Dynamic Rate-Selection for Extending the Lifetime of Energy-Constrained Networks *

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Abstract

Wireless networks have a constraint on their functional lifetime. This is due to the limited energy capacity of batteries powering the wireless nodes. For extending the lifetime of such battery-operated networks, we present a scheme for dynamically selecting the transmission rate for each node in the network. The transmission rate is based on the available energy budget in each node's battery. The goal is to increase the network capability of delivering more packets. The rate selection for each node is subject to satisfying a QoS timing constraint on the packet delivery time. Through adaptively varying each node's rate, we extended the lifetime 10 times on average more transmitting at a maximum rate and delivered on average 7.5 times more data packets. When compared with a scheme that transmits data at a lower rates independent of the battery levels, our scheme delivers up to 12% more packets for the same available total energy.

1 Introduction

Wireless networks such as ad-hoc and sensor networks are composed of nodes that are powered using energy limited batteries. This limitation urges the need for power-aware strategies that regulate and conserve the energy consumption at each node to extend the functional lifetime of the network. Recently, some researchers have been focusing on the energy efficiency of wireless networks. Several strategies propose energy conservation through power-aware routing or the use of less energy consuming transceivers [13].

Current routing schemes in wireless networks select their routing decisions irrespective of the battery budget of the selected nodes constituting a path. A common power-aware routing technique [3][12] forwards data to the closest neighbor to reduce the total energy by exploiting a quadratic relation between energy and propagation distance. As a result, some nodes in a network may suffer a high battery depletion rate based on their physical location in the network. Centrally located nodes are candidates to have their batteries depleted faster than the other nodes. This is because they are mostly considered "vital nodes", in a sense that they are heavily used to forward data to the other nodes in the network. This can create a chain of negative effects on the overall performance and energy consumption of the network. As a first effect, the connectivity of the network may decrease due to the quick failure of those "vital" nodes. Next, as a result of intermediate nodes failures, a power aware routing algorithm selects the second lowest cost alternate path. Thus the network overall energy consumption increases and the network capacity for delivering messages decreases. Moreover, more overhead is encountered in discovering and setting new routes.

We propose an algorithm that increases the lifetime of an energy constrained network by varying the data bit-rate at each node in a given path (route). Assuming that the energy consumed in data transmission is directly proportional to the transmission rate, we present a scheme that assigns for each node a transmission rate based on the path's available energy budgets. That is, nodes with low battery levels are allowed to transmit data with low rates to save their scarce energy. This is at the expense of the other nodes with higher battery levels that have to transmit data at higher data rates to satisfy an imposed Quality of Service (QoS) constraint on the overall packet delay.

In the next section, we describe the models of the different network components used by this work. Section 3 discusses the rate selection scheme detailing the methodology for modeling the energy budget at each node and how to compute the data rates accordingly. Section 4 shows the experimental results for networks with different battery configurations. Some of the related work is presented in Section 5 followed by brief conclusions and future work.

2 Models

2.1 Node Model

It is common for each node in the network to have a different battery level from other nodes. This is primarily due to dif-

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ferent traffic loads passing through each node, or due to different battery manufacturing techniques that yield different battery capacities and decay rates. A node's main tasks that involves communicating with other nodes are: (1) to participate in route discovery and maintenance and (2) to transmit, receive, or forward data to other nodes in the network. The energy consumed during node's activity in route discovery is beyond this work. We assume no heavy CPU processing is performed in each node (as in the case of nodes in sensor networks), thus a node consumes its energy mainly to transmit and receive data packets. Idle nodes are assumed to consume a negligible amount of energy. We assume that all the nodes in the network are homogenous, i.e., all nodes exert the same amount of power to transmit data and the same amount of power to receive data. The transmitter and receiver powers are not necessarily equal.

2.2 Timing Model

We consider applications that have a QoS constraint on the packet delivery time. Each packet has a certain deadline, D, by which it should reach its destination. This time is set by the source node based on an application's requirements for its data delivery. Other delays may be generated in the system due to factors such as interference, congestion, and routing. The total delay also includes the buffering time of messages awaiting transmission while the node's transceiver is busy receiving data. These delays are roughly estimated and factored as a percentage of D that can be deducted to get the total available air-time (transmission time), T_{tot}.

We consider media applications, where packets are generated periodically with a known average rate. The assigned rates at each node should be larger than or equal the packet generation rate. This precaution is taken to avoid the existence of an unstable network when the arrival rate at a critical node exceeds its transmission rate and a buffer buildup takes place.

