Towards Energy Efficient and Robust Routing with Delay Guarantees in AdHoc and Sensor Networks

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ABSTRACT

Saving energy while providing end-to-end delay guarantees and robust operation have long been regarded as of paramount importance in real-time adhoc and sensor networks. In this paper we explore how rate-adaptation can save energy in adhoc and sensor networks that have real-time requirements, and how robustness requirements, achieved by multipath routing, affect the achievable energy savings. We formulate the problem of finding the most energy efficient data rate for each link, propose an adaptive data rate selection algorithm, and demonstrate that our scheme can save up to 15% energy, when compared with state of art, while still meeting the end-to-end delay guarantees.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols—*applications, routing protocols*

General Terms

Algorithms, Measurement, Performance

Keywords

data rate selection, energy efficiency, multihop routing

1. INTRODUCTION

Wireless adhoc and sensor networks, that require soft real-time guarantees, have recently been developed and evaluated successfully [1]. For these applications, meeting the application end-to-end delay requirements, operating in an energy efficient and robust manners are of paramount importance.

Among the techniques that have been proposed for energy efficient operation is the dynamic data rate adjustment. Adhoc networks, in which mobile devices are equipped with 802.11 interfaces, and more recently, wireless sensor networks [2] have the capability to transmit at multiple data rates, by employing various modulation and channel coding schemes. For example, the 802.11b radio can use data rates of 1, 2, 5.5 or 11Mbps [3], while [2] demonstrates 802.15.4 rates of 0.25, 0.5, 1, and 2 Mbps. While the data rate adaptation helps saving energy (e.g., for some radio transceivers, a lower data rate is more energy efficient), it affects the end-to-end delay in delivering the packet to the destination. In this paper, we address the challenge of meeting the end-to-end delay guarantees, while operating in an energy efficient and robust manner. We propose a data rate selection algorithm that allows a radio transmitter to use the power sufficient enough for communication with a receiver, at the most energy efficient data rate. Previous work on energy efficient routing only considered the peak data rate and a fixed transmit power.

The primary contributions of this paper can be summarized as follows: i) we propose a novel energy saving technique, based on rate-adaptation for applications having end-to-end delay upper bound; ii) we formulate an optimization problem of finding the most energy efficient data rates for each link of a given path with the constraints of bandwidth and end to end delay, and provide an optimal solution; iii) based on the optimal solution, we introduce the adaptive data rate adjustment (ADRA) algorithm, which can be applied to real system with arbitrary type of multi-path routing protocols; iv) we provide an extensive simulations to compare with other state of the art energy efficient multipath routing protocols.

This paper is organized as follows. In Section 2, we motivate our work and formally describe the problem. In Sections 3 and 4, we introduce the system model and derive the optimal data rate, respectively. We present out adaptive algorithm for the data rate selection in Section 5, and its performance evaluation in Section 6. We present our conclusions in Section 8.

2. MOTIVATION AND PROBLEM FORMULATION

In order to achieve a desired data rate, the received signal strength must be higher than the corresponding receiver sensitivity. A typical data rate, receiver sensitivity mapping is shown in Table 1. Thus, based on the relationship between the data rate and the receiver sensitivity (if the channel gain g is known) the minimum transmission power for the selected data rate can be computed as: $P_{\min} = g \cdot P_{req}$. g can be obtained using broadcast messages. Broadcast messages are

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usually transmitted using maximum transmission power in order to avoid the hidden/exposed terminal problem. The link's condition can then be obtained as follows: $g = \frac{P_{\max}}{P_{rcv}}$, where P_{max} is maximum transmission power at the sending node, P_{rcv} is the received power at the receiving node and g is the link's condition.

We simulated energy consumption for data rates and receiver sensitivities shown in Table 1, corresponding to distances from 10m to 120m. Figure 1 shows that the per packet energy for lower data rate (of this particular radio transceiver) is always lower than that of the higher data rate.

Table 1: Receiver sensitivity for different data rates.

