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

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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 reliable data transfer over a single link. We do this analysis for both the ideal case from an information-theoretic perspective, and also 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. Through detailed simulations we 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

Most minimum-energy routing protocols for multi-hop wireless networks assign link costs as some function of the transmission power used to sustain communication over a link. The signal attenuation on a wireless link, $\langle i, j \rangle$ typically varies as $D_{i,j}^{\alpha}$ for $2 \leq \alpha \leq 4$, where $D_{i,j}$ is the distance between the nodes i and j. Algorithms that compute end-to-end minimum energy paths typically assume that transmitter nodes can dynamically vary the transmission power levels for packet transmission. Therefore, 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 [8], [17]. However, these algorithms do not necessarily yield minimum-energy paths for *reliable packet delivery:* since the link metrics of such algorithms depend solely on the energy spent in a single transmission, they do not capture the effects of transmission errors, and the additional energy expended on retransmissions in the presence of link errors.

In this paper, we consider algorithms for computing minimum-energy paths for reliable wireless communication. Our approach leverages the techniques employed in [1], which showed how link costs can be modified to account for the energy spent in reliable packet transmission. Such a cost incorporates both the power needed for a single transmission,

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and the number of retransmissions needed to achieve reliable packet forwarding. However, [1] continues to make the assumption that the transmission power level on an individual link is determined *solely* by the corresponding link distance and that the *transmission error probability is independent of the transmission power level.* In this paper, we argue that such a choice of transmission power level is not optimal in finding minimum energy costs — to achieve this objective, the transmission power must be adapted in a more sophisticated way.

We first focus on determining the optimal power level for reliable communication *over a single link.* Our approach is motivated by the fundamental observation that the error rate for a particular link is not independent of the transmitted signal power but is strongly influenced by it. More accurately, the error rate for packet reception is a function of both the received signal power, the channel conditions and noise levels at the receiver. An optimal choice of the transmission power must balance the energy spent in a single transmission with the error rate (and thus the expected number of retransmissions needed) generated by that power level. Since the channel conditions and receiver noise conditions for different links are essentially independent and can exhibit considerable variation, it follows that the optimal transmission power for different links can be appreciably different, *even if the links have the same distance.*

We provide a mathematical framework for deriving the optimal transmission power and minimal reliable transmission cost as a function of the link's characteristics. In particular, we initially use results from information theory to establish that any link is associated with a lower bound on the optimal energy efficiency (the energy needed per bit of reliably transmitted information), and that this optimal energy efficiency is achieved asymptotically as the transmission power $\downarrow 0$. This theoretical result is, however, misleading in practice since supporting such infinitesimal power levels requires asymptotically infinite channel code words, and leads to an unbounded increase in the communication latency. For a more practical perspective, we consider the case of a commonly used wireless LAN modulation scheme and derive the associated optimal transmission power level. In particular, our analysis demonstrates the existence of an optimal transmission power level in such schemes, such that a reduction or an increase in the transmission power both lead to a higher energy cost per reliably transferred bit. We also show how the transmission power level affects the retransmission probability, and hence, the average communication latency. These results also demonstrate how the transmission power level can also be used to effectively *trade off between the energy efficiency and the latency of data transfer.*

A. Key Idea

Consider a frame is transmitted by a node, t, with transmit power, P_t and is detected by the receiver, r, at power level, P_r. Assuming the use of omni-directional antenna, and the use of homogeneous receivers at all nodes, P_r can be related to the transmit power P_t as :

$$P_r = \kappa \times \frac{P_t}{D^{\alpha}} \tag{1}$$

where κ is a proportionality constant. Since our focus is more on investigating the relative nature of the relationship between P_r and P_t, we assume $\kappa = 1$ without any loss of generality in the rest of the paper. The path attenuation coefficient α has been typically observed to be ~ 2 for short-distance links (less than 100 meters) and ~ 4 for longer links in the 2.4 GHz transmission band. In the model used in [1], the authors assume that the nodes choose the transmit power, P_t, such that the received power at the destination is at least P_{thresh}, a threshold value. Based on this assumption, minimum energy consumption is achieved with the transmit power chosen such that the received power *minimally exceeds* the threshold, i.e.

$$P_t = P_{thresh} \times D^{\alpha} \tag{2}$$

In this paper we argue that such a choice of the transmission power across a link does not always provide optimal energy costs. In the reliable data transfer case, a frame may need to be retransmitted more than once to guarantee delivery. Choosing a transmission power higher than a minimum necessary value has a significant impact on the link error rate. More specifically, increasing the transmission power leads a decrease in the link error rate, and consequently a decrease in the potential number of frame retransmissions necessary.

This is a crucial observation in choosing the transmission power for reliable data transfer. In our paper, we show how the transmission power for packet transmission across each wireless link needs to be chosen so that the cost of reliable transmission is minimized across that link. Additionally, we show that such a choice of transmission powers lead to the *absolute minimum* end-to-end energy costs for reliable packet delivery across a multi-hop wireless network.

Our simulation studies show that such an intelligent adaptation of the node transmission power helps in significantly reducing the energy requirements for end-to-end reliable packet delivery. More specifically, non-adaptive schemes incur upto 10% more costs in low noise environments, and upto 165% more costs in high noise environments, than our adaptive scheme.