2.3 Network Topology and Lifetime

In our work, we consider a network consisting of nodes that are set apart from each other such that each node can only reach its direct neighbor as shown in Figure 1. This constraint is set to extract the sole effect of varying the data rates on the network lifetime without being affected by other factors such as messages' collision and interference. For example, we consider a single connection flow $ABCDE$ (shown in bold) in Figure 1, while the other connection flows in the network are shut down.

As there are no alternative minimum-cost route that can be found from A to E, the lifetime of the connection and the network is limited by the battery capacity of the critical node B. We measure the lifetime of the network by the lifetime of its critical node (first node to die). A node dies if its battery is unable to transmit any more packets due to its energy constraints. Since nodes can only reach their direct neighbors, no alternate paths can be found and the connection is permanently disconnected as soon as any node dies.

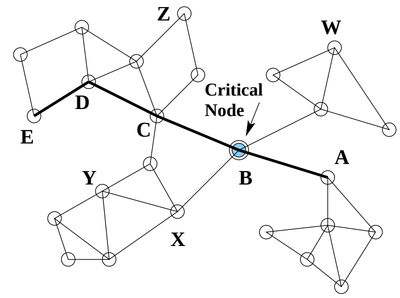

Figure 1: Network with multiple flows and a critical node B.

2.4 Rate versus Energy

Work in [9] presented power aware modulation scaling for reducing the communication energy in wireless networks. The authors showed that reducing the number of bits per symbol and the symbol rate reduces the transmission power, P_{TX}, at the expense of increasing the bit transmission time, t_{bit}. They exploited the energy-per-bit, E_{bit}, versus delay tradeoff saving energy consumption by reducing the number of bits per symbol transmitted. The transmission rate, R, is the product of the number of bits per symbol, b, and the symbol rate, R_s, (thus $t_{bit} = \frac{1}{R_s b}$) The formulation of E_{bit} as a function of R is dependent on the modulation algorithm used. Work in [9] [15] and [7], analyzed Quadrature Amplitude Modulation (QAM) where the average power equals $C\ R_s(2^b-1)+\ F\ R_s)$, where C is determined by the quality of transmission and the noise power, and F determines the power consumption of the electronic circuitry of the transmitter. Thus E_{bit} equals:

$$E_{bit} = (C(2^b - 1) + F) * \frac{1}{b} \tag{1}$$

Based on derivations in [15], in this work we use $F = 10^{-8}$ and $C \approx 7 * 10^{-9}$ for a transmission range of $\approx$ 32 m and the output power of 10 mW. In this work we follow the QAM scheme. However, different formulations of the energy can be easily substituted without major change in our scheme Similar to the transmission power, we assume that the reception power rate dependent and follows Equation 1. However, constant reception power can be easily applied in our model.

For selecting an appropriate rate for each node, a single selected node (which can be the source node, the destination node or any monitoring node) has to solicit some information about other nodes along the path. The required data that needs to be known are: (1) what nodes constitute the route, and (2) the energy budget of each of those nodes. The selected node is responsible for computing the rates of all the other nodes and notifying them with their corresponding computed rates.

In the next section, we show how to evaluate R for each node such that the overall network lifetime increases while satisfying the total delay QoS constraint.

3 Dynamic Rate Selection Scheme

A scheme for dynamically selecting the transmission rate at each node is introduced in Section 3.2. To achieve an approximately equal battery depletion rate in all nodes, our dynamic rate selection scheme bases its calculation on the available energy budget at each node computed as in Section 3.1. For practical consideration, we propose an efficient technique to map the computed continuous bit-rates to available discrete rates in Section 3.3.

3.1 Energy Budget Modeling

An energy budget is the amount of available energy that can be dedicated to transmitting and/or receiving data in the given connection flow at a specific node. In order to compute the data rates that are proportional to the available energy budget at each node, we model the energy budget at each link in the path.

A naive way to model the energy budget at node i is to account for the node's current battery capacity, E_i, as the energy budget available for packet transmission at this node. However, this model does not consider the effect of the consumed energy at the receiving node. There exists a constraint at each link that the receiver has to receive data with at least with the same rate as the transmitting node to avoid buffer overflow. A common situation that can occur is when a node with a high battery level enforces its receiving neighbor node to receive data at an equal rate, even if the latter's budget is low.

