Adapting Transmission Power for Optimal Energy Reliable Multi-hop Wireless Communication

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(Extended Abstract)

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***Abstract*— We define a transmission power adaptation-based routing technique that finds optimal paths for minimum energy reliable data transfer in multi-hop wireless networks. This optimal choice of the transmission power depends on the link distance between the two nodes and the channel characteristics. Typical energy efficient routing techniques use a transmission power such that the received signal power at the destination minimally exceeds a desired threshold signal strength level. In this paper we argue that such a choice of the transmission power does not always lead to optimal energy routes, since it does not consider differences in the receiver noise levels.**

We first analyze the optimal transmission power choices for both the ideal case from an information-theoretic perspective, and for realistic modulation schemes. Subsequently we define our technique for transmission power adaptation that can be used in existing routing protocols for multi-hop wireless networks. Our simulations show that current best-known schemes incur upto 10% more energy costs in low noise environments, and upto 165% more energy costs in high noise environments compared to our proposed scheme.

I. Introduction

We define a distributed route computation technique that computes minimum-energy paths for reliable multi-hop wireless communication. This technique consists of two parts — (1) adaptation of the transmission power level for each wireless link, and (2) assignment of link costs to individual links which will be used by standard routing protocols to compute end-to-end paths. Both these mechanisms take into account the specific channel characteristics of the links and are necessary and sufficient to compute the optimal energy-efficient path for reliable communication. In this work we show that our technique is optimal, i.e. it computes the minimum-energy path for *reliable packet delivery* in a multi-hop wireless network.

Typical minimum-energy routing protocols for multi-hop wireless networks assign the transmission power required to sustain communication over a link as the link cost. Subsequently they use standard route computation techniques to obtain appropriate end-to-end paths. Due to the properties of wireless signal attenuation these algorithms observe that the total energy requirements for packet transfer over the entire path can be minimized by choosing a route consisting of a large number of small-distance hops over an alternative one with a small number of large-distance hops [3], [4]. However, these algorithms do not necessarily yield minimum-energy paths for reliable packet delivery. This is because the the link metrics in these algorithms depend solely on the energy spent in a single transmission attempt and do not capture the additional energy expended on retransmissions in the presence of link errors. In [2] the authors had shown how link costs should be assigned to account for the total energy spent in reliable packet delivery, which also includes energy consumed in packet retransmissions. However the authors in [2] continue to make the assumption that the transmission power level on an individual link is determined solely by the corresponding link distance. In this work, we argue that such a choice of transmission power level is not optimal in finding minimum energy costs — appropriate adaptation of the transmission power based on the channel noise characteristics is a crucial component in reaching this objective.

An extended version of this paper appears as a Technical Report [1].

II. Optimal Transmission Power for Individual Links

In our analytic study we first use an information-theoretic approach to show how the optimal transmission power and the associated minimum reliable transmission energy depends on both the link distance and the channel characteristics. Since the resulting bounds are essentially theoretical and not practically realizable due to severe buffering and delay constraints, we then apply our framework to practical channel models. Due to space constraints in this extended abstract, we only summarize the main results. Specific details of the analysis can be found in [1].

A. Information-Theoretic Bounds on Optimal Transmission Power

We utilize the information-theoretic bound on the maximum capacity of the well-known band-limited Gaussian channel in order to ascertain the existence of an optimal transmission power for energy efficient reliable data forwarding across a link. The Gaussian channel models an environment where the noise component (both thermal and due to interfering transmissions) at the receiver is assumed to have a Gaussian spectral distribution and is additive in nature. In our analysis we use Shannon's channel capacity theorem to show that if a node transmits at a power level P_t, it follows that the *normalized reliable transmission energy* (i.e. the energy needed per bit of reliable transfer) is related to its transmit power level, P_t, as :

$$E(P_t) = \frac{P_t}{W \times \log_2(1 + \frac{P_t}{D^\alpha \times \eta \times W})} \quad (1)$$

where W is the spectral width of the channel, η is the spectral noise density, and D is the distance between the transmitter and the receiver. This an increasing function of P_t.

Thus in theory, the smaller we make the transmission power, the more energy-efficient the communication process. The greatest energy efficiency (lowest cost per reliably transferred bit) is achieved as $P_t \downarrow 0$.