We shall explain why a traditional minimum cost routing algorithm can be applied in this scenario only when link layer retransmissions are used. If reliability is only possible through end-to-end retransmissions between a packet source and its final destination (for example, using a reliable transport layer such as TCP), the multiplicative nature of error probabilities makes the derivation of a globally optimum solution intractable. However, link-layer retransmissions is an inherent feature of almost all wireless link-layer protocols due to the potentially high link error rates (often as large as $20 - 40\%$ for individual transmissions) in wireless environments. Accordingly, our proposed link-adaptation algorithm can be combined with standard minimum-cost routing algorithms to yield optimum-energy paths in almost all practical cases of interest.

Our problem formulation and routing solution assumes that each node in the ad-hoc network is able to detect the packet error rate on its outgoing links. Sensing the channel noise conditions can be done either at the link layer, a capability that is built into most commercial wireless 802.11 interfaces available today, or through higher layer mechanisms such as periodic packet probes or aggregated packet reception reports from the receiver [1].

B. Roadmap

The rest of this paper is organized as follows. In the next section we describe currently known techniques for energy aware routing in wireless environments. In Section III we formulate a framework to determine the choice of transmission power that leads to optimal energy consumption across a single link for both ideal and practical modulation schemes. In Section IV we describe the optimally minimum energy routing scheme using adaptive transmission power

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[1] Similar ideas were proposed for link sensing in the Internet MANET Encapsulation Protocol [4] which is used by another ad-hoc routing protocol (TORA [13]).

at the nodes. In Section V, we present results from detailed simulation studies under realistic wireless environments using the *ns-2* simulator [2]. Finally, we present our conclusions in Section VI.

II. RELATED WORK

Metrics used by conventional routing protocols for the wired Internet typically perform minimum-hop routing (or sometimes "widest-shortest path routing" that takes into account the available bandwidth at links [10]), but does not consider any energy-related parameters. In fixed-power scenarios, the minimum-hop path would also correspond to the path that uses the minimum total energy for a single transmission of a packet.

In contrast, energy-aware routing protocols (e.g. PAMAS [17] and PARO [8], [9]) for variable-power scenarios aim to directly minimize the total power consumed over the entire transmission path. In particular, PAMAS is a MAC-layer protocol that conserves battery power by intelligently powering off nodes that are not actively transmitting or receiving packets, and by using control fields in MAC headers to adjust the transmission power to the minimum level needed to ensure that the receiver signal strength lies above a specified threshold. Minimum-cost routing protocols can then be employed to compute energy efficient paths by simply setting the link cost to the transmission power level.

In the case where nodes can dynamically adjust their power based on the link distance, such a formulation often leads to the formation of a path with a large number of hops. A link cost that includes the receiver power as well is presented in [16]. This approach results in the selection of paths with smaller number of hops than PAMAS.

The basic idea of optimizing communication energy over wireless links has been explored fairly extensively in literature. However, the focus has been on the use of intelligent *link scheduling* algorithms, rather than on transmission power control, to minimize the energy wastage in unsuccessful (re)transmissions. For example, Zorzi and Rao [20] proposed the use of short, periodic probe packets to detect the recovery of a channel from the bad to good state; actual data packet transmissions were deferred during the 'bad' state. A similar idea for energy-efficient scheduling of packets from a base station to a set of downstream wireless hosts has been explored in [2], [15], [5].

Ad-hoc routing protocols aim to compute minimum-cost paths; in contrast to generic (non ad-hoc) routing protocols, they contain special features to reduce the signaling overheads and convergence problems caused by node mobility and link failures. So, ad-hoc protocols, such as AODV [14] or DSR [11], can (in principle) be adapted, with suitable modifications, to yield minimum-energy paths by setting the link metric to be a function of the transmission energy.

Apart from minimum energy path problem, research in in energy-aware routing has also focused on other problems with related objectives. For example, *battery-aware routing* algorithms typically aim to extend the lifetime of all the ad-hoc nodes by distributing the transmission paths among nodes that currently possess greater battery resources. Typical solutions to this problem have been based on a residual capacity formulation [18], [19], [12]. While minimum energy algorithms are most efficient, these network lifetime maximizing schemes are more "fair." A combination of both these approaches can therefore be useful as shown in [19], [12].

Link error probabilities have been considered for single hop spread spectrum links in [7]. In contrast, we focus on end-to-end energy costs for multi-hop wireless networks.

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[2] Available at http://www.isi.edu/nsnam/ns.

III. OPTIMAL TRANSMISSION POWER FOR INDIVIDUAL LINKS

In this section, we develop the theoretical model for estimating the 'optimal' transmission power level. In particular, we first perform an information-theoretic study of 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.

A. Information-Theoretic Bounds on Optimal Transmission Power

We first utilize the information-theoretic bound on the maximum capacity of the well-known band-limited Gaussian channel and try to ascertain the existence of an optimal transmission power in this case. 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. Information theory shows that the idealized information transfer rate (in bits/sec) on such an Additive White Gaussian Noise (AWGN) channel with a spectral width of W Hz and a spectral noise density of η Watts/Hz varies with the power P_r of the received signal as

$$C = W \times \log_2(1 + \frac{P_r}{\eta \times W}) \text{ bits/s} \tag{3}$$

C represents an upper bound on the maximum amount of information that can be transferred per unit time by any realizable and consistent signaling scheme on this channel. Since the received signal strength is related to the transmission power at the sender by the expression $P_r = \frac{P_t}{D^\alpha}$, the relation between the transmitter power and the maximum possible rate of reliable data transfer is then:

$$C(P_t) = W \times \log_2(1 + \frac{\frac{P_t}{D^\alpha}}{\eta \times W})\text{bits/s} \tag{4}$$