To achieve a slower discharge rate at critical nodes – taking into consideration the energy consumed during data reception– we choose to assign the energy budget to each link instead of assigning it to each node. For the link energy budget, we compute the amount of power that can be consumed by both the sender and the receiver node to forward a packet. A link energy budget is the sum of two components; a weighted battery energy level of the transmitting node i and receiving node $i+1$. The computed weights, w_{tx} and w_{rx}, indicate the portions of the available energy at the transmitting and receiving nodes that can be used for the flow's packet transmission and reception respectively. The energy budget for link $\langle i, i+1 \rangle$, LE_i, equals:

$$LE_i = w_{tx}\ E_i + w_{rx}\ E_{i+1} \quad (2)$$

where $w_{tx} = \frac{P_{TX}}{P_{TX}+P_{RX}}$ and $w_{rx} = \frac{P_{RX}}{P_{TX}+P_{RX}}$. P_{TX} and P_{RX} are the transmitting and receiving powers, respectively. The weights are assumed equal for all nodes.

Typically, data transmission requires more power than reception. The ratio of P_{TX} to P_{RX} ranges from 0.65 to 0.85 in widely used IEEE 802.11 cards for general purpose computers [18] [19] [20]. In special purpose transceivers, different values of P_{TX} and P_{RX} may be found.

3.2 Rate selection

The transmission rates at each node are selected in proportion to the computed energy budget at the node. That is, nodes/links with higher energy budgets can bear to transmit at high rates and endure higher energy consumption than critical nodes. On the other hand, energy-constrained nodes experience more delays to transmit data at lower rates; however, it saves more energy. To compute the transmission rate, R_i, at node i, we indirectly compute the allotted time for each bit to get transmitted on link $\langle i, i+1 \rangle$. The time, allotted for transmitting a bit from node i to node $i+1$, t_i, is the total end-to-end time factored by the ratio of the inverse of the link's energy budget to the sum of the inverse of all links' energy budgets as show in Equation 3.

$$t_i = T_{tot} \frac{1/LE_i}{\sum_{k=0}^{n-2} (1/LE_k)} \quad (3)$$

where n is the number of nodes in the path.

Each node slows down the packet transmission rate based on its allotted time for transmission. The rate at node i, R_i, is computed as the ratio of the bit transmission time at full rate, t_{max}, and the computed bit time at node i as in Equation 4.

$$R_i = (t_{max}/t_i)\ R_{max} \quad (4)$$

where R_{max} is the maximum available transmission rate. R_i is lower bounded by the rate of data generation at the flow's source node.

3.3 Discrete Rates Setting

Current 802.11 wireless cards support a set of discrete transmission rates rather than a continuous range of data rates. For example, the Cisco Aironet 350 [18] wireless card supports four data rates: 1, 2, 5.5 and 11 Mbps. Similarly, QAM supports only even integer values of bits per symbol [9]. Thus we need to map the continuous rates computed from Section 3.2 to the set of available data rates supported by the used card. To avoid increasing a message delay over its nominal deadline, a simple choice would be to transmit packets using the lowest discrete rate that is higher than the computed continuous rate. As a result, the end-to-end message delay would decrease; nevertheless, nodes would consume extra energy due to operating at transmission rates above the desired rates.

We further optimize this technique by exploiting the generated time slack (from using above mentioned discretization technique) in reducing the rates at other nodes in the path. This enhanced discretization technique would be of benefit in cases where there is a large difference between the desired rate and the corresponding discrete rate for a link. For example, QAM can support rates 2, 4, 6, and 8 Mbps. Assume that the desired rates for three links in a network are 6.1, 6.2, and 6.3Mbps. According to the simple rate discretization method, all of the links would operate at 8 Mbps. However, if the third link transmits at 8 Mbps, then the time difference between transmitting at 6.3 Mbps and 8 Mbps can be used to reduce the rates of the first and second links. As a result, the first two links can transmit at 6 Mbps and the total energy consumed in the network is reduced.

Figure 2 shows the algorithm used in exploiting the slack time generated from rate discretization. The algorithm iterates over all the links in a path, starting with the highest energy budget link that is not assigned a discrete bit-rate. A continuous rate is computed for this link, and then bumped to a higher discrete rate. The slack is added to T_{tot} before computing the rate for the next link. The algorithm terminates when all the links in the path are assigned discrete rates.

i = highest_link_energy_id()
while (not all nodes are assigned discrete rates)
    CR_i = compute_contious_rate (i)
    DR_i = lowest_rate_higher_than (CR_i)
    T_{tot} += tx_time(CR_i) - tx_time(DR_i)
    i = next_highest_link_energy_id(i)

where CR_i and DR_i are the continuous and the discrete rates for link $\langle i, i+1 \rangle$, respectively.

Figure 2: Pseudo-code for the enhanced rate-discretization

4 Evaluation

We present a primary evaluation of the dynamic rate selection scheme and measurements of the potential network lifetime extension gained by using our scheme.