Data Rate (Mbps)	Receiver Sensitivity (dBm)
1	-95
2	-91
5.5	-86
11	-82

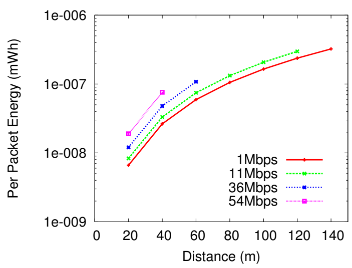


Figure 1: Minimum required received power corresponding to data rate

While changing the data rate has the potential to save energy, it increases the end to end delay due to longer transmission time and increased interference. The challenge we address is that given the application specific allowable end to end delay requirement and bandwidth, what are the optimal data rates for each link of a routing path to save the maximum amount of energy. We formulate this problem as an optimization problem that assigns the most energy efficient data rates to each link on a given routing path under the constraints of bandwidth and end to end delay threshold, as follows:

$$minimize \sum_{i=1}^{m} r_i \tag{1}$$

$$s.t. \;\; max\{r_i : 1 \leq i \leq m\} \leq B$$
$$\mathcal{T} - (\textstyle\sum_{i=1}^{m} MD_i(r_i) + \sum_{i=1}^{m} QD_i(r_i)) \geq 0$$

where, m is the number of links on a given path, B is the bandwidth requirement, $\mathcal{T}$ is the delay requirement, $QD_i(r_i)$ is the queueing delay of link l_i for data rate r_i, and $MD_i(r_i)$ refers to the medium access delay of link l_i when the data rate is r_i. Here we assume that the transmission delay TD_i of link l_i is negligible.

3. SYSTEM MODEL

We consider a network with uniformly distributed N nodes $\{n_1, n_2, ..., n_N\}$, each of which is equipped with a single-channel wireless transceiver that can communicate at different data rates. The data rate, representative of the PHY layer modulation scheme, requires different sensitivities, and assumed to have continuous value. We further assume that a loose time synchronization protocol is present.

We let n_{src} be the source node, n_{dst} be the destination node, and a set $\{\mathcal{P}_1, \mathcal{P}_2, ..., \mathcal{P}_n\}$ denote the multiple paths between the two nodes, each of which consists of a set of links, i.e., $\mathcal{P}_j = \{l_1, l_2, ..., l_m\}$, where l_i is a ith link of a jth path. Associated with each link, l_i, are the three types of delay as a function of data rate r_i of the link, namely, the transmission delay, medium access delay, and queuing delay, denoted $TD_i(r_i), MD_i(r_i)$, and $QD_i(r_i)$ respectively. The end to end delay $\mathcal{D}_j$ for $\mathcal{P}_j$ is simply the sum of all the delays for each link of the path as following:

$$\mathcal{D}_j = \sum_{l_i \in \mathcal{P}_j} (TD_i(r_i) + MD_i(r_i) + QD_i(r_i)) \tag{2}$$

3.1 Link Delay Estimation Model

We adopt the medium access delay estimation model [4] for adhoc networks (similar analysis can be performed for MAC protocols specific to sensor networks). A packet arrival follows Poisson distribution [5]. Let λ be the arrival rate. The probability that n packets arrive during time t is given as $P_n(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t}$. Consider a link l_j between the two nodes, n_i and n_j. Let $|Adj(i)|$ be the number of neighbors of n_i. Now $P^i_{idle}(t)$ can be defined as the probability that n_i senses the channel being idle during time t s.t. $P^i_{idle}(t) = e^{-\lambda(i)t}$, where $\lambda(i) = |Adj(i)| \cdot \lambda$. The medium access delay MD^r_j of a link l_j with data rate r can then be estimated as follows [4]:

$$MD^r_j = \frac{P^{(j)}_{AB}(RTS+SIFS+CTS+\overline{B})+DIFS+\overline{N}^r}{P^{(j)}_{AB} P^{(j)}_{BT}} - \overline{N}^r$$

where the following probabilities are used to estimate the medium access delay of a link l_j:

