A Power Efficient MAC Protocol for Wireless Ad hoc Networks that uses Directional Antennas

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Abstract—In this paper we address the issue of designing an adaptive power aware MAC layer protocol for multi hop ad-hoc networks which comprises of wireless nodes that are equipped with directional antennas instead of the traditional omni-directional ones. The fact that nodes have the ability to transmit directionally facilitates spatial reuse and optimises the use of transmission power. Our MAC layer protocol focuses primarily on power optimization in such multihop ad hoc networks. It does this in two different ways-(a) by adaptively optimizing the transmission power of a node such that unnecessary interference between parallel transmissions are eradicated yet network connectivity is maintained. We achieve the above task by implementing a local algorithm for constructing a one-parameter family of θ graphs, where each node increases its power until it has a neighbour in every θ sector around it. We show that it is possible to use such local geometric θ -constraint to ensure full network connectivity, (b) by putting a node to "sleep" when it is not transmitting, receiving or routing data. This local decision again yields a connected, capacity-preserving, global topology. We evaluate the performance of our protocol with that of the classical versions of 802.11on the network simulator called NS-2. Our protocol shows significant improvements in throughput, power conservation and network life time when compared to standard 802.11.

Keywords: Ad hoc networks, power conservation, sleep, graph theory, directional antenna

I. Introduction

A wireless ad hoc network is a self-configuring network composed of a set of battery powered wireless nodes without any centralized administration. An approach to reduce energy consumption in such batter powered devices is extremely crucial to prolong the system life time. Studies [1] have shown that the wireless network interface is a node's single largest consumer of power and a wireless device which is capable of being in active (i.e. transmitting or receiving data), idle (i.e. neither transmitting nor receiving but actively sensing the channel) or sleep state (i.e. the transmitting, receiving and channel sensing circuitries are all turned "off") consume considerably less power while in sleep state than being in the idle state during its non communication phases. Thus intuitively it would appear to "put" a node to sleep during its non-communication phase. However it should be noted that the low power state has a corresponding high energy cost to revert back to the active state [1]. Thus for a wireless node it might not be economical to transit to the sleep state during every period of inactivity.

Moreover, rampant and random sleeping reduces number of relay nodes in the network which hampers multi-hop data transfer and disrupts the construction of an optimal topology in the network. Thus, we propose a scheme which "selects" nodes to remain in the "awake" state such that network connectivity is maintained, total capacity of the original network (i.e when all nodes are in the awake state) is not compromised upon and packets are forwarded between the source and destination nodes with minimal delay. Thus the fundamental challenge is determining how to ensure global connectivity using minimal network power i.e. keeping just the required number of nodes awake AND having the awake nodes transmit in the "right" direction with the "right" amount of power, even when location of nodes and their linkages can change over time. To solve this problem, we study a distributed and local construction for building up communication edges between initially isolated nodes located on a two-dimensional plane, which is referred to as a θ graph.

The rest of the paper is organised as follows: Section II describes our proposed scheme. Section III elaborates on the simulation set-up. In section IV, we present our results and analyse the results. We conclude the paper in Section V.

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II. Our Protocol

In this section we describe the various aspects of our protocol. We first start out with a brief description of our antenna model. We then follow it with a schematic description of how our topology control protocol works. We next prove the validity of our protocol using a result from graph theory and finally we discuss the salient features of our MAC layer scheme which facilitates periodic "sleeping".

A. *Antenna Model*

We use directional antennas instead of omni-directional ones in our study. This is because we wanted to leverage the benefits of directional antenna over their omni counterparts. Specifically, directional antennas provide us with the facility to focus the transmission energy in the intended direction and consequently improve spatial reuse. Moreover, the direction specificity entails longer transmission range when using the same power as omni-directional antennas [3] as outlined in equation (1). Let us assume that the transmission range of directional antenna is r_d, and that of Omni-antenna is r_o. If the beamwidth of directional antenna is α and if both the Omni-directional antenna and directional antenna have the same transmit power then we can say that [5]:

$$r_d/r_o = \frac{2}{\tan\left(\frac{\alpha}{2}\right)} \quad (1)$$

We assume that each node has n directional antennas with beamwidth α, such that $n\alpha = 360$ degrees. These antennas are connected to the radio interface via a switching logic. In the "Listen"(channel sensing) state the radio interface listens on all antennas i.e. the signals are simply added up before they reach the radio. In the "Transmit" state the radio chooses an appropriate antenna to transmit and turns off the other antennas. In the "Receive" state, only one antenna is typically used. The above task can be accomplished by monitoring the signal power incident on all antennas using the switching logic. A particular antenna is kept active (and the rest of the antennas are turned off) only when that particular antenna's power is more than the receiver's threshold of the radio interface on any of the antenna. The above technique reduces probability of collisions due to different packet receptions on different antennas that are overlapped in time.

B. *Minimum Power Distributed Topology Control Algorithm*

We consider a set of $\boldsymbol{V}$ nodes distributed randomly in a two-dimensional space. We begin from the isolated nodes and consider an algorithm for establishing links (edges) E, and building a graph G_θ very similar to the one described in [5]. Our algorithm requires the directional information of a node which it gets from the directional antennas as described in the "Antenna Model" section. Alternatively, this information could also have been gathered from a GPS module installed in the nodes.

Each initially isolated node embarks on a process of discovering its neighbouring nodes. It begins by broadcasting a connection request at low power and then ramping up its power (till it reaches its maximum power) until its neighbourhood satisfies a local geometric constraint (which we discuss shortly). If acknowledgements to these requests are received, then a communication link (edge) is established with the neighbouring node. With each new connection made, the geometric information is assessed. In general, at each step, we consider the vectors drawn originating from a node and ending at its say p neighbours. These vectors divide the area around the central node into p disjoint sectors. If the angle of each sector is less than θ, the constraint is satisfied and the node sets its operating power at the current value. If any angle is greater than or equal to θ, the construction continues. If a node reaches its maximum operating power before satisfying the constraint, it halts execution and lowers its power back down to the level where the last new connection to a neighbour was first made (or to zero if no neighbours were discovered in its broadcast range). This summarizes the adaptive power control algorithm that we use in our MAC protocol. The case $\theta=\pi$ was introduced in [5].

Each node can thus locally determine the point where it satisfies the θ-constraint and communicate the information to the rest of the network. If some nodes cannot satisfy the θ-constraint, then G_θ is a sub-graph of the maximum power graph. It can be shown that if each node has sufficient power to satisfy the θ-constraint, then connectivity in G_θ is guaranteed [5].

Each node c sets its operating range r_c independently of all other nodes in the network, giving rise to unidirectional links. However, realistically, we want G_θ to be a bi-directional graph. We achieve this during the graph construction time as follows: When node c broadcasts an acknowledgement to a connection request from node j it must create a link to node j even if the length of that link exceeds r_c. Node c would transmit with range r_c. at all times, except when it needs to send a transmission directly to node j. We achieve this by maintaining an internal table of connected neighbours at each node and corresponding broadcast ranges. We refer to the underlying undirected graph as G_θ.

The next step of our MAC protocol is to run a shortest path finding algorithm, namely the Dijkstra's algorithm [4] to find the "best" path from the source to the destination node. We quantify "best" in terms of the minimum transmission power required to reach the destination node. If the destination node is within the neighbourhood of the source node (as would be evident from our above mentioned topology control scheme), then the transmission would be a 1-hop transmission without the requirement of any relay nodes. Otherwise, intermediate relay nodes will be required.

For each node required for the transmission, a signal strength analysis on all the sectors of the antenna for that particular node is executed. The sector which has the highest signal strength is kept active while the others are nullified. Thus, the transmission direction is governed using the switching logic of the antenna as explained in the "Antenna Model" sub-section of this paper.