4.1 Experimental Setup

In our simulation, we modify the ns-2 network simulator [16] for evaluating our dynamic rate selection scheme. Simulations are run using a topology as shown in Figure 1. Each node is only reachable by its immediate neighbor. A single flow of UDP traffic from node A to node E is generated from an MPEG trace file [17] and routed using Dynamic Source Routing (DSR). The DSR routing agent module in the ns-2 package required several modifications to accommodate our rate changing scheme. We disable the route request reply from caches in intermediate nodes to force the route replies to be sent by the destination. Other changes to the ns-2 package include the implementation of a rate dependent energy model as well as MAC layer support for variable bit-rates.

The source node calculates transmission rates of all other nodes. It collects the energy budgets of all nodes during the route discovery phase of the DSR protocol. The destination node returns the discovered route with the collected energy metrics in the route reply packet. When the source node receives a route reply, it uses the collected energy metrics to calculate the transmission rates of each hop along the route. These calculations return a continuous rate R_i that is then mapped to one of the available discrete rates. We use 2, 4, 6 and 8 Mbps as our supported data rates. The discretization is done using the simple or the enhanced techniques discussed in Section 3.3. The source encodes the set of computed rates in each packet's header. When a packet reaches a node, it gets transmitted to the next node using the rate in the header corresponding to the sending node. All network control packets such as request-to-send, clear-to-send, and route discovery are transmitted using the minimum bit-rate.

To test the applicability of the concept using different modulation schemes, we experimented with a hypothetical modulation scheme that possess a quadratic relation between rate and energy (rather than the exponential relation in QAM). We achieved a significant lifetime time improvement over a no power-aware scheme. However, the results were omitted due to the space constraint.

The rate for each node is periodically updated through the invocation of the DSR agent every second. Periodic rate updates are useful in balancing rate of battery depletion along a path. The energy overhead of the transmitted DSR packets are accounted for in the total energy consumed at each node.

4.2 Lifetime Extension Evaluation

In our experiments we vary the critical nodes energy budgets. Lifetime is measured in seconds and also in the number of successful packets received at the destination until the first node dies. The network lifetime due to the dynamic rate selection, DRS, scheme is compared against a no power-management base case, $No\ PM$, where all the nodes transmit with a default maximum rate of 8 Mbps. Also we compare against a scheme that transmits data at a fixed lower rate independent of the energy budgets. All the experiments use the same topology while varying the battery level at each node.

Effect of varying the traffic load on the lifetime: To demonstrate the effect of lowering the rate based on nodes' battery levels, we vary the available energy budget of the critical node B (in the example given in Section 2.3). The initial available battery level in B (as a percentage of the maximum battery capacity) varies as represented by the X-axis in Figure 3, while all batteries of the other nodes in the flow: A,

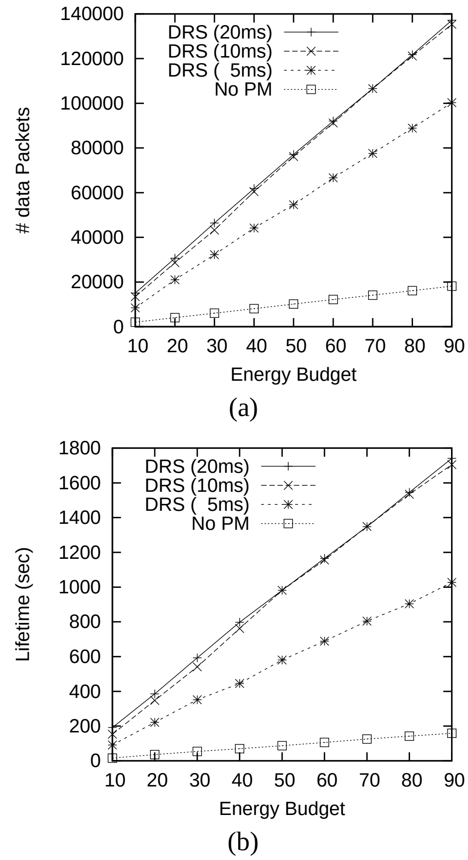

Figure 3: Dynamic Rate Selection improvement at different loads (T_{tot}) measured in: (a) number of packets successfully received at the destination, and (b) network's lifetime.