Since a node is transmitting at a power level P_t, it follows that the *normalized reliable transmission energy* (or the energy needed per bit of reliable transfer) is related to its power level as :

$$E(P_t) = \frac{P_t}{W \times \log_2(1 + \frac{\frac{P_t}{D^\alpha}}{\eta \times W})} \tag{5}$$

To study this behavior graphically, Figure 1 plots $E(P_t)$ for a set of typical values encountered in IEEE 802.11 [3] wireless LAN based networks, with a link distance $D = 100$, a channel bandwidth of 2 MHz and a spectral noise $\eta \times W$ of 4.0 × 10^{-11}W. The above plot demonstrates a very interesting aspect of the theoretical behavior of the optimal transmission energy. Due to the sub-linear (logarithmic) nature of the denominator in Equation 5, *the normalized (ideal) transmission energy is an increasing function of the transmission power.* In other words, from a theoretical perspective, we achieve maximum energy efficiency (lowest cost per reliably transferred bit) as $P_t \downarrow 0$. Thus, at least in theory, there is no optimal transmission power level — the smaller we make our transmission power, the more energy-efficient our communication process. In particular the normalized transmission energy of a packet approaches the minimum value as $P_t \rightarrow 0$ This minimum value can be obtained by observing that both the numerator and the

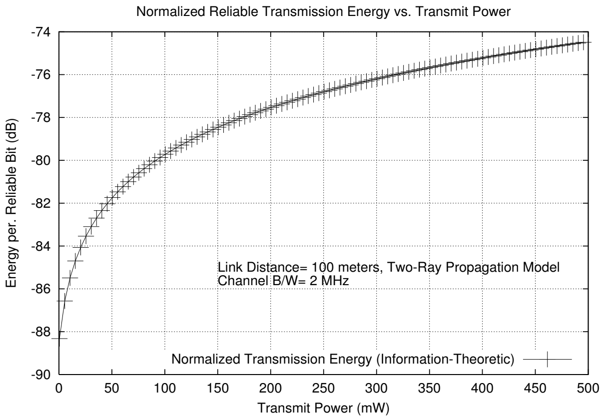

Fig. 1. Idealized Energy per Bit vs. Transmission Power

denominator of Equation 5 $\rightarrow\ 0$ as $P_t \downarrow\ 0$. Accordingly, by applying the L'Hospital's rule and differentiating both the numerator and denominator, we can see that:

$$E_{opt}(channel) = ln(2) \times \eta \times D^{\alpha}. \tag{6}$$

In other words, the optimal energy cost associated with reliable information transfer is directly proportional to the rate of attenuation with link distance (D^{α}). For example, for the channel of Figure 1, this bound on the normalized transmission energy/bit is given by $ln(2){*}100^4{*}2{*}10^{-17}$ Joules/bit ≈ -128 dB. 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. In the next sub-section, we shall, however, consider a *practical* communication sub-system. We shall then see that there indeed exists an 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 activity.

B. Information Capacity for Practical Modulation Schemes

An information-theoretic evaluation of the normalized reliable transmission energy only serves as a theoretical performance bound. Practical systems must consider additional tradeoffs between the implementation complexity, the processing delays and the sustainable data rates. We now consider the performance of such communication systems and show how the performance of a single such link can be optimized by appropriate variation in the transmission power.

The relation between the bit error rate p_b and the received power level P_r in most modulation schemes follows the generic relationship:

$$p_b \propto erfc(\sqrt{\frac{constant \times E_r}{\eta}}, \tag{7}$$

where η is the noise-spectral density, E_r is the received energy per bit, and *erfc*(x) is defined as the complementary function of *erf*(x) and is given by

$$erfc(x) = 1 - \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$

As specific examples, the bit error rate for coherent OOK (on-off keying) is given by $p_b = erfc(\sqrt{\frac{E_r}{2\times\eta}})$, for M-ary FSK (frequency shift keying) by $p_b = (M-1) \times erfc(\sqrt{\frac{E_b \times \log_2 M}{\eta}})$ and for binary PSK (phase-shift keying) by $p_b = 0.5 \times erfc(\sqrt{\frac{E_r}{\eta}})$. Now, the energy per transferred bit E_r is related to the receiver signal strength by the expression $E_r = \frac{P_r}{f}$, where f is the raw channel bit-rate, and the noise-spectral density is related to the noise signal power N_r as $\eta = \frac{N_r}{W}$, where W is the channel bandwidth (in Hz). Accordingly, the energy per transferred bit is related to the noise spectral density by the generic relation:

$$\frac{E_r}{\eta} = \frac{P_r \times W}{N_r \times f}$$

Furthermore, since $P_r = \frac{P_t}{D^\alpha}$, we can see that:

$$\frac{E_r}{\eta} = \frac{P_t \times W}{D^\alpha \times N_r \times f}. \tag{8}$$