The nodes that are not transmitting, receiving or relaying data are then put into "sleep" mode for a pre-determined period of time. This helps minimize power consumption at these nodes. We address salient features of the "sleep" mechanism in a following sub-section. Finally, data is transmitted directionally by the transmitting node either in a single hop or via one or several intermediate nodes as outlined by the minimum power routing algorithm (Dijkstra's algorithm). The major functionalities of our protocol are neighbour discovery by a node, constructing a connected topology based on minimum transmission power, deciding on the direction of transmission (the selection of the right antenna sector), putting the non-functional nodes to "sleep" and finally directional data transmission using minimum power (i.e exactly the power required to reach the neighbouring node).

C. *Network Connectivity Criteria*

The local geometric constraint that we mentioned in the previous sub-section is sufficient to ensure network connectivity [5]. The result applies to finite size systems though special consideration has to be paid for boundary nodes. We define "boundary nodes" as the nodes that lie on the boundary of the imaginary circle drawn from node j with radius r_j where r_j is the operating range of node j. The group of boundary nodes on the convex hull of the network is referred to as $\boldsymbol{B}$. Two nodes are adjacent in $\boldsymbol{B}$ if they are neighbours in the description of the convex hull, regardless of the distance between them. All other nodes are called interior nodes. We consider a family of boundary constraints in $\boldsymbol{B}$ and in general, the more restrictive the boundary constraints, the lesser the restrictions that need to be imposed on the transmitting nodes radio range to guarantee connectivity [5].

If the boundary nodes are identified as such as we know that they are all connected, then for $\theta < \pi$ the θ-constraint on all the internal nodes is sufficient to ensure global connectivity. This observation and other conditions with less restrictive assumptions about the boundary node which still leads to global connectivity in the network can be found in [5]. In our protocol we abide by those guidelines. However, below, we enumerate the simplest case for network connectivity assurance. Greater details of the proof below can be found in [5].

D. *"Slep" Facilitating Features of Our MAC Protocol*

The algorithm described above that is used to generate the G_θ graph is integrated within our protocol. Along with it, our protocol also has provision for nodes to "sleep" during their period of inactivity. Inspired by PAMAS [2], our MAC layer protocol sets the radio to sleep during transmission of other nodes. Once the decision on the routing backbone has been made by the network, the nodes that do not participate in the data transfer process are put to sleep by their respective MAC. The period of time for which the node will transition to the sleep state will depend on the duration of the message exchange. Our protocol uses the CSMA/CA channel access scheme with RTS/CTS/DATA/ACK packet exchange methodology. Nodes within the radio range of a transmitting and receiving node will overhear the duration of data exchange in the RTS/CTS packet exchanges that will happen between the sender and the receiver node before the actual data transfer can take place. If a node does not hear a RTS/CTS packet (which indicates that it is not geographically close to any node that wants to initiate a communication), it concludes that no node wants to communicate with it in the near future and thus enters a "sleep" state for a "short" period of time. Note that this "sleep" duration can be a randomly chosen variable. However, we choose this duration based on the recent history of the node. We pick the smallest duration for which the node has slept in the recent past. This entails building a "memory" into the node but we observe that retaining this data adds negligible overhead. Also note that our scheme does not require tight time synchronisation between nodes. Each node follows a "listen" – "sleep" a-periodic cycle. Nodes are free to choose their listen/sleep schedules. Also, since the listen duration is significantly longer than clock-error or drift, tight synchronization amongst nodes is not required. For example, the listen duration of 0.5s is more than 10^5 times longer than the typical clock drift [4]. A node goes to sleep only when it realises that it is not a part of the network backbone carrying data. Hence the listen-sleep cycle is a-periodic. When a node does go to sleep, it broadcasts that information in a very small SYNC packet as in S-MAC protocol in [4] to its neighbouring node. We chose to do this transmission such that if a node is required to act as a relay node or happens to be a destination node for a particular data transmission during its sleep period then the information that this node still exists but is in the "sleep" state temporarily, is available in the network. Otherwise, we run the risk of other nodes in the network assuming it to be a non-existent node which has left the network.

