Design and Implementation of a Low Cost Energy Efficient IEEE 802.11-based Ad Hoc Network

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***Abstract*—Network energy consumption is a critical issue in mobile communications and especially so in ad-hoc and sensor networks where small sized battery operated nodes must communicate for a long duration in dynamic network topologies. This paper presents a low cost energy efficient solution for IEEE 802.11 based ad hoc networks. Energy efficiency is achieved by the combination of a low power mode algorithm and a power aware routing strategy in order to reduce communication energy consumption and increase node lifetime. Another objective of the proposed routing strategy is the selection of stable links in order to achieve robust network operation. Simulation studies indicate a reduction in energy consumption and a significant increase in node lifetime whereas the network performance (delivery ratio and routing overhead) is not affected significantly. Finally, the hardware/software architecture of the wireless nodes is presented for a low cost design implementation.**

Index Terms-power aware, routing metric, low power mode

I. INTRODUCTION

In recent years there has been increased research interest in the area of ad-hoc networks, which can operate without the presence of any preinstalled network infrastructure, have distributed robust operation and can adapt well in network dynamics such as mobility of hosts or topological changes. These network properties are desirable in many situations such as military, law enforcement or disaster relief operations.

This work is based on the design and implementation of a low cost ad-hoc network for disaster relief operations [1]. Our application objective was a search and rescue operation after an earthquake in a collapsed apartment, building or house [2]. In each apartment or building there should be a number of small preinstalled, low-cost, battery operated autonomous devices (sensor nodes) equipped with a camera CMOS sensor, an audio microphone and a wireless interface. The rescue teams using mobile central units, roaming over the building should collect captured images and recorded audio from the remote sensor nodes inside the collapsed building in order to find trapped people and rescue them.

The constraints and challenges of our application are the first limited wireless transmission range due to high attenuation, network topological changes due to node movement, node failure or moving machinery, second low energy consumption of the sensor nodes due to battery limitations and third the demand for a high rate connection oriented traffic of video/audio content. Although the mobility requirements in the network are rather low, yet the high attenuation, the multi-path propagation environment and the movement of obstacles and machinery in the area can result in significant topological changes in the network at unpredictable times and rate. Therefore, an ad-hoc routing protocol was developed in order to maintain strong connectivity to support communications among the nodes.

Another objective is the energy consumption in the sensor nodes, since they contain vital information about trapped people and furthermore a single node failure, due to exhausted battery, can result in network partition. This work focuses on network energy consumption issues. A combined efficient way for dealing with idle time (low power mode) and communication (power aware routing) is proposed for a powerful network energy management solution. Although this work is based on DSR [3] and IEEE 802.11b, the principles apply to other routing and MAC protocols.

II. LOW POWER MODE ALGORITHM

Since the mobile nodes of an ad hoc network operate using batteries, it is important to minimize the power consumption of the network. Existing network solutions that improve energy efficiency can be classified in three categories: transmit power control, low power mode algorithms and power aware routing algorithms.

While transmit power control increases the network capacity and reduces interference, its use in reducing energy consumption is based heavily in the hardware specifications of the wireless interface [4]. The use of multi-hop paths saves energy only when the path attenuation dominates the static energy consumption of the hardware, a case that occurs less frequently than is typically believed. As a result our energy efficient solution is based on the combination of a low power mode algorithm and a power aware routing strategy, presented in the next sections.

The basic idea of the proposed Low Power Mode algorithm (LPM) is to reduce the idle power consumption by turning off the radios of nodes that are idle. The algorithm's operation is driven entirely by the communication in the network. The main design considerations of our LPM implementation are the following: distributed robust operation in ad hoc networks, the use of the algorithm should not affect significantly network performance, no need for synchronization between the nodes (the synchronization of nodes proposed in [5] is difficult to implement in dynamic topologies and induces a significant network overhead), no periodic exchange of packets or beacons (periodic transmission of packets or beacons proposed in [6] increases the energy consumption unnecessarily when the network is idle, also channel bandwidth and network capacity is decreased while the beacons or control packets content for channel access with normal data packets), low implementation complexity, no need for modifications at the MAC layer in order to be easily deployed with current commercial and future wireless products.