It is clear that for any given modulation scheme, the bit error rate p_b is a function of the transmitter power level. We express this generic relationship as:

$$p_b = f(P_t, \cdots) \tag{9}$$

We assume that bit errors are due to channel noise, and not due to MAC layer issues (e.g. collisions). Now, assuming independent packet losses, the packet error rate p for a single packet of size L is related to the bit error rate p_b according to the relationship [3]:

$$p = 1 - (1 - p_b)^L \tag{10}$$

For low bit error rates, p can be approximated as $L.p_b$. Since the original transmission and subsequent retransmissions of a single packet are essentially independent events, it follows that the number of transmissions needed for successful delivery of a single packet is *geometrically distributed* with parameter p. Accordingly, N, the *expected number of transmissions needed* for the reliable transfer of 1 packet (or L bits) is thus:

$$N = \frac{1}{1-p} \tag{11}$$

Since each such reliable transfer of a single packet uses $1/(1-p)$ attempts, it consumes $\frac{L}{f} \times P_t \times \frac{1}{1-p}$ transmission energy (since the transmission time of an L bit packet is $\frac{L}{f}$), it follows that the effective reliable transmission energy

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[3] This expression for packet error rate will be different if other techniques like FEC, are used. For example, if we assume the use of a code where bits are transmitted in Q-bit chunks, and where successful reception occurs as long as the number of errors is less than 2, the probability of successful transmission of the chunk is given by $(1-p)^Q + Q * p * (1-p)^{Q-1}$. While the specific relationship between the packet error rate and the bit error probabilities will thus change with specific system parameters, the general nature of the relationship will still hold.

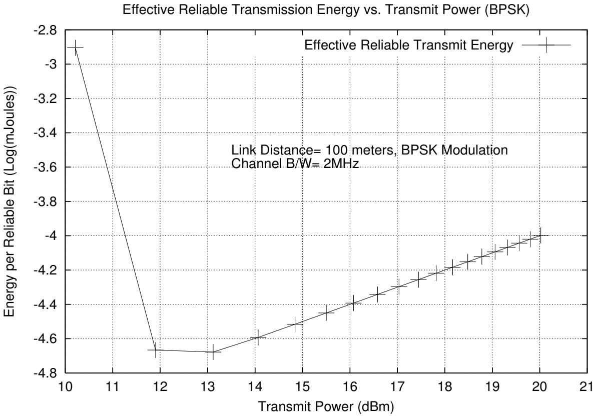

Fig. 2. Reliable Transfer Energy Behavior (BPSK)

per bit is given by:

$$E(P_t) = \frac{L}{f} \times P_t \times \frac{1}{1 - p(P_t)} \times \frac{1}{L} \tag{12}$$

$E(P_t)$ in Equation 12 is in general a non-convex function of P_t when p_b follows the relationship in Equation 7. However, for any value of L that is practical, $E(P_t)$ has only a single minima for values of P_t that do not result in an abnormally high value of packet loss rates. We represent this minima point by P_t^*. Increasing or decreasing the transmission power level from P_t^* both result in an increase in the transmission energy per reliable bit transfer. While values smaller than P_t^* lead to a sharp rise in $p(P_t)$ and hence an overall increase in $E(P_t)$ (as well as unacceptably high packet transfer latencies), a larger value of P_t leads to an increase in the numerator of Equation 12 without a corresponding decrease in $p(P_t)$.

To illustrate this relationship between the transmission power level P_t and the resulting energy per reliably transferred bit, we now consider a specific case — the Binary Phase Shift Keying (BPSK) modulated channel, where the bit error rate is given by:

$$p_b = 0.5 \times erfc(\sqrt{\frac{P_t \times W}{D^\alpha \times N_r \times f}}) \tag{13}$$

BPSK modulation is used in wireless environments, for example in the 1 Mbps version of the IEEE 802.11 wireless LAN standard.

Figure 2 shows 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 assumed to be 100 meters and the spectral noise N_r is assumed to be 4.0×10^{-11} W. We can see that the optimal transmission power for this channel is ≈ 20 mW.

While we have so far concentrated solely on the energy efficiency, it is perhaps worth noting that the transmission power level P_t also indirectly affects the latency of the data transfer. A higher value of P_t will, in general, lower the probability of packet error and hence, the expected number of retransmissions needed to reliably transfer a single packet. Since each transmission of an L bit packet takes $\frac{L}{f}$ seconds, it follows that the expected time (assuming back-

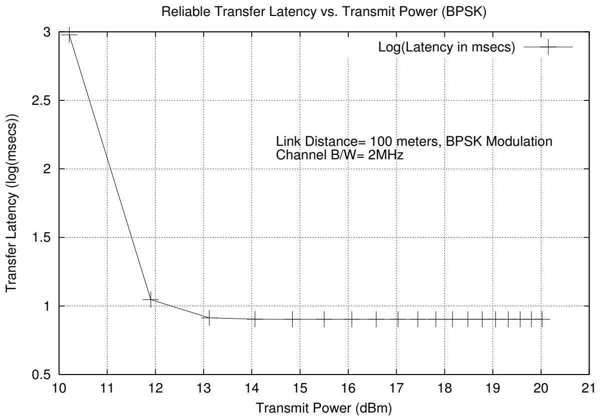

Fig. 3. Transfer Latency Dependence (BPSK)

to-back retransmissions) for the reliable transmission of such a packet over a link with packet error rate p is $\frac{L}{f\times(1-p)}$. Figure 3 plots the expected reliable transfer latency for the 2 MHz BPSK channel and the 100 meter link discussed earlier. As expected, the transfer latency monotonically decreases with increasing transmit power. More interestingly, Figures 2 and 3 show that choosing a transmission power level below the optimal P_t^* results in both a higher value of the average transfer energy per bit, as well as the average transfer latency. These graphs thus not only illustrate the possibility of using the transmit power to implicitly tradeoff between the energy efficiency and the latency, but also show that choosing a power level lower than the optimum is sub-optimal from the standpoint of *both* metrics. Accordingly, it is very important to ensure that the transmit power level is not set to a value that is lower than the optimal value for a given link.