This minimum energy value can be obtained by applying the L'Hospital's rule to Equation 1, as is given by:

$$E_{opt} = \ln 2 \times \eta \times D^\alpha \quad (2)$$

Therefore, *every channel is associated with a fundamental theoretical (non-zero) lower bound on the minimum energy needed to reliably transfer a single bit.*

The above results show that maximum energy efficiency is achieved by transmitting at as low a power level as possible, and that a non-zero communication rate can be sustained even if the received power is much smaller than the channel noise. This is clearly not possible in any *practical* communication system with realistic bounds on the transfer latency. Indeed, Shannon's result is based on the use of asymptotically long coding sequences, resulting in unbounded transmission delays. Now we will consider a *practical* communication sub-system. We shall then see that there exists a non-zero optimal transmission power-level P_t^*: while smaller values of the transmission power result in a sharp increase in the total number of retransmissions needed, values larger than the optimum end up wasting unnecessarily large amounts of energy in a single transmission.

B. Optimal Transmission Power for Practical Modulation Schemes

Consider a wireless channel with a simple retransmission based error correction mechanism; if a data packet is lost in transmission across any link, it is retransmitted by the upstream node of that link. Assuming independent packet losses, the expected number of transmissions needed for the reliable transfer of one data packet across any link is $1/(1-p)$, where p is the packet error rate of the link. Let us assume that data packets are L bits long. Then for such a wireless channel with data transmission rate, f, the normalized reliable transmission energy (energy required per bit of reliable transfer) is given by:

$$E(P_t) = \frac{L}{f} \times P_t \times \frac{1}{1 - p(P_t)} \times \frac{1}{L} \quad (3)$$

The packet error rate depends on the chosen transmission power, P_t, and hence so does the normalized energy requirements. The packet error rate can be computed as:

$$p(P_t) = 1 - (1 - p_b(P_t))^L \quad (4)$$

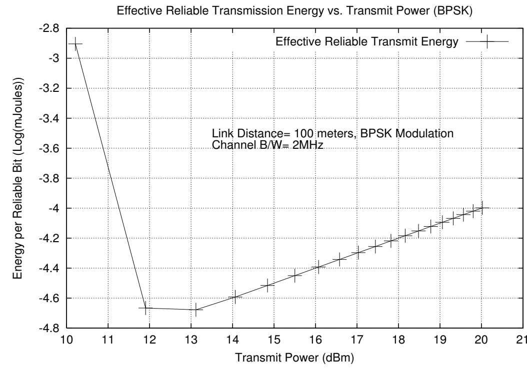

Fig. 1. Reliable Transfer Energy Behavior (BPSK)

where p_b is the bit error rate of the wireless channel. Consider Binary Phase Shift Keying (BPSK) as an example of a practical channel modulation scheme, where the bit error rate is given by:

$$p_b = 0.5 \times erfc(\sqrt{\frac{P_t \times W}{D^\alpha \times N_r \times f}}) \quad (5)$$

where D is the link distance, W is the channel bandwidth, N_r is the noise signal power, and and f is the data transmission rate. BPSK modulation is used in wireless environments, for example in the 1 Mbps version of the IEEE 802.11 wireless LAN standard.

In Figure 1 we plot the variation in $E(P_t)$ for a channel employing BPSK modulation as a function of the transmission power P_t and a packet size of 1000 bytes. We set the channel parameters to be representative of the 802.11b standard, with a bit rate of 1 Mbps and a noise bandwidth (post de-spreading) of 2 MHz. The link distance D is 100 meters and the spectral noise N_r is 4.0×10^{-11} W. We can see that the optimal transmission power for this channel exists, and is ≈ 20 mW.

In our analysis we have also explored how the optimal transmission power for a link varies with changes in link distance. Our results show that this optimal transmission power *increases at a slightly slower rate than* D^α where α is the constant is the signal attenuation model. Accordingly, conventional protocols, such as [2], [3], [4], which assign link costs to be proportional to D^α, penalize longer links more than needed. From Equations 3, 4, and 5 it also follows that the optimal transmission power depends on the spectral noise in the channel. Our study also showed that a policy of maintaining a "constant target Signal to Noise Ratio" at the receiver (by appropriately adjusting the transmission power) is a good informal rule that achieves "close to optimal" energy efficiency. In the full version [1] of this paper, we also show how the optimal energy efficiency of a practical modulation scheme compares with the theoretical lower bound provided by Equation 2.

III. MINIMUM ENERGY ROUTING — ASSIGNING LINK COSTS

Consider a node that transmits a packet with transmit power P_t across a link. Let the corresponding energy required for

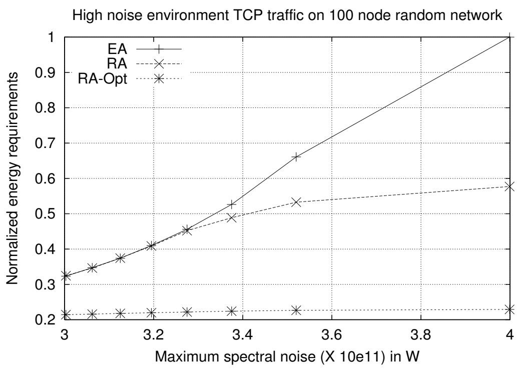

Fig. 2. Normalized energy costs for TCP flows (High Noise Random Topology).