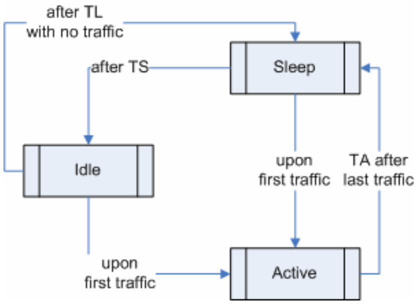

Fig 1 State diagram of the LPM algorithm

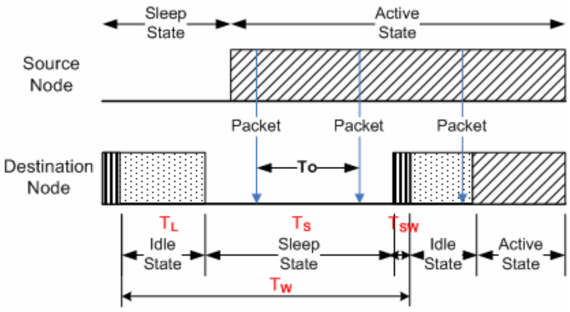

Fig 2 Packet retransmission mechanism

The algorithm has been implemented as an intermediate network driver at the LLC OSI layer for commercial IEEE 802.11 wireless cards. In Fig 1 we present the state diagram of the algorithm. When a node is idle it periodically turns off its radio for duration *Ts* entering the *Sleep* state. After T_S it enters the *Idle* state for a period of T_L where it listens for incoming packets. When it receives a broadcast or unicast packet addressed to that node it enters the *Active* state where it remains for duration of T_A. The same state transition occurs when there is a packet available at the egress queue ready for transmission. When a node is in the *Sleep* state it cannot receive any packets from any other node. As a result, a mechanism must be implemented in order to guarantee the successful reception of packets for a node that periodically enters the *Sleep* sate. This mechanism is presented in Fig 2. Every node that transmits a packet remains in the *Active* state for T_A. If the destination is a node that is possibly in the power saving state (namely transits periodically between the *Idle* and the *Sleep* state), the source node must retransmit the packet R times with an interval T_O in order to overlap the packet transmission with the destination's *Idle* state.

In order to reduce possible local congestion or overhead in the network the following mechanism has been implemented. Each node maintains a table (*Next-hop Nodes Table*) with the possible states of its next-hop neighbours in order to decide if it has to make the R re-transmissions or not. If the node transmits or receives a packet from a neighbour node, it marks this node as active in its table. After T_A seconds it marks the same node as possible-inactive (power-saving state) until it transmit successfully or receive another packet from that node. If the wireless interface is working in promiscuous mode, the nodes can trace any packet transmission in the network in order to update the status of next-hop nodes, improving the algorithms performance.

The information regarding the active state of a destination node in the next-hop table is accurate enough to coordinate transmissions since the source node has detected a successful transmission or reception of a packet from that node based on a MAC layer acknowledgement. If the destination node is in the power saving state then the source node will initiate the retransmission mechanism. If the destination node enters the active state the source node will receive an acknowledgement and will stall any pending retransmissions of the packet.

However, during a broadcast transmission there is no MAC-ACK, so the source node has to transmit a broadcast packet every T_O seconds for R times. In order to reduce this overhead, a variable is maintained (*T_last_broadcast*) which contains the last time that a broadcast packet has been transmitted. Broadcast packets will cause every next-hop node to enter the active state for at least a period of T_A. Thus, when a sending node transmits a broadcast packet at time $t < T_A +$ *T_last_broadcast* it assumes that all its next-hop nodes are still in the active state and the packet is transmitted normally without any retransmissions. This mechanism reduces significantly the number of retransmissions in the network which are caused by the use of the algorithm.