Optimal Transmission Energy vs. Link Distance/Noise: While it is now clear that any particular link is associated with an optimal transmission power that minimizes the energy per reliably transferred bit, we now explore the relationship between this optimal power level P_t^* and the link distance D. The optimal transmission power does not vary as D^α even if different links have identical channel characteristics and receiver noise conditions. This is because the choice of the optimal power depends on the error probability which is a “non-polynomial” function of D (see Equation 13). Accordingly, even if all links had the same receiver noise, the optimal transmission power would not vary as D^α.

We first explore the relationship between the optimal transmission power level P_t^* and the link distance for *invariant channel and receiver conditions.* In particular, Figure 4 plots the optimal transmission power P_t^* as a function of the link distance for the BPSK channel mentioned earlier. All the data point correspond to the same value of f, N_r and W. Since the attenuation was assumed to be $\propto D^4$, we plot Figure 4 on a log scale and include the straight line with a slope of 4 as a reference. As expected, the optimal power P_t^* increases with increasing D; however, Figure 4 also shows that this optimal transmission power *increases at a slightly slower rate than* D^4. Figure 5 plots the actual value of the optimal reliable transfer energy/bit as a function of the link distance. Once again, we plot the straight line with a slope of 4 as reference: while information theory (Equation 6) shows that this optimal reliable transfer energy should vary as D^α ($\alpha = 4$ for Figure 5), the increase is slightly lower (slope less than 4) for practical communication systems.

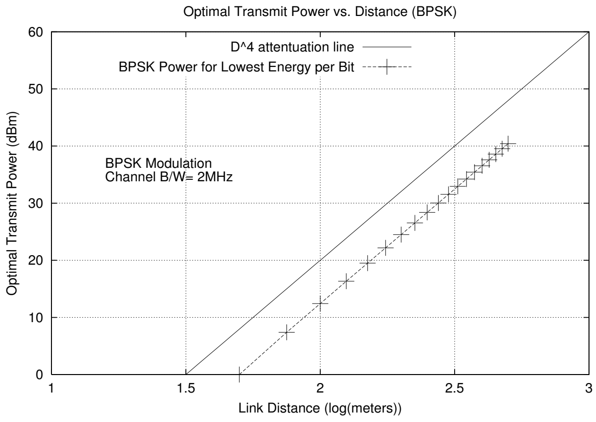

Fig. 4. Optimal Transmission Power vs. Link Distance (BPSK)

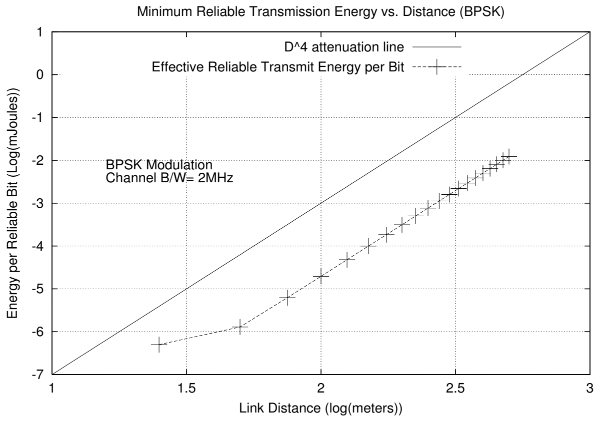

Fig. 5. Minimum Energy per Bit vs. Link Distance (BPSK)

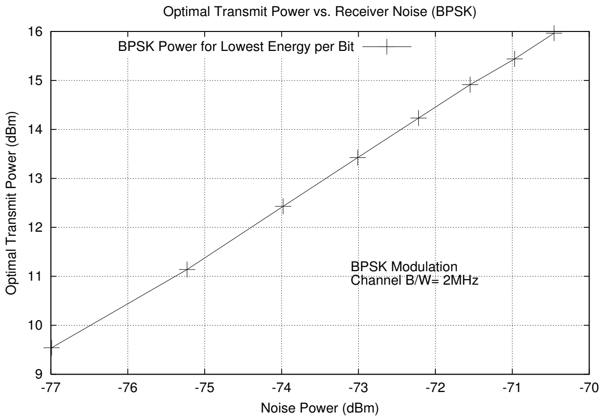

Fig. 6. Minimum Energy per Bit vs. Receiver Noise (BPSK)

We can thus see that even if all links had identical properties, the optimal transmission power for a single link rises at a slightly slower rate than that assumed by simply using the attenuation model. *Accordingly, conventional variable-energy protocols, such as [9], [17], [1], which assume that the transmission power varies with the link distance as* D^{α}*, may penalize longer links more than needed.*