- $P^{(j)}_{AB}$: the probability that no nodes transmit packets during DIFS on link l_j:
$$P^{(j)}_{AB} = e^{-\lambda(j)DIFS}$$
- $P^{(i)}_{AN}$: the probability that n_i senses the channel busy during DIFS:
$$P^{(i)}_{AN} = 1 - e^{-\lambda(i)DIFS}$$
- $P^{(j)}_{BT}$: the probability that a node successfully exchanges RTS/CTS with its neighbor on link l_j:
$$P^{(j)}_{BT} = e^{-\lambda(j)2\delta - \Lambda(j)(RTS+SIFS+2\delta)}$$
where $\Lambda(j) = (|Adj(j)| - |Adj(i \cup j)|) \cdot \lambda$
- $P^{(i,j)}_{BN}$: the probability that n_i receives the NAV
$$P^{(i,j)}_{BN} = 1 - P^{(i,j)}_{BT}$$
- $\overline{N}^r$: expected NAV time for data rate r
$$\overline{N}^r = RTS + CTS + ACK + 3SIFS + T^{(r)}_{data} + 4\delta$$
where $T^{(r)}_{data} = s(packet\_size)/r(data\_rate)$.

- $\overline{B}$: mean random backoff time according to the binary backoff algorithm in CSMA/CA protocol

$$\overline{B} = \sum_{n=0}^{4} (P_{idle}^{(j)}(\eta)(1 - P_{idle}^{(j)}(\eta))^n \cdot 2^{n-1}W) + (1 - P_{idle}^{(j)}(\eta))^5 \cdot 2^4 W$$

where the minimum window size $= 32\eta$ and the maximum window size $= 1024\eta$.

Queueing delay is estimated such that $QD_j^r = \sum_{i=1}^{n} (QB_j^{r_i} \cdot MD_j^{r_i})$, where $QB_j^{r_i}$ is the number of packets queued in buffer with data rate r_i, and n denotes the number of available data rates.

3.2 Energy Model

We use the following energy model to estimate the energy consumption in a link with data rate r.

$$E_j = \mathcal{Q} \cdot P_{rcv}^r \cdot \frac{pkt\_size}{r} \cdot slot\_time + P_{proc} \cdot slot\_time,$$

where $\mathcal{Q}$ is the channel gain, P_{rcv}^r is the received power for data rate r ($\mathcal{Q} \cdot P_{rcv}^r$ is thus the minimum transmission power), and P_{proc} is the consumed power for processing a packet.

4. OPTIMAL DATA RATE SELECTION

In this section, we find the optimal data rate for each link that maximizes the energy saving while satisfying the delay and bandwidth guarantees.

THEOREM 4.1. *For a given path with delay constraint $\mathcal{T}$ and bandwidth constraint B, the optimal data rate for link i is given by:*

$$r_i = \sqrt{\frac{1 - \frac{1}{P_{AB}^{(i)} P_{BT}^{(i)}}}{1 - \frac{1}{P_{AB}^{(j)} P_{BT}^{(j)}}}} \cdot r_j, \quad i \neq j$$

where, $r_j = max\{r_i : 1 \leq i \leq m\}$, $1 \leq j \leq m$.

Proof:

The Lagrangian for the optimization problem is:

$$L(r_i, \lambda) = \sum_{i=1}^{m} r_i - \lambda_1(B - r_j) - \lambda_2(\mathcal{T} - (\sum_{i=1}^{m} MD_i^{r_i} + \sum_{i=1}^{m} QD_i^{r_i}))$$

The first order equalities are:

$$\frac{\sigma L(r_i, \lambda)}{\sigma r_1} = 1 + \lambda_2(\frac{1}{P_{AB}^{(1)} P_{BT}^{(1)}} - 1)\frac{s}{r_1^2} = 0$$

$$\dots$$

$$\frac{\sigma L(r_i, \lambda)}{\sigma r_j} = 1 + \lambda_1 + \lambda_2(\frac{1}{P_{AB}^{(j)} P_{BT}^{(j)}} - 1)\frac{s}{r_j^2} = 0$$

$$\dots$$

$$\frac{\sigma L(r_i, \lambda)}{\sigma r_m} = 1 + \lambda_2(\frac{1}{P_{AB}^{(m)} P_{BT}^{(m)}} - 1)\frac{s}{r_m^2} = 0$$

Note that $QD_i^{r_i}$ can be pre-computed regardless of r_i. Complementary slackness conditions are given as:

$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0$$

$$\lambda_1 \cdot (B - r_j) = 0 \quad (3)$$

$$\lambda_2 \cdot (\mathcal{T} - (\sum_{i=1}^{m} MD_i(r_i) + \sum_{i=1}^{m} QD_i)) = 0 \quad (4)$$

Consider Equation 4. Assume that $\lambda_2 = 0$ and substitute it into one of the first order equalities except for $\frac{\sigma L(r_i,\lambda)}{\sigma r_j}$. Then we get $1 = 0$, a contradiction. Hence, $\mathcal{T} - (\sum_{i=1}^{m} MD_i(r_i) + \sum_{i=1}^{m} QD_i) = 0$, which implies that the optimal data rate is achieved when the resulting delay hits the threshold $\mathcal{T}$. Now assume that $(B - r_j) = 0$ in Equation 3, that is, r_i $(1 \leq i \leq m)$ is optimal when $r_j = B$. Consider the route consisting of only a single link l_1. Since l_1 is the only link, the data rate of this link r_1 is automatically the maximum data rate, i.e., $r_1 = r_j$. By assumption, r_1 is optimal when it is B regardless of the delay threshold $\mathcal{T}$, which is a contradiction. Hence, $\lambda_1 = 0$.

After substituting $\lambda_1 = 0$ into $\frac{\sigma L(r_i,\lambda)}{\sigma r_j}$, we solve the equalities with respect to the data rate r_i:

$$r_i^2 = \lambda_2(1 - \frac{1}{P_{AB}^{(i)} P_{BT}^{(i)}})s, \quad i \neq j$$

$$r_j^2 = \lambda_2(1 - \frac{1}{P_{AB}^{(j)} P_{BT}^{(j)}})s$$

To eliminate λ_2, we divide r_i by r_j:

$$r_i = \sqrt{\frac{1 - \frac{1}{P_{AB}^{(i)} P_{BT}^{(i)}}}{1 - \frac{1}{P_{AB}^{(j)} P_{BT}^{(j)}}}} \cdot r_j$$

□

5. ADAPTIVE DATA RATE SELECTION

In this section, we describe an adaptive data rate adjustment (ADRA) algorithm. The algorithm is based on a greedy approach to approximate the optimal result using the finite set of available data rates in dynamically changing traffic. The source node n_{src} builds multiple paths when it wants to send a packet to the destination node n_{dst}. Once the paths are set up, n_{src} starts sending a packet along the multiple paths using "round robin" method. n_{dst} maintains a timer for each path. When the timer expires, the adaptive data rate adjustment (ADRA) algorithm starts to run to recompute the data rate for each link.

In the algorithm, n_{dst} first compares the measured end to end delay $\mathcal{D}_i$ with the end to end delay requirement $\mathcal{T} + \epsilon$. ($\mathcal{D}_i$ is measured by allowing n_{src} to piggyback the timing information when it enqueues the packet so that when the packet is received at n_{dst}, this timing information is subtracted from the packet reception time, yielding the measured end to end delay value.) If the measured delay of $\mathcal{P}_i$ does not meet the delay requirement, this path is not used until the next path setup. Otherwise, n_{dst} executes the initialization phase (Line 3), in which for each link l of the path $\mathcal{P}_i$, delay gain (d^+), delay loss (d^-), energy gain (e^+), and energy loss (e^-) are computed using the link delay estimation model and the energy model introduced in Section 3.

After the initialization phase, n_{dst} attempts to decrease data rate (Line 5-16) if the measured delay $\mathcal{D}_i$ is smaller than the delay threshold. n_{dst} first computes the "delay margin" (denoted $\mathcal{M}$) which is the maximum amount of delay that we can increase by lowering data rate without exceeding the