In the presence of unstable links or high mobility the above mechanism performs sufficiently and in some cases improves network performance as a result of the additional retransmissions imposed in unicast and broadcast packets. The major disadvantages of the proposed LPM algorithm are the increased latency during a route discovery (a basic problem found in most of the asynchronous low power mode algorithms) and the additional overhead induced by broadcast packets that are transmitted in the network (and especially for packets that are flooded in the entire network).

In the next paragraphs we present a systematic approach to address the LPM algorithm's design parameters and we calculate the maximum achieved energy efficiency of such an algorithm. An idle node not implementing the LPM algorithm in a time period $T_W=T_L+T_S+T_{SW}$ will consume energy

$$E_1 = P_L * T_L + P_L * T_S + P_L * T_{SW} \tag{1}$$

During the same period an idle node that implements the algorithm will consume energy

$$E_2 = P_L * T_L + P_S * T_S + P_{SW} * T_{SW} \tag{2}$$

Where P_L is the power consumed at the active state, P_S is the power consumed when the radio is off, *Ts* is the time a node spends in the sleeping state and T_L in the listening state. *Tsw* is the time needed to switch the radio from off to on plus the time needed to switch from on to off, during this period the power consumption approaches P_L ($P_{SW} \approx P_L$) [4],[8].

Using equations (1) and (2) we define the power efficiency factor P_{EFF} of the algorithm for idle nodes by

$$P_{EFF} = \frac{E_1 - E_2}{E_1} = \frac{(P_L - P_S)*T_S}{P_L * T_W} \tag{3}$$

$$K_{DEV} = \frac{(P_L - P_S)}{P_L} \tag{4}$$

The constant value K_{DEV} depends on the hardware specifications of the wireless card and bounds the maximum value of the power efficiency factor. The maximum number of retransmissions required for a sleeping node to receive a packet is defined by

$$R = T_w / T_O \text{ , where } T_L > T_O \tag{5}$$

Also we define the ratio $D = T_S / T_O$ (6)

Using equations (3), (4), (5) and (6) the power efficiency is found to be,

$$P_{EFF} = K_{DEV} * \frac{D}{R} \text{ , where } R \in N^+ \text{ and } R > 1 \tag{7}$$

A guideline to select adequate parameters for the algorithm is the following; T_S must have a small value to reduce latency. A positive integer is selected for the number of retransmissions R in order to achieve the desirable energy efficiency. The minimum value of T_L depends from the MAC layer specifications. Also T_O must be lower than T_L with a value that applies to possible transmission delays caused by the driver, operating system, packet transmission delay or the MAC congestion avoidance mechanism. A set of values that has been used in the implementation and in simulations of section 4 is the following: T_L=69ms, T_{SW}=1ms, T_S=290ms, T_O=60ms and R=6. This set in case of the Orinoco wireless card (P_{TX}=1408mW, P_{RX}=914mW P_{IDLE}=785mW P_{SLEEP}=65mW) can achieve *PEFF*=0.73.

III. POWER AWARE ROUTING

Although the use of the LPM can decrease the total network consumption, giving power efficiency as high as 70%, the network lifetime may not be increased. Using a network topology with 50 nodes in a 1000*1000m square area, and a traffic pattern of 5 continuous TCP flows, we considered the node energy distribution in the network using the DSR as a routing protocol. We have measured the node energies at the end of simulation with and without the use of the LPM algorithm. As one could expect in the second case the energy is about the same for all nodes at the end of the simulation (average 0.208Wh, minimum 0.200Wh, maximum 0,215Wh). The energy distribution of the 50 nodes in the case of LPM retains the maximum energy at the same level of 0.2Wh while presents a minimum value of 0.045Wh. The standard deviation of node energies is very high implying that for a static network the same nodes are used to forward packets between the source and destination nodes. Thus batteries of some nodes will be overly exerted and eventually will be exhausted and the network will be partitioned. As a result a power aware routing algorithm is critical especially in the case where the LPM algorithm is used.