III. Simulation Set-up

We perform extensive simulation on the network simulator platform – NS2 [7] to quantify the utility and gains earned by our MAC protocol in contrast to the classical standard 802.11 protocol for WLANs. We created a network with 100 wireless ad-hoc mobile nodes placed randomly in a square area. We manipulate node density by changing the area in which these 100 nodes are scattered. We vary this area between 100square meters (to simulate a dense network) and 1000 square meters (to simulate a sparse network). Mobility is generated amongst the nodes using a random mobility generator supplied in NS2. The routing protocol used to route packets from one node to another is the Dynamic State Routing (DSR) [6] though the shortest path is detected using the Dijkstra's algorithm. Constant bit rate (CBR) traffic is generated with a packet size of 512 bytes. We vary the inter arrival packet duration from 1 second to 10 seconds in order to simulate various traffic loads on the network. Each simulation is run for a period of 1000 seconds. The simulation results that we showcase in this paper are results that have been averaged over 100 such runs. Every node is equipped with 1000 joules of energy at the onset of the simulation.

A. *MAC Considerations*

We have used a modified S-MAC [4] scheme as our medium access control mechanism. The major modification that we made to the S-MAC protocol was that the periodicity of the sleep-listen cycle of the nodes was altered. As stated in the previous section, in our MAC protocol, nodes do not periodically undergo the "sleep" state. They only transit to the "sleep" state only when the decision on them not being a part of the routing backbone is made (and of course they are neither the transmitting nor the receiving node). We ran the modified S-MAC on top of the 802.11 DSSS Physical layer using the two-ray model for modelling our propagation path loss.

B. *Power Scheme*

The simulation was performed on a radio interface that simulates the 914MHz Lucent Wave LAN DSSS radio. We use two different models to account for the short distance and long distance free space propagation. For a "short" distance transmission, we use the free space propagation model while for the "long" distance transmission we use the asymptotic (small reflection angle) form of the two-ray (flat-earth) model. We define "short" distance as the distance that can be reached by a node without a relay node, i.e. a one-hop distance away. We define "long" transmission range as the physical distance that cannot be covered in a single hop but will require relay nodes. We use the following algorithm to change the transmission power adaptively. We use the following power equation to estimate the power of the signal at the receiver [4].

$$\mathbf{P_r} = P_t * G_t * G_r * \frac{\left(1/path_{loss}\right)}{L} \tag{2}$$

where P_r represents the received power of the signal at the receiver, P_t denotes the transmitted power, G_t represents the transmitter's antenna gain and G_r represents the receiver's antenna gain. L represents various system losses (like antenna cable, building penetration, orientation, etc.). Note that L is independent of the path loss model used.

For the free space propagation model, the path loss equation that we use is :

$$Path\ loss = \left(4\pi\frac{d}{\lambda}\right)^2 \tag{3}$$

and for the two ray propagation model, the path loss equation that we use is as follows:

$$Path\ loss = \frac{d^4}{(h_t * h_r)^2} \tag{4}$$

where d denotes the distance between the sender and the receiver, h_t denotes the height of the transmitter's antenna and h_r denotes the height of the receiver's antenna. Equating the two path loss equations gives us the "crossover distance" as:

$$Crossover\ Distance = {4\pi h_t h_r}/{\lambda} \tag{5}$$

Qualitatively speaking, the cross-over distance signifies the distance travelled by the signal in direct and reflected mode between the source and destination.

Our algorithm first checks the propagation model that would be applicable to a particular transmission. If the two-ray ground model is applicable for the transmission, then the algorithm next calculates the crossover distance using equation (5). If the transmission range is less than or equal to the crossover distance, then the algorithm uses the free space short distance communication and the transmission power of the sender is calculated as follows:

$$P_t = \frac{\{Rx_t(4\pi R)^2\}}{(\lambda^2 G_t G_r)} \tag{5}$$

Otherwise, two ray ground communication is used with the transmission power of the sender calculated as follows:

$$P_t = \frac{\{Rx_t(R)^4\}}{(h_t h_r)^2} \tag{6}$$

where Rx_t denotes the receiver's threshold power, λ is the wavelength of the signal and R the transmission range of the antenna.