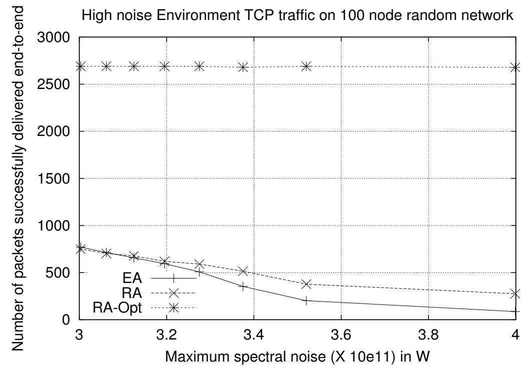

Fig. 3. Comparison of throughput for TCP flows (High Noise Random Topology).

this single transmission be E_t. (Assuming packets are of constant size, E_t differs from P_t by a proportionality constant.) Let E_{max} be the packet transmission energy corresponding to the maximum transmission power level at which the node can transmit. Similarly let E_{min} be the packet transmission energy corresponding to the minimum transmission power necessary to ensure that the signal strength at the receiver exceeds a desired threshold.

In this extended abstract we only describe the scenario where the wireless links implement link-layer retransmissions to recover from packet losses. However our proposed technique is equally applicable for alternative link layer reliability mechanisms like forward error correction. In another alternative scenario, if the wireless links do not implement any recovery mechanisms, data needs to be recovered using end-to-end retransmissions. Description of these alternative cases can be found in the full version of the paper [1].

Let $p(E_t)$ denote the packet error probability corresponding to the packet transmission energy, E_t. The optimal value of the energy required for reliable packet delivery across a single link is given by the solution to:

$$\frac{d}{dE_t} E_t(reliable, HHR) = 0 \tag{6}$$

$$\frac{d^2}{dE_t{}^2} E_t(reliable, HHR) \geq 0 \tag{7}$$

where $E_t(reliable, HHR) = E_t/(1 - p(E_t))$. It follows that this optimal value, E_t^*, that minimizes the energy cost for a link satisfies:

$$E_t^* . p'(E_t^*) - p(E_t^*) = 1 \tag{8}$$

where $p'(.)$ denotes the first derivate of $p(.)$ with respect to E_t. E_t^* can be computed using efficient numerical techniques. However, this optimal solution may exceed E_{max}. In such a case our choice of optimal transmission energy, $E_t^* = E_{max}$. Similarly if the computed E_t^* falls below E_{min}, we assign $E_t^* = E_{min}$. In the routing protocol, we assign each wireless link a cost which is given by energy required for reliable packet transmission across that link, given by $E_t^*/(1 - p(E_t^*))$. The end-to-end route can therefore be computed in a distributed manner by any standard routing protocol capable of computing minimum cost paths. It follows that shortest cost path found by the routing algorithm will be the *optimal energy-efficient route* for that end-to-end path.

IV. Simulation Results and Conclusions

We have performed extensive simulation-based studies on the performance impacts of our proposed modifications in the *ns-2* simulator. In this extended abstract we only present some sample results for randomly generated topologies of 100 wireless nodes with 12 TCP source-destination pairs. We compare three schemes — (a) Energy-Aware (EA) scheme in which link costs are assigned based only the energy requirements for a single transmission attempt across the link. This scheme does not account for energy requirements for retransmissions and is equivalent to [3], [4], (b) Re-transmission Aware (RA) scheme [2] in which link costs also account for energy required for retransmissions, and (c) our proposed Optimal Re-transmission Aware (RA-Opt) scheme which additionally performs optimal adaptation of transmission power. Figure 2 shows compares the enenergy requirements of the different schemes, normalized with respect to the specific experiment which had the maximum energy consumption. Figure 3 shows the corresponding data throughput achieved over the same time interval. The RA-Opt scheme consumes significantly lower amount of energy per bit for reliable data transfer (Figure 2) , and still achieves significantly higher throughputs (Figure 3).

In different experiments we observed that our proposed techniques can provide significant energy savings over the best existing schemes [2], [3], [4] — about 10% energy savings in low-noise environments, and about 165% energy savings in high-noise environments. Our detailed study can be found in [1].

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