There have been several research efforts regarding power aware routing algorithms. These algorithms must select the best path to minimize the total power needed to route packets on the network and maximize the lifetime of all nodes. Minimum cost battery routing MCBR [9] proposes the remaining battery capacity of the nodes as a metric. Min-max battery routing MMBR [10] defines as a cost metric of a route the maximum battery cost value of the nodes that constitute the path. Although the previous algorithms reduce network consumption and increase node lifetime, or both, in networks where the wireless channel is characterized by multi-path propagation it is observed that some links may experience an increased packet error rate. These unstable links can decrease the network performance significantly [7] due to packet losses and the initiation of the route discovery mechanism.

Efforts towards this direction have been also made to add criteria based on a combination of shortest-path, link quality, or least congested paths, that is, network load. Link quality estimations can be based on either the signal-to-noise ratio or the expected transmission count (ETX) metric [12]. The results in [12],[13] show that with stationary nodes the ETX metric significantly outperforms shortest path routing; also network-load and packet delay metrics perform poorly because they are load-sensitive and hence suffer from self-interference. However, Draves et al. in [13] concludes that in a mobile scenario shortest-path routing performs better, compared to ETX, because it reacts more quickly to fast topology change. Therefore the path length is also considered in the metric for our route selection.

In this work we present a route selection algorithm that combines link stability metric with the battery level of the nodes and the route length. When the nodes have battery levels above some threshold and the links are stable, shortest path routing is performed. In case of link failures stable links are preferred and as the battery level of nodes is decreased a combination of the above metrics is encountered in route selection. Following the methodology used in [9] we define the path cost $C(n_0, n_k)$ of a path from a source node n_0 to a destination node n_k by:

$$C(n_0, n_k) = \sum_{i=1}^{k} z(n_{i-1}, n_i) \tag{8}$$

Where $z(n_{i-1}, n_i)$ is the cost of the link from node n_{i-1} to node n_i. The path cost C depends on the path length of the route and the cost of the links that compose the route. The link cost is defined as a function of the energy cost *Zen* and the stability cost *Zst* of the link from node n_{i-1} to node n_i by:

$$z(n_{i-1}, n_i) = f(Zen(n_i), Zst(n_i)) = Zen(n_i) * Zst(n_i) \tag{9}$$

The multiplication of the above metrics increases the cost of nodes that have unstable links and low energy levels, as a result longer hop paths are preferred and packets are routed over these nodes. The energy cost metric of a node is defined as:

$$Zen(n_i) = 1 + EF * g(n_i) \tag{10}$$

Where $g(n_i)$ is the normalized energy consumed by the node, $g(n_i) = \left(E_{INITIAL} - E(n_i)\right)/E_{INITIAL}$

EF is the energy cost factor which bounds the maximum value of the energy cost, $E_{INITIAL}$ is the initial and $E(n_i)$ the current residual energy level of the node.

The stability cost metric is defined as:

$$Zst(n_i) = 1 + \frac{1+SF}{stability\ (n_i)} \tag{11}$$

Where $stability(n_i)$ is the stability metric of that node and *SF* a stability cost factor which bounds the maximum value of the stability cost. An optimal assignment of EF and SF factors is required for meeting the network communication constraints. Increasing EF a priority is given in power aware routing whereas increasing SF more stable links are preferred.

The stability metric was first proposed by [11] in order to estimate a dynamic link timeout cache policy the Link-Max-Life (LMF) link cache. When a node is added in the cache it has an initial link stability value (*SINITIAL*). When a link from the route cache is used in routing a packet originated by that node, the stability metric of the two end point nodes is additive increased by a stability increase factor *SINCF*.

$$stability(n_i) = stability(n_i) + SINCF$$

Upon a link error, the source node will receive a route error packet containing the broken-link, in this case the stability metric of the two end point nodes is multiplicatively decreased by a stability decrease factor *1/SDECF* (where $SDECF \geq 2$).