C. Antenna Model:

A node is equipped with six sector antennas that transmit directionally, each with a beam width of 60 degrees thus covering the 360 degree plane. The transmission range is 250 meters. As described in Section II, these antennas are connected to the radio interface via a switching logic. In the "listen" state the radio interface listens on all six sector antennas i.e. the signals are simply added up before they reach the radio. In the "transmit" state the radio chooses an appropriate antenna to transmit and turns off the rest of the antennas. In the "receiving" state, only one antenna is typically used. An antenna element is kept active and the rest of the antenna elements are turned off only when that particular antenna power is more than the receiver threshold of the radio interface on any of the antenna. The above technique also reduces the probability of collisions due to different packet receptions on different antennas that are overlapped in time. Directional transmission of data not only increases the overall network capacity but also helps for the higher spatial reuse of the network. Use of directional antennas in place of Omni-directional antennas drastically increases the overall network lifetime of the network due to the low interface and effective use of energy in the intended direction and curtailing its waste in the unintended directions. We also compared the energy consumption of our algorithm with the conventional wireless protocols under different conditions using various traffic loads. These results are documented in the next section.

IV. Performance Analysis

In this section we present a detailed analysis of our simulation results. The performance metrics we use to compare the performance of our algorithm against 802.11 are namely – network throughput, the power consumption of the network and packet delay.

A. Network "Throughput"

Figure 1 depicts the "throughput" comparison between our scheme and that of the standard 802.11.We define "throughput" as the average amount of data that successfully reached the final destination in unit time. The X-axis denotes simulation time in seconds while the Y-axis denotes the average amount of data that successfully reached the final destination in unit time. The scale we use to denote "throughput" is Kilobits-per-second (Kbps). The simulation scenario (for this particular result) comprised of 100 wireless nodes randomly dispersed over a 100 sq-meter area – thus simulating a dense topology. There were at least 10 pairs of transmitting and receiving nodes at all points in time during the entire simulation for both schemes (802.11 and ours). We sometimes had as many as 30 transmitting nodes. The results in Figure 1 depict throughput values averaged over 10 simulation runs. As we can see, our scheme shows as much as 50% increase in the amount of successful data transmission. This is because, the topology that we create and the transmission power that our MAC protocol chooses to carry out a transmission is low enough to see the transmission through yet eradicate unnecessary interference to neighboring simultaneous transmissions. The directional transmission (instead of the omni transmission as in the case of 802.11) also facilitates curbing interference and promoting successful parallel transmissions. This leads to the higher number of successful transmissions in our scheme when compared to the 802.11 scheme. In the 802.11 scheme, though the same number of packets (hence Kilo-bits) were transmitted by the transmitter as in the simulations with our scheme, very few of them actually made it to the intended receiver. Signal interference caused data bits to be garbled resulting in unsuccessful transmissions leading to significantly low "throughput" values. Omni-transmission without any power control on the transmitted signal caused interference with neighboring parallel transmissions which proved detrimental to the "throughput" value of the network.