C, D, and E, are fully charged at 50 joules. Figure 3 shows that as the amount of available energy at the critical node increases, the network is able to deliver more packets before this node dies. We measure the lifetime at different values of T_{tot}: 5, 10 and 20 msec. As T_{tot} increases, more time can be exploited to reduce the transmission rates and thus achieve a larger lifetime. The lifetime extension due to the dynamic rate selection ranges from six times improvement at tight QoS (T_{tot} = 5 ms) and 10 times the lifetime at more relaxed load (T_{tot}=10 and 20 ms). The network functionality in terms of the number of packets successfully received rises on average 7.5 times for relaxed deadline and 6 times for tighter deadline. The average delay (other than packets' air-time) per packet increases in the range from 0.2% to 16% over the base case.

To mimic different network conditions, we experimented with other variation of battery configurations where nodes have randomly assigned battery levels. Results show a significant increase in lifetime; however, graphs were not included for space limitations.

Effect of using the enhanced rate discretization: By applying the enhanced rate discretization technique that takes advantage of the dynamically generated slack time, we succeeded in reducing the rates of links with lower energy budgets. We also tested our scheme against a scheme that slows the transmission times at all nodes uniformly such that the total transmission time for a packet to reach the destination equals T_{tot}. All nodes transmit at equal rates independent of the node's battery level. We call this scheme *static rate assignment*. Figure 4 shows the percentage increase in the number of successfully delivered packets normalized to static rate assignment scheme. Using the simple discretization technique in DRS, we achieve up to 5.7% increase in delivered packets. However, the enhanced discretization technique achieves up to 12% increase in packets over the static rate assignment scheme. The lifetime improvement is larger in case of networks containing nodes with relatively large variation in their battery levels.

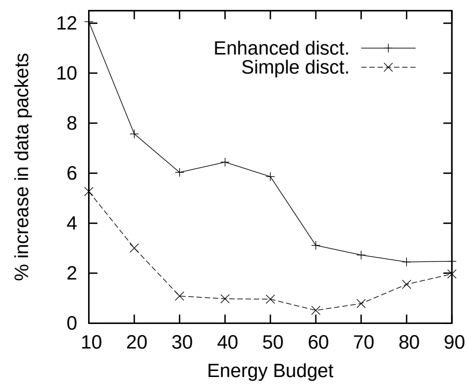

Figure 4: Effeciency of the enhanced over simple rate discritization; both normalized to the static rate assignment (at T_{tot} = 5ms).

5 Related Work

Tuning network link frequency for power savings was introduced by researchers for wired environment. Work in [4] [5] and [14] proposed variable frequency links for power savings. Authors of [10] proposed a history based DVS policy that uses past network activity to predict the future network needs and sets the link rate accordingly. Their scheme was proposed for interconnection networks.

For wireless networks, several energy-aware techniques for wireless microsensor networks as presented in [7]. One of the techniques is selecting a modulation scheme by which the energy-per-bit is a function of the data symbol rate. Work in [8] and [2] exploited the directly proportional relationship between energy and data rate in devising an algorithm to reduce the transmission energy per bit. Their transmission time is subject to deadline; however, the authors did not consider the node's battery levels to extend the lifetime of the energy-critical nodes. The notion of lifetime in a sensor network is introduced in [1] where, upper bounds on the lifetime of sophisticated sensor networks are derived. Another technique for reducing the communication energy is by decreasing the amount of data transmitted in the network. The work in [6] manages to decrease the traffic by distributing the processing components near its data gathering sites. This reduces the number of raw data that need to be transmitted all the way to a centralized processing node.

6 Conclusions and Future Work

In this work, we presented a scheme for extending the lifetime of battery operated networks. The lifetime extension is achieved by using modulation scaling in wireless cards that vary their transmission rate based on the available energy budgets at each node/link. The energy-delay tradeoff is considered by bounding the total delay on a packet obeying a QoS constraint. Nodes with large energy budgets transmit with higher data rates than small energy budget nodes, thus saving the energy of low battery level nodes. The results show that a network with dynamically varying data rates at each node outlives a network that transmits all its packets at a maximum default data rate. As a result a data path using variable rate outlives a path with constant data rates for that same energy budget. Our network lifetime extension reaches 10 times the life of a base case network with no power-management, and our scheme increases the number of delivered packets by 7.5 times more packets than the base case. Furthermore, By applying an enhanced rate discretization technique that takes advantage of the slack time resulting from increasing the rates of the high energy budget links, we succeeded delivering up to 12% more data packet than a scheme that transmits data at a fixed data rate independent from a node's energy budget.

Future extensions for this work would increase the applicability of the scheme by considering more factors affecting the energy consumption in the network. Applying the dynamic rate selection scheme for larger networks with multiple connections while maintaining fair resource allocation is the next step to test the efficacy of the scheme. Integrating the rate selection scheme on top of a power-aware routing algorithm can further increase the network lifetime.

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