$$stability(n_i) = stability(n_i)/SDECF$$

In every case the stability metric is bounded in a set [2, MAX_STAB]. Using equations (10), (11) and (12) the path cost is equal to:

$$C(n_0, n_k) = \sum_{i=1}^{k}\left(1 + EF * g(n_i)\right) * \left(1 + \frac{1+SF}{stability(n_i)}\right) \tag{12}$$

In the presence on unstable links in the network, nodes that route packets capture the received route error messages and update the stability metric of the nodes in the network. Each node maintains in the route cache a local view of the stability metric of links in the network. As a result, nodes that experience a high link loss ratio have decreased values of stability. Using equation (12) source nodes in the network route packets avoiding the use of unstable links and nodes with low energy, increasing the network lifetime and communication robustness. A set of values that has been experimentally evaluated in the deployed wireless ad hoc network is the following: *EF*=1, *SF*=2, *SDECF*=2, *SINCF*=2, *SINITIAL*=25, *MAX_STAB*=300.

IV. IMPLEMENTATION

The prototype nodes were implemented using the Altera Excalibur EPXA10 chips with an incorporated ARM922T CPU core and a PLD with 1 million gates in order to lay the road for a low cost SoC design. The network protocol stack is a custom implementation with small code size (less than 120 Kbytes), that executes from internal SRAM in order to reduce CPU energy consumption. The wireless node (Fig 3) includes a camera CMOS sensor with resolution 640x480 pixels an audio microphone and operates from a 200mAh Lion battery.

Fig 3 Prototype design of the wireless sensor node

The routing protocol is the most critical design issue in the protocol stack of a wireless ad hoc node. Our routing protocol implementation is based on Dynamic Source Routing (DSR) [3] which has better performance and lower power consumption [8] compared to other ad-hoc protocols like AODV, DSDV and TORA. Another important property of DSR is that it does not transmit any periodic routing control packets and as a result there is no energy consumption imposed from the routing protocol during idle network periods.

Our DSR implementation is based on the IETF Internet-Draft version 9. The protocol stores topology information in the route cache, which has a link-cache structure. A source node executes the Dijkstra's algorithm, on the link-cache using the cost function in equation (12), in order to find the best route towards a destination node. As depicted in Fig 4, DSR uses feedback from the link layer to react to link failures. Outgoing packets at the protocol stack are stored in an egress queue at the traffic control module. The egress queue consists of three FIFO queues with priorities. Routing control packets have the highest priority, TCP packets have medium priority and all other packets are stored in the low-priority queue. A packet, during the transmission process, is removed from the egress queue and processed by the LPM module where is scheduled for transmission.

The proposed architecture of the LPM algorithm is depicted in Fig 4. During a unicast transmission the outgoing packet is transferred from the egress-queue to the *maintenance buffer* at the LPM subsystem. A *packet filter module* searches the next-hop nodes table for the state of the destination node. If the destination node is possibly in the power saving state a *packet scheduler* (at the source node) coordinates the retransmission of the packet. If the packet scheduler receives a MAC layer acknowledgment it cancels any pending retransmissions while the destination node enters the *Active* state. If the packet scheduler fails to transmit a unicast packet after *R* retransmissions the packet is stored in a special queue (*Tx Failure Queue*) and the routing protocol is triggered with a link failure event. The link failure event handler removes the broken link from the route cache and, if this node is an intermediate, issues a route error message to the source node. In both cases, packets that contain the broken link in their source route are removed from the egress queue and the protocol tries to route them from an alternate route.