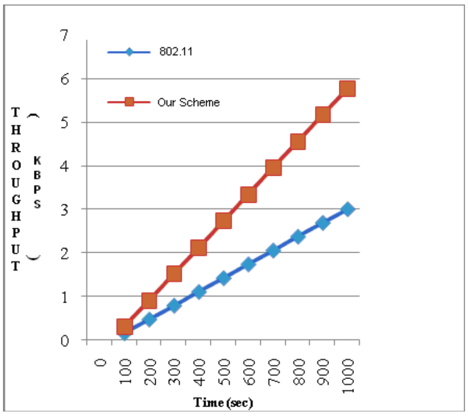

Figure 1: Throughput comparison of our scheme with 802.11

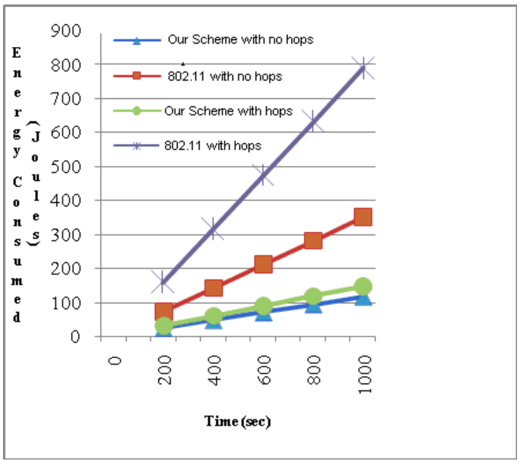

Figure 2: Overall Energy Consumption of our schema versus 802.11

C. Network Energy Consumption

Figure 2 compares the overall energy consumption of the network during a period of 1000 seconds of simulation time. The X-axis represents simulation time in seconds while the Y-axis represents energy consumption in joules. We showcase energy consumption of the network when all transmissions are carried out on a single hop and on a multi hop basis. In single hop communication the transmitting node can ramp up its power to reach the destination node directly without requiring any relay nodes to carry its data to the receiving node. In such a scenario, in a network comprising of 10 transmitting nodes and 10 receiving nodes the energy consumption in our scheme is as low as 52% less than that of 802.11's. This tremendously low energy consumption in our scheme is attributed to several facts: (a) Our scheme puts the "non-receiving" and "non-transmitting" nodes to "sleep" whereas in 802.11 such nodes are left in an "idle" mode. [1] has documented that there is almost a 80% saving in energy consumption when a node switches from an "idle" state to a "sleep" state. (b)In our scheme, nodes transmit with a power that has been carefully chosen so as to be just sufficient to reach the receiver node. Thus unnecessary power usage is banned. Moreover a directional transmission focuses power exactly in the direction of the receiving node and prevents unnecessary power dissipation and loss in unwanted directions.

When we consider the scenario where nodes require multiple hops to reach the destination node, i.e relay nodes are required to carry the data from the sender to the receiver, we notice the same trend. Our MAC scheme generates as much as 75% energy savings in comparison to the 802.11 scheme. In addition to reasons (a) and (b) as explained in the previous paragraph, we also account for the fact that in a multihop scenario a node equipped with directional antenna requires less number of relay nodes to reach the destination node when compared to a node equipped with omni directional antenna. This is owing to the longer transmission range that is inherent of directional antennas. Thus the number of relay nodes that need to stay awake to transfer data between a sender and receiver situated "*d*" distance apart using directional antenna can be much less than the number of nodes required to relay the same message between the same sender-receiver pair located the same "*d*' distance apart when using omni-directional antenna. The presence of relay nodes does hike up the total power consumption of the network in both cases when compared to the single hop scenario. However, it is to be noted that the increase is very less in our scheme (at most 14%) as compared to 802.11 (at most 50%).

Figure 3 documents the fact that the individual energy consumption of transmitting nodes in our scheme versus the 802.11 scheme is also considerably lower. This energy saving is attributed to our smart and adaptive power allocation scheme. In Figure 3, we see that as traffic density falls (X-axis denotes the data inter-arrival rate – a higher inter-arrival rate (10 secs) indicates low traffic density), the transmitter node spends more time in the "sleep" state thus saving on energy consumption. The fact that our power saving scheme adapts to the traffic condition, is evident from the fact that at high traffic density (message inter-arrival period of 1 second) entails a higher energy consumption (close to 100 joules) as opposed to a low traffic intensity period (message inter-arrival period of 10 seconds) where energy consumption is almost 1/10th of the former case (about 10 joules). Without such smart power saving scheme, nodes spend the entire duration

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of their lifetime operating at their maximum power which is denoted by the blue line in Figures 3. This leads to nodes depleting their power reserves quickly thereby decreasing the network lifetime.