It is also interesting to study the impact of changes in the receiver noise characteristics on the optimal transmission energy for any given channel. To this end, Figure 6 plots the optimal transmission power P_t^* as the spectral noise N_r is varied from 2×10^{-11}W to 8.0×10^{-11}W for the 100 meter link of Figure 2. We can see that the optimal transmission power varies appreciably with a change in the receiver noise level. Accordingly, simply setting the transmission power $\propto D^{\alpha}$ may result in significantly sub-optimal performance. Moreover, our plots show that the $log(P^*)$ vs. $log(N_r)$ graph is almost linear, with a slope fairly close to 1. This indicates that a policy of maintaining a “constant target SNR” (adjusting P_t to ensure a constant ratio of P_r/N_r) will result in ‘close to optimal’ energy efficiency for reliable packet delivery over a given link. Our analysis not only provides a theoretical framework for determining this ‘target ratio’, but also demonstrates how this *target ratio itself is a function of the link distance.*

IV. MINIMUM ENERGY ROUTING

In the previous section, we have seen why energy efficient transmission of packets *on a single link* must consider both the attenuation due to the link distance and the receiver noise characteristics to determine an optimal transmission power. In this section, we present our technique to find optimal energy routes for reliable packet delivery over an entire data path, consisting of multiple individual wireless links in a practical multi-hop wireless network.

Consider a node that transmits a packet with transmit power P_t across a specific link so that the packet is received with signal power greater than the threshold, P_{thresh}. Let the corresponding energy required for this single transmission be E_t. (Assuming packets are of constant size, E_t differs from P_t by a proportionality constant.) Therefore,

$$E_t \geq E_{thresh} \times D^{\alpha} \text{ defined to be } E_{min}$$

where, E_{thresh} is the energy corresponding to P_{thresh}. Let E_{max} be the energy required to transmit the packet using the maximum transmission power at that node.

Let $p(E_t)$ denote the packet error probability corresponding to the packet transmission energy, E_t.

A. Hop-by-hop Retransmissions (HHR)

We first describe the scenario where hop-by-hop link-layer retransmissions are available. This is the most typical scenario for wireless link layers.

Then, from Equation 12, it follows that the expected energy required to *reliably* transmit across the link is given by

$$E_t(reliable, HHR) = \frac{E_t}{1 - p(E_t)} \tag{14}$$

where $p(E)$ represent the error on the link when a transmit power P (with corresponding packet transmission energy, E) is used.

Therefore, the optimal value of the energy required for reliable packet delivery across a single link is given by:

$$E_{min} \leq E_t \leq E_{max} \tag{15}$$

$$\frac{d}{dE_t} E_t(reliable, HHR) = 0 \tag{16}$$

$$\frac{d^2}{d{E_t}^2} E_t(reliable, HHR) \geq 0 \tag{17}$$

In Section III-B we had showed that the minima of the expected energy costs per bit indeed exists for some example modulation schemes. Indeed, Equation 17 holds for the entire range of realistic modulation schemes. However, the solution of Equation 16 may lie outside the range $[E_{min}, E_{max}]$. It follows that the transmission energy that minimizes the energy cost for a link satisfies:

$$E_t^*.p'(E_t^*) - p(E_t^*) = 1 \tag{18}$$

E_t^* can be computed using efficient techniques within the range E_{min} and E_{max}. For this transmission energy, the optimal reliable transmission energy costs across the link is given by

$$E_t(reliable, HHR)^* = \frac{E_t^*}{1 - p(E_t^*)} \tag{19}$$

In our optimal energy efficient routing scheme, we assign the cost of a wireless link as given by Equation 19. Assuming that E_t^* is less than the maximum transmission energy that can be used by node, t, it will use E_t^* to transmit packets across the given link [4].

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.

B. End-to-End Retransmissions (EER)

In this case, there are no link-layer retransmission mechanisms available. Instead, reliability of end-to-end data transfers are provided using end-to-end retransmissions (e.g. using reliable protocols like TCP).

Unlike the hop-by-hop case, the optimal transmission energy across a given link depends not only on the characteristics of the given link but also on the packet error rates and transmission energy choices on all the other links on the end-to-end path.

Consider a M-hop path where p_i represents the packet error rate and E_i represents the transmission energy required for link $\langle i, i+1$. Then the average energy consumed in each end-to-end transmission attempt can be shown to be, $E_{\textit{avg. attempt}} = \prod_{j=1}^{M}(1-p_j)(\sum_{j=1}^{M} E_j) + \sum_{j=1}^{M}\prod_{j=1}^{i-1}(1-p_j)p_i(\sum_{j=1}^{i} E_j)$. It follows that the end-to-end energy requirements for reliable packet transmission over the M-hop path is given by:

$$E_{\textit{reliable, EER}} = \frac{E_{\textit{avg. attempt}}}{\prod_{i=1}^{M-1}\{1-p_i(E_i)\},} \tag{20}$$

if we assume that the source continues to try sending the packet to the destination until it is successful. If we assume that each link retries a transmission upto a maximum of max attempts and that a link failure at an intermediate node implies no transmission activity at all downstream links, then the total transmission energy has a slightly more complex representation that has been derived and analyzed in the Appendix of [6].

In either case, the optimal choice of packet transmission energy at each node on an end-to-end path can be evaluated by solving the set of equations given by:

$$\nabla E_{\textit{reliable, EER}} = 0 \tag{21}$$

$$\mathcal{H}(E_{\textit{reliable, EER}}) > 0 \tag{22}$$

where, for a function $\mathcal{F}$, $\nabla(\mathcal{F})$ represents its gradient, and $\mathcal{H}(\mathcal{F})$ is the Hessian. The coupled nature of these equations make it hard to compute the optimal solution in a distributed routing protocol.