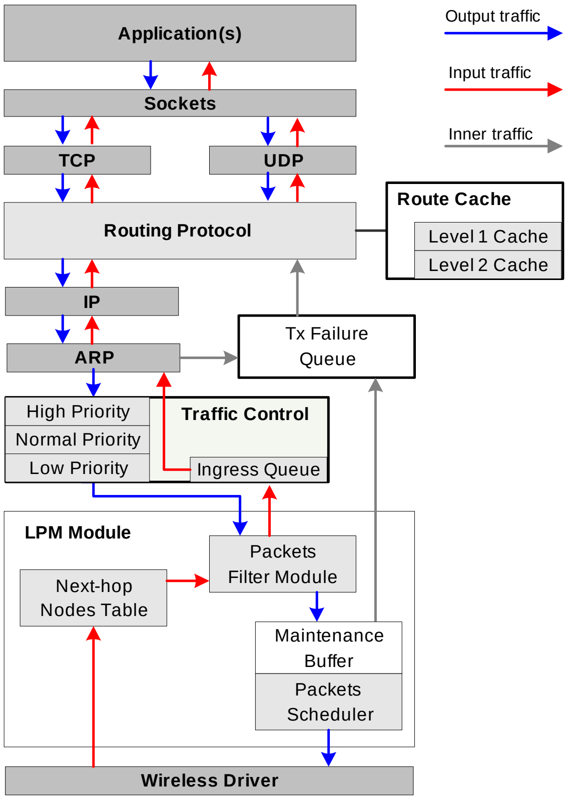

Fig 4 Protocol stack of the wireless sensor node

In order to incorporate the proposed power aware routing strategy in the DSR protocol the nodes must have information about the topology and the node energies in the network (energy map). To accomplish this scope satisfactory more accurate network topology information is required compared to shortest path routing because the source nodes must have alternative paths to route packets energy efficiently.

The following modifications have been implemented in the DSR routing protocol in order to support power aware routing. The battery levels are included in the route request (RREQ) and route reply (RREP) messages. During the route discovery the initiator node broadcasts a RREQ message with a unique sequence number and its battery level. Intermediate nodes rebroadcast the first RREQ and any other with the same sequence number and a *Zen* cost (which is calculated from the message's header) lower from any other received so far. In a similar way, the target node responds to the first RREQ and any other with a lower *Zen* by sending a RREP to the initiator. In this way the initiator of the route discovery locates the shortest path and any other disjoint path that has a lower *Zen* cost and thus, is more energy efficient.

Besides the above modifications, the route maintenance mechanism has been extended as following. When an intermediate node forwards packets towards a destination, it searches its route cache and if there is a more energy efficient path it sends a gratuitous cached reply message to the source node. The dynamic link timeout cache policy invalidates old links and the cache is updated with topology and new energy information (battery levels of nodes) during the route discovery operations.

In order to meet the requirements of high rate connection oriented traffic, among the nodes of the network, a lightweight version of TCP Reno with fast retransmit and fast recovery has been used at the transport layer. At the application layer a simple client/server protocol has been implemented using a request response scheme.

For the wireless network interface, IEEE 802.11b DCF was chosen because it supports high transmission rates, there is availability of low cost products, it is suitable for multi-hop ad hoc networks and its power consumption is reasonable.

V. SIMULATION STUDY

In this section we evaluate the performance of the proposed LPM and PAR algorithms and their effect in communication efficiency with simulations using the ns-2 network simulator. The network topology consists of 50 nodes randomly distributed in a 1000mx1000m square area. The results are average values for a number of simulations in which the nodes are either static or have a random way point movement with relatively low mean speeds varying from 0 to 5m/sec.

In Fig 5 we measure the power efficiency factor for different values of R and with variable number of 80Kbps CBR traffic flows. When the traffic in the network is relatively low (3 CBR flows) and R=6 the simulated power efficiency in Fig 4 is $P_{EFF} = 0.65$. Using the same parameters in an idle network, the maximum theoretical value of P_{EFF}, given by equation (3), is equal to 0.91*290/360=0.73. Comparing the above results we conclude that as the communication traffic in the network is decreased, the power efficiency of the proposed LPM algorithm approaches its theoretical maximum value, since the number of idle nodes in the network is increased.

In Fig 6 we present the routing overhead (routing packets transmitted / total packets transmitted) induced by the use of the LPM as a function of R and a number of CBR traffic flows compared to the case where an LPM algorithm is not used. In the case where the number of simultaneous communication flows is relatively small, the use of LPM will increase the number of packets in the network by 1% to 3%. In the case where the number of flows is increased and the network becomes congested, the overhead will reach a value of 5%. As expected the overhead is increased with the number of retransmissions R.

