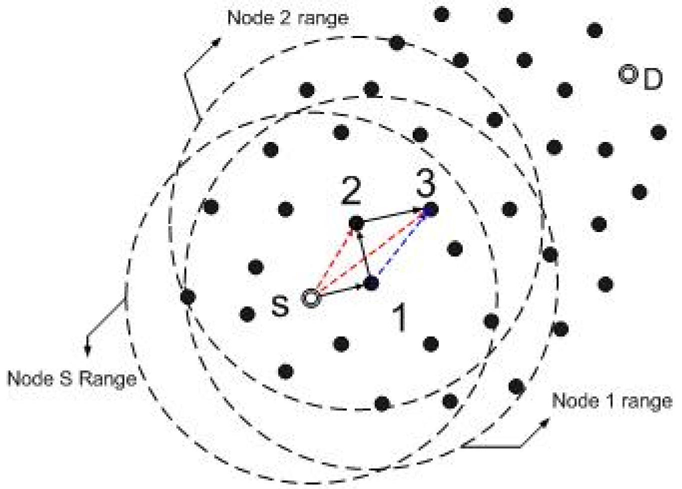


Fig. 4. Node S transmits to node 1 instead of node 2 or node 3, as node 1 is the strongest link. The path is also established using this concept.

Another important functionality of the MAC layer focused in this paper is to decide and choose the next hop among its neighbors. This aspect of MAC layer combined with advantages of variable range directional antenna transmission has also been exploited to achieve energy efficiency. Considering the scenario in Fig.4, node S is the source and node D is the final destination, nodes 1, 2, 3 are the intermediate nodes and the circles show the ranges of nodes S, 1, and 2. If node S is to transmit the message to node D, it will have a choice to transmit the message to nodes 1 or 2 or 3 but the current MAC protocol suggests choosing the strongest link, which will be node 1. Similarly node 1 chooses to transmit to node 2 instead of node 3. This concept is one of the main requirements for the proposed protocol.

IV. VIRTUAL WIRED TRANSMISSION SCHEME

In this section, we describe the details of the Virtual Wired Transmission scheme. As mentioned earlier the directional antennas are capable of transmitting with variable power, which is the major necessity of exploiting the advantages in this scheme. The MAC layer identifies the strongest neighboring link that is closest to the destination and chooses it as the next hop for transmitting the message. As the transmitting distance decreases, the spatial coverage area or the range of the coverage decreases. When the directional gain of the antenna is very high it is possible to transmit the signal at a very narrow bandwidth, which occupies very low area. For global evaluation of the routes, each hop occupies fewer channels and the transmission seems like a wired transmission. The influence of interference is very low and simultaneous transmissions and receptions can be done in different directions. This is called virtual wired transmission as the transmission for the whole path does not interfere with the neighboring nodes and the wireless path is similar to a wired path.

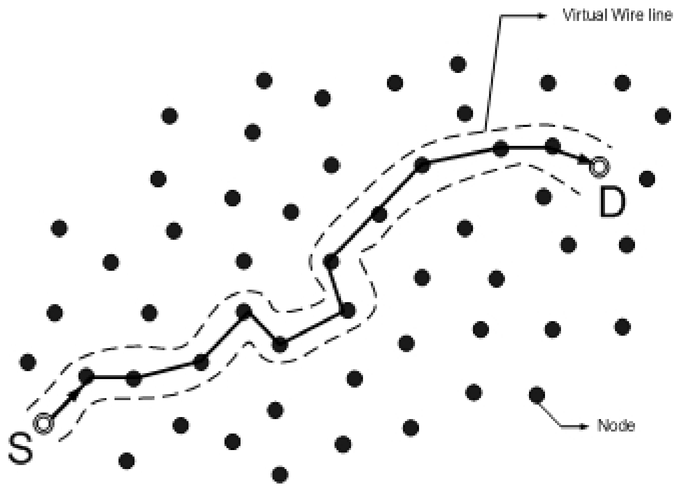


Fig. 5 Illustration of Virtual Wired Transmission Scheme

Apart from the better energy efficiency, implementing this scheme could significantly improve the capacity of the system. Fig. 5 illustrates the virtual wired transmission scheme. Node S is transmitting to node D through multiple hops by selects the strongest link in each hop. The dotted lines indicate that the channel usage is very limited. Since the strongest link is used in each hop, there is a least probability of link breakage in the path and hence a strong connection exists between source and destination. The resultant end-to-end path is similar to a wired connection. Since the number of hops is bound to increase, energy efficiency is not obvious and might still be a question. But the simulation results show that the scheme is also more energy efficient.