Nevertheless, since almost all wireless links use hop-by-hop retransmissions, this solution is of limited interest from a practical perspective.

V. SIMULATION STUDIES AND PERFORMANCE EVALUATION

In this section, we report on extensive simulation-based studies on the performance impacts of our proposed modifications in the *ns-2* simulator. In these studies, we only consider the hop-by-hop retransmission scenario. We perform

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[4] If the maximum transmission energy is lower than E_t^*, then we will transmit with the maximum transmission energy and the link cost metric will be appropriately modified to reflect this choice.

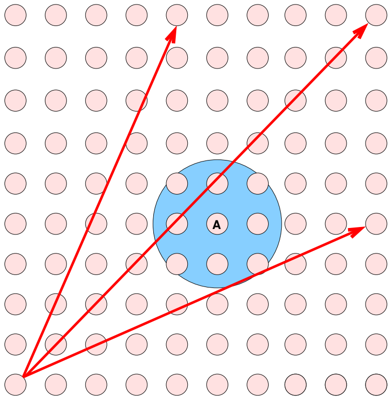

Fig. 7. The 100-node grid topology. The shaded region marks the maximum transmission range for the node, A. There are three flows from each of the 4 corner nodes, for a total of 12 flows.

studies using both TCP and UDP traffic sources to study the effect of our routing schemes on these transport layer mechanisms. For the TCP flows, we used its NewReno variant. In UDP flows, packets were inserted by the source at regular intervals. For all these simulation studies, we use link-layer retransmissions to recover from packet losses.

To study the performance of our suggested schemes, we implemented and observed three separate routing algorithms:

1) The Energy-Aware (**EA**) routing algorithm, where the cost associated with each link is the energy required to transmit a single packet (without retransmission considerations) across that link. In this scheme the wireless link error rates are ignored while formulating the link's effective energy cost.
2) The Retransmission-Energy Aware (**RA**) algorithm [1], where the link cost includes the packet error rates, and thus considers the impact of retransmissions necessary for reliable packet transfer. However, the transmit power chosen by nodes are given by Equation 2, i.e. the transmit power minimally exceeds the required receive power threshold.
3) Our Optimal Retransmission-Energy Aware (**RA-Opt**) algorithm where the transmit power is adaptively chosen by nodes (as given by Equation 18) to minimize the energy required to reliably transmit a packet across that link.

A. Network Topology and Link Error Modeling

For our studies, we used different topologies having upto 100 nodes distributed over on a square region, to study the effects of various schemes on energy requirements and throughputs achieved.

1) *Grid topologies:* For comparison the performance of our scheme with that presented in [1], we first present results on the performance of the schemes on a 100 node grid topology (as shown in Figure 7) similar to one used in [1]. The nodes are separated 100 units apart along each axis, and the maximum transmission radius of the node was limited to 150 units. Thus, each node has between 3 and 8 neighboring nodes on this topology [5].

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[5] Our-energy aware routing formulation does not directly define a transmission range. It is possible that a longer link with lower receiver noise may consume less effective energy that a shorter link with higher receiver noise. Real-life scenarios, however, impose both an upper bound on the maximum possible transmission power as well as a minimum energy threshold for successful packet reception — if the received power level

2) *Random topologies:* We also present simulation results for randomly generated topologies. In the random topologies, the nodes were distributed uniformly at random in a 1000×1000 square grid. We experimented with different transmission radii for the nodes. In our random topology generator, we specified the desired number of links [6]. To avoid uni-directional links, we assigned the same transmission radii to all nodes. Note that a hop-by-hop retransmission scheme works only for bi-directional links. In the results presented in this section for the random topologies, we specified the number of wireless links to be one-eighth of a complete graph on these set of nodes. The consequent transmission radii for each node was about 210 units.

Each of the routing algorithms was then run on these topologies to derive the least-cost paths to each destination node. To simulate the offered traffic load typically of such ad-hoc wireless topologies, each of the corner node on the grid topology had 3 active flows, providing a total of 12 flows. In the random topology, we chose 12 random source-destination pairs from the entire set of nodes.

Since our objective was to study the transmission energies alone, we did not consider other factors such as link congestion, buffer overflow etc. Thus, each link had an infinitely larger transmit buffer; the link bandwidths for all links (point to point) was set to 2 Mbps. Each of the simulations was run for a fixed duration.

We choose BPSK as our representative modulation scheme and hence, use Equation 13 to derive the bit-error-rate. We varied the ambient noise to obtain different data points. For the non-adaptive transmission power algorithms (EA and RA) we chose a transmit power of 20 mW. The spectral noise for the different channels was chosen to vary between two configurable parameters, N_{min} and N_{max} corresponding to minimum and maximum noise respectively. less than a configurable parameter N_{max}.

We simulated two different environments:

1) *Low noise environment:* In this case, we chose N_{min} to be $1.8 \times 10^{-11}W$, while N_{max} was varied between $2.0 \times 10^{-11}W$ and $3.0 \times 10^{-11}W$. For the non-adaptive schemes (EA and RA) a maximum spectral noise of $2.0 \times 10^{-11}W$ leads to a corresponding channel packet error rate of 0.1 on a 100 unit link. Our adaptive transmission algorithm (RA-Opt) appropriately chose a transmission power for each link so that the energy consumption for reliable data transfer across that link is minimized.
2) *High noise Environment:* In this scenario, we chose N_{min} to be $2.8 \times 10^{-11}W$; we varied N_{max} between $3.0 \times 10^{-11}W$ and $4.0 \times 10^{-11}W$.