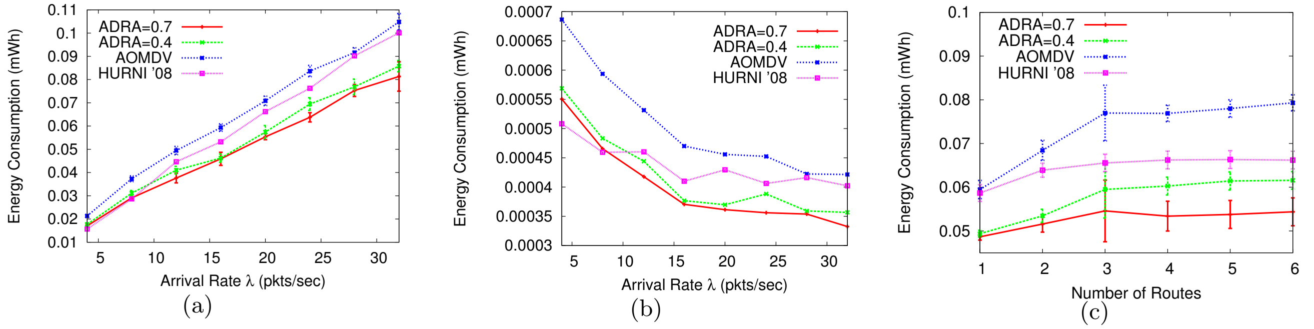


Figure 2: a) Total energy consumed in the network when one data stream is present; b) per packet energy consumed in the network when one data stream is present; c) the effect that the maximum number of routes has on the total energy consumption.

Algorithm 1 Adaptive Data Rate Adjustment (ADRA)

Input: $r \in R = \{1Mbps, 2Mbps, 5.5Mbps, 11Mbps\}$
Output: $r'(l)$ /* new data rate for each link */

if $\mathcal{D}_i \leq \mathcal{T} + \epsilon$ **then**
  for each link l on $\mathcal{P}_i$ **do**
    compute $d^+(l,r), e^+(l,r), \forall l, \forall r < current\_rate$
    compute $d^-(l,r), e^-(l,r), \forall l, \forall r > current\_rate$
  end for
  if $\mathcal{D}_i \leq \mathcal{T}$ **then**
    $\mathcal{M} \leftarrow \mathcal{T} - \mathcal{D}_i$
    while $\mathcal{M} \geq 0$ **do**
      find l s.t. $\max_l\{e^+(l,r)\}$
      if $d^+(l,r-1) \leq \mathcal{M}$ **then**
        $\mathcal{M} \leftarrow \mathcal{M} - d^+(l,r-1)$ /* $r-1$ refers to the */
        $r'(l) \leftarrow r-1$ /* previous element of r in R. */
      else
        return
      end if
    end while
  end if
end if

delay threshold. Next, n_{dst} finds the link that can save the maximum amount of energy among all the links on the path when the data rate is lowered. If the increase in the link delay due to the lowered data rate does not exceed the delay margin, n_{dst} lowers the data rate of the link. This procedure is repeated until the delay requirement is met. However, due to the error of the link delay estimation model and the dynamic nature of network traffic, the end to end delay may exceed the threshold during the operation. In this case, we decrease the delay by increasing the data rate. The logic for increasing data rate is very similar (uses $d^-(l,r)$ and $e^-(l,r)$ instead) with that of decreasing data rate.

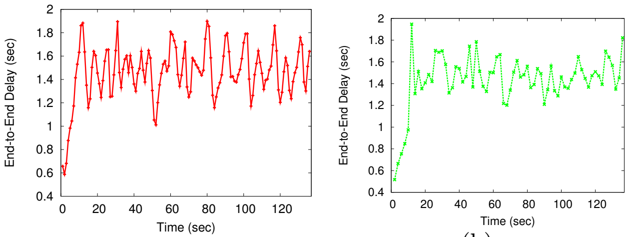
6. PERFORMANCE EVALUATION

We performed simulations using GlomoSim [6]. The radio range of a node was approximately 82m. We uniformly deployed 64 nodes in $250{\times}250\text{m}^2$ region. A source node generated traffic which follows the Poisson packet arrival [5]. The packet size was 512B. We used 802.11b MAC protocol. Each simulation was performed for 120 seconds. Results represent averages over 30 runs. Our ADRA algorithm was implemented on top of AOMDV [7]. We compare the energy efficiency of our scheme with AOMDV, and for fairness, with one other recently introduced AOMDV-based energy efficient multipath routing protocol HURNI [8].