V. SIMULATION AND RESULTS

The simulation model considers the topology size as 500 square units containing several nodes with 8 directional antennas. The range of directional antenna is considered to be 60 units. It is proposed in the protocol that the strongest link is always selected as the next hop, but in the case of the simulation, the strongest link will be the nearest link to the source and also close to destination. We compare our approach with the farthest link selection method, where the farthest point in the range of transmitting antenna is chosen for every next hop. Energy consumption ratios for both methods are compared and plotted for different node densities. The energy consumption in a network is the summation of five components E_{TR} (energy of transmission), E_{RC} (energy of reception), E_{IDLE} (energy consumed during IDLE state), E_{SENSE} (energy consumed for sensing) and E_{DROP} (energy spent in dropping packets). The terms E_{SENSE}, E_{IDLE}, E_{DROP} are ignored, as more than 80% of the network's energy consumption is due to E_{TR} and E_{RC}. However, the proposed method indicates that the E_{SENSE}, E_{IDLE} and E_{DROP} would be low when compared to other methods of transmission because the spatial usage is minimum along the path. The interaction between two antennas in far field is given by Friss transmission equation as given below

$$P_t = \frac{P_r (4\pi)^2 r^2}{G_t G_r \lambda} \quad (1)$$

where P_r is the minimum receiving threshold power of the receiving antenna, P_t is the transmission power of transmitting antenna, λ is the wavelength of transmission, r is the distance between the transmitting and receiving antenna, G_t and G_r are the transmitting and receiving antenna gains.

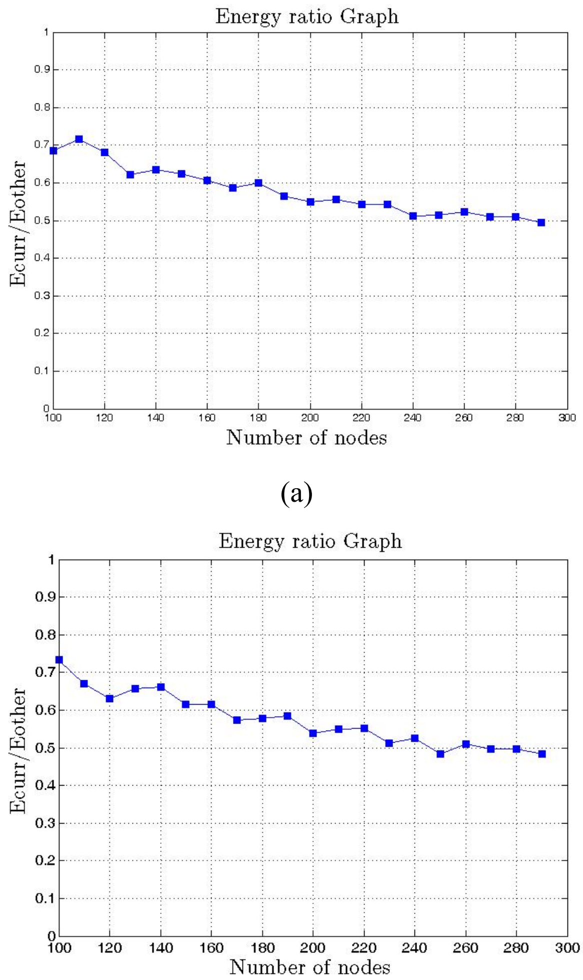
The ratio of energy consumption for our approach and the farthest link selection method is given by :

$$\frac{P_{t_1}}{P_{t_2}} = \frac{r_1^2}{r_2^2} \quad (2)$$

where P_{t_1} and r_1 are the parameters of the antenna in the proposed method, P_{t_2} and r_2 are the parameters of the antenna in the farthest reach method It can be observed that except for the distances and transmission power all the other parameters are the same for both methods as both use directional antennas with variable transmission power control.

The simulation evaluates the path in MATLAB for both methods for each run of the simulation step and calculates the energy ratio depending on equation 2. Fig. 6 shows the plot containing the energy ratio of the proposed method selecting the strongest link and farthest link selection method selecting the farthest node in its range. Ratio of energy consumption has been noted for various densities of nodes ranging from 100 nodes to 300 nodes. Several simulations are executed with random placements and movements of these nodes and the Energy ratio varied from 0.75 to 0.45 for 100 to 300 nodes. Figure 6.a and figure 6.b show the results for two runs of the simulation.

As illustrated by Fig. 6(a &b), the energy efficiency improves when the number of nodes increase and it can also be derived that the energy usage of the proposed method is lower than the other method.



(a)

(b)

Fig. 6(a)&(b) Energy Ratio Graphs for two simulation runs. X-axis is the number of nodes and Y-axis is the Energy Ratio.

VI. CONCLUSION

In this paper, another key function of MAC layer is exploited so that power consumption reduces and also the complete MAC protocol has been discussed in detail. A new term Virtual wired transmission has been introduced and explained in detail. Simulations are done to evaluate energy consumption for the complete route to compare the current protocol with earlier methods of next hop selection. The simulations show that the proposed protocol definitely improves the energy efficiency of the adhoc network. Practical implementation parameters such as type of antenna, size of equipment, cost of implementation has not been considered in this paper. Further work can include the evaluation of other network parameters and also the practical scope. Implementation of the proposed protocol could be a successful military application as low energy consumption is of vitality in battlefield communications.

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