D. Packet Delay

Putting nodes to sleep come with an inherent drawback of increasing the packet delay. If a packet has to be delivered to a sleeping node or a packet is generated at the sleeping node, that data packet has to wait for the sleeping node to wake up before it can be delivered. Thus we were apprehensive about implementing our aperiodic sleep scheme in our MAC protocol. But it so turned out as seen from Figure 4, that our scheme has no extra overhead in terms of delay. We calculate packet delay based on the difference in time (read from the time stamp on the packet) between the packet generation and the successful reception of the packet. The reason that our scheme does not have higher packet delay as compared to 802.11 although our scheme implements the "sleep" mechanism is because, nodes in our scheme sleep "strategically" as opposed to in a regular cycle. In our scheme, a node goes to sleep only when it is not a part of the transmitting backbone. Thus its sleep duration does not contribute to packet delay as conventionally seen in other schemes that deploy sleep mechanisms. Moreover, our topology building scheme coupled with the right power allocation for each transmission translates to very high successful packet transmission rate (as observed in Figure 1) thus alleviating the problem of packet re-transmission. In classical 802.11 with omni-directional transmissions, data packets end up colliding with each other when multiple transmissions happen simultaneously as will be the case in a traffic intense network, leading to multiple retransmissions hence higher packet delay. This single-handedly leads to almost a 30% more delay in packet transmission in 802.11 as compared to our scheme. Figure 4 compares the average packet delay of all the transmitting-receiving nodes in a network comprising of 100 nodes distributed randomly on a 1000 square meter area with 10 pairs of transmitting and receiving nodes. The X-axis in Figure 4 denotes the simulation time whereas the Y-axis denotes the average packet delay in milliseconds.

V. CONCLUSION

In this paper we focus on power conservation techniques in wireless ad-hoc networks equipped with directional antennas. We design a power aware MAC protocol that advocates power savings. Using adaptive transmission power control, effective topology control and strategic sleep mechanism we see a tremendous increase in energy saving, substantial increase in successful packet reception rate and a decrease in average packet delay. We have simulated our work on the network simulator platform – NS-2, results from which are documented in the previous section.

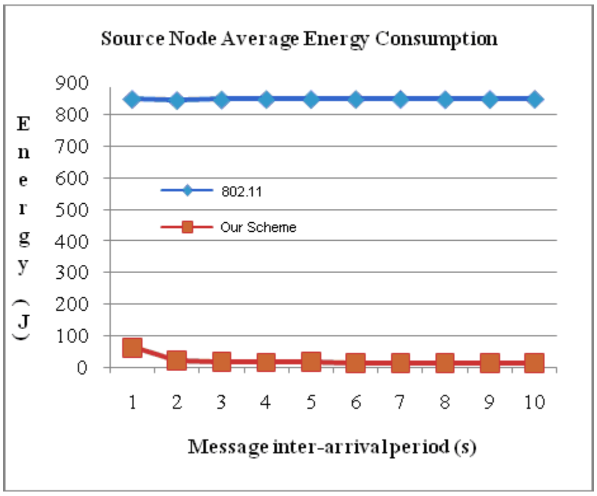

Figure 3 : Source node energy consumption of our schema vs 802.11

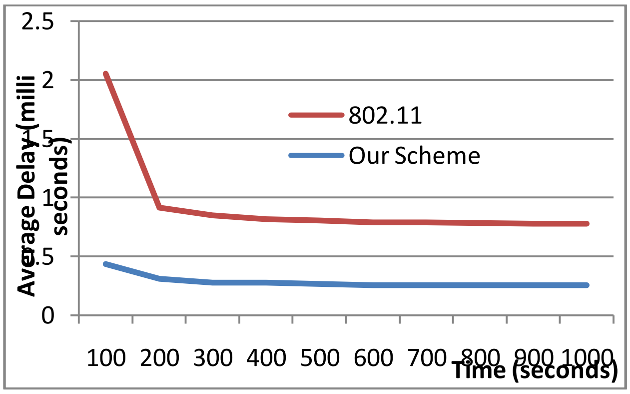

Figure 4: Overall average end-to-end delay of our scheme vs 802.11

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