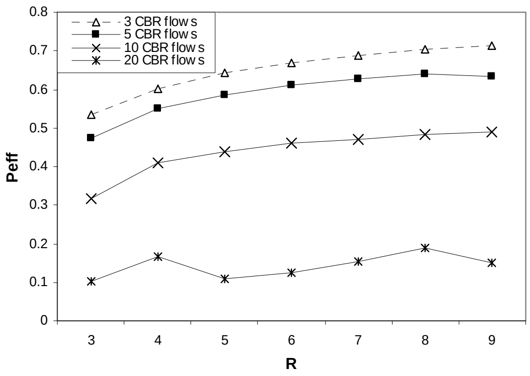

Fig 5 Power efficiency as a function of variable R

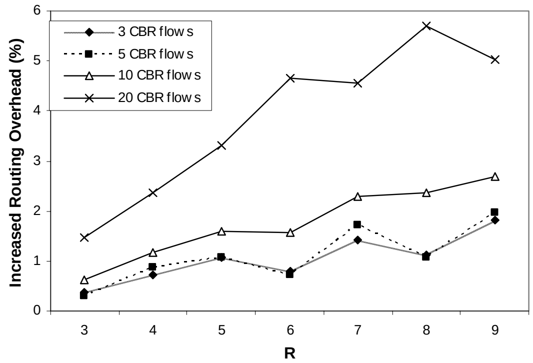

Fig 6 Routing overhead induced by the use of the LPM algorithm

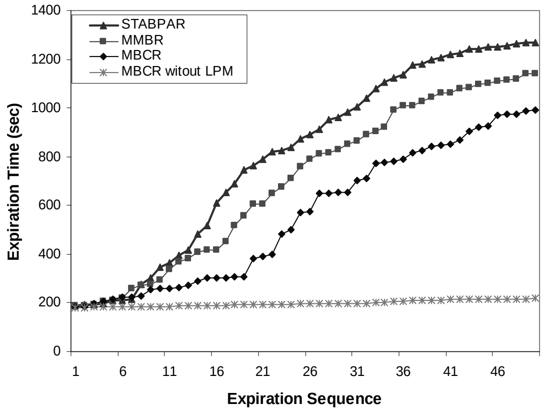

Fig 7 Expiration time vs. expiration sequence

In Fig 7 we present the expiration time of each node in the network (i.e., the time when a node exhausts its battery) for four different cases: when the LPM is not used and the routing strategy is MMBR, when LPM is used with MBCR and MMBR routing and when LPM is used with the proposed power aware routing (STABPAR). The presented simulation results are in a network topology with 50 nodes and 5 simultaneous CBR traffic flows of 80Kbps. As we can observe, the combination of the proposed power aware routing and the LPM algorithm can achieve a significant increase in the lifetime of nodes. In this case energy efficient routes that experience a lower link-loss ratio are preferred for routing packets, as a result there is a significant decrease in route errors and route discovery operations that waste energy.

VI. CONCLUSIONS

In this paper we have presented a Low Power Mode (LPM) algorithm and a Power Aware Routing (PAR) strategy to reduce network consumption and increase node lifetime in an efficient way. Although this work is focused on 802.11 and DSR it can be applied to other MAC and routing protocols, as well. The LPM algorithm can reduce the energy consumption of the wireless card up to 70%, while the network performance is not affected significantly. The PAR strategy proposes a new metric for route selection which combines the link stability and the node battery levels. As a result, energy efficient stable links are preferred for routing packets and, thus, node lifetime and network robustness is increased. The combination of the proposed LPM and PAR algorithms can lead to powerful energy efficient solutions for ad-hoc wireless networks.

During some preliminary experiments in real wireless networks, deployed with embedded sensor nodes and mobile PCs as central units, the network lifetime was increased significantly and the network performance was improved. As part of our on-going work we experimentally evaluate the PAR and LPM algorithms and several aspects of the protocol stack, such as TCP performance and tuning, in a wireless network with a large number of nodes.

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