Energy Consumption. Figure 2(a) depicts the total energy consumption for AOMDV, HURNI, and ADRA with delay requirement of 0.7sec and 0.4sec. As figure shows, the energy consumption for all protocols increases as λ increases. This is because with higher λ, more packets are transmitted. In particular, AOMDV consumed higher energy compared with ADRA, since it used a peak data rate for each link. Even though HURNI showed a lower energy consumption than that of AOMDV by using less number of routes, it still consumed more energy than our scheme did. Also note that there was a slight difference in energy consumption between ADRA with delay threshold of 0.7 sec and ADRA with delay threshold of 0.4sec. This is because the higher delay threshold allowed a lower data rate can be chosen. Figure 2(b) depicts the per packet energy for the three different protocols, showing the energy efficiency of our scheme.

Number of Routes. Figure 2(c) depicts the total energy consumption as a function of the maximum number of routes. The maximum number routes is a parameter that bounds the number of paths that AOMDV can establish. As shown in the graph, the total energy consumption increased as the maximum number of routes increased, but it stopped increasing from when the maximum number of routes is 3. This implies that in our simulation scenario, the average number of routes that AOMDV can build is roughly 4. There are two reasons for the increase in energy consumption. The first reason is the increased interference. As the network has more paths, the inter and intra path interference increases, and this causes a higher chance of a packet retransmission. Second reason is that as the number of paths increases, a path with more hop counts is established, which involves more transmissions to deliver a packet.

Interval for Data Rate Adjustment. Selecting an appropriate interval for data rate adjustment is a difficult problem, because the decision depends on various factors such as network condition, available number of data rates, and packet arrival rate. Figure 3(a) and Figure 3(b) show the end to end delay change as a function of time when the delay threshold was 1.5sec. The lower interval for data rate adjustment is expected to keep the end to end delay close to the delay requirement due to the frequent data rate update. However, this is not always the case because of the traffic



(a) (b)

Figure 3: Dynamic data rate adjustment for an intervals of 1sec and 2sec.

caused by the control packets. As shown in the graphs, there are higher spikes in the result of 1sec interval than that of 2sec interval. This shows that selecting a lower data rate does not always provide a good result. In typical 802.11b, we can choose only four different data rates: 1, 2, 5.5, and 11Mbps. As long as we have to make a discrete selection like in 802.11b, the fluctuation in resulting end to end delay is inevitable. In other words, sometimes, the algorithm changes the data rate from 11Mbps to 5.5Mbps even though the estimated end to end delay is only slightly below the delay threshold. This change in data rate, however, will result in abrupt spike in end to end delay.

7. RELATED WORK

Two different types of data rate selection algorithm have been proposed. One is based on the reception of ACKs. After receiving a number of ACKs, the sender adapts the data rate. Auto rate fallback (ARF) is proposed in [9], with more dynamic rate adjustment schemes in [10] [11]. However, these schemes select date rate at the sender. The estimated channel quality at the sender is less accurate than the estimated channel quality at the receiver. In addition, it is hard to decide to adapt data rate after a fixed number of ACKs, given that the channel condition varies frequently. The second one, on which we base our work, is the SNR-based data rate selection algorithm [12] [13]. The receiver monitors the received power and sends the feedback about the channel quality information to the sender. The channel quality is exchanged in RTS-CTS duration. The sender adapts the data rate according to the information. The SNR-based data rate selection algorithm is more accurate because the receiver provides more timely and more complete channel quality information.

Routing with data rate adjustment has been investigated in [14] [15] [16] [17]. Zeng et al. [14] proposed a new metric to avoid using the long range links often selected by shortest path routing. Multiple data rates have been recently addressed in opportunistic routing in [15] [16] [17]. These schemes improve the network throughput, but they do not consider energy-efficiency.

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8. CONCLUSION AND FUTURE WORKS

This paper addresses a fundamental issue for wireless adhoc and sensor networks: saving energy while meeting end-to-end delay guarantees required by real-time applications, and robust operation. We propose a data rate adaptation algorithm that maximizes energy savings, while meeting the end-to-end delay guarantees. We investigate how robustness guarantees, through multipath routing, affect the energy savings of our scheme. Additional preliminary results, omitted due to space constraints, constitute the basis for future work: the development of algorithms for better selection of multipath routes and the analysis of how interference between intra and inter routes affect data rate selection.

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