Our results show that the RA-Opt scheme outperforms the other schemes in environments (other than zero noise environments). Additionally, our scheme shows significant benefits as the noise in the environment increases, as a comparison between these two environments show.

B. Metrics

To study the energy efficiency of the routing protocols, we observed two different metrics:

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is below this threshold, no reception is possible even in the absence of any receiver noise. Since any signal suffers channel attenuation $\propto D^4$, the transmission range is an alternative way of assuming that the received power level beyond a distance of 150 units is always lower than the minimum reception threshold, even if the transmitter operates at the maximum power level.

[6] We count each pair of nodes that are within the transmission range of each other as one wireless link.

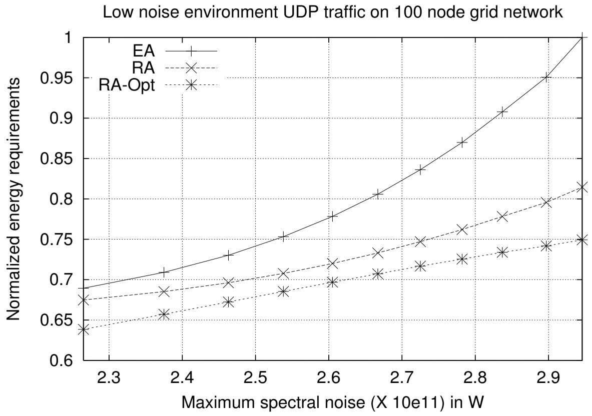

Fig. 8. Normalized energy costs for UDP flows (Low Noise Grid Topology).

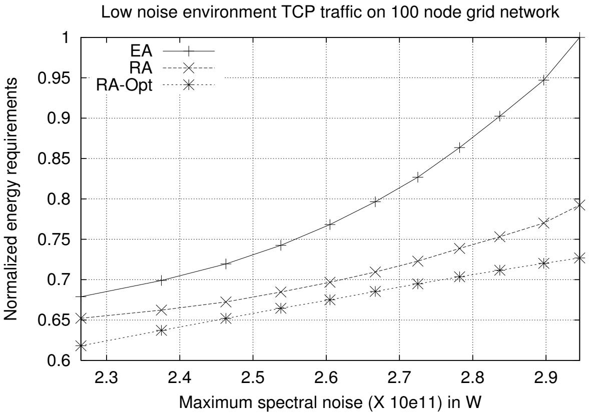

Fig. 9. Normalized energy costs for TCP flows (Low Noise Grid Topology).

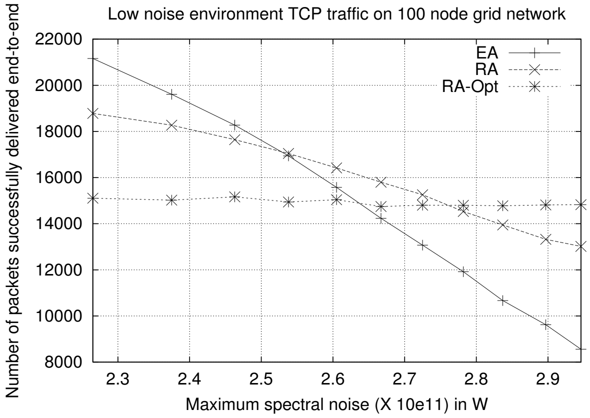

Fig. 10. Comparison of throughput for TCP flows (Low Noise Grid Topology).

1) **Normalized energy:** We first compute the average energy per data packet by dividing the total energy expenditure (over all the nodes in the network) by the total number of unique packets received at any destination (sequence number for TCP and packets for UDP). We defined the normalized energy of a scheme, as the ratio of the average energy per data packet for that scheme to the average energy per data packet required by the maximum-energy experiment between all the schemes among all these experiments. This provides an easy representation for comparison of the different schemes with each other and with changing maximum spectral noise for different sets of studies.
2) **Effective Reliable Throughput:** This metric counts the number of packets that was reliably transmitted from the source to the destination, over the simulated duration. Since all the plots show results of runs of different schemes over the same time duration, we do not actually divide this packet count by the simulation duration. Different routing schemes will differ in the total number of packets that the underlying flows are able to transfer over an identical time interval.

C. *Low noise Environment for Grid Topologies*

We first present the results for the low noise environment.

UDP Flows: Figure 8 shows the normalized energy consumption for the different schemes for the UDP flows. For example, when N_{max} was set to $2.9 \times 10^{-11} W$, the relative energy requirements of RA-Opt, RA and EA were 0.74, 0.8 and 0.95 respectively. As expected, the energy requirements of all the schemes increase with increase in spectral noise. The EA scheme has the highest energy requirements among all the schemes when the maximum channel noise on links was high. Both the RA and the RA-Opt scheme performs significantly better than this scheme for the entire range of spectral noise. RA-Opt has the best performance among the three different schemes for the entire range of spectral noise. The EA scheme consumes about 10% to 33% more energy per packet, while the RA scheme consumes about 8% to 10% more energy per packet than the RA-Opt scheme,

It is interesting to note that in this low noise environment the energy costs of both the EA and RA schemes have a convexity property, while that of the RA-Opt scheme has a concavity property. This implies that the benefits of the RA-Opt scheme becomes more and more significant with increase in the spectral noise.

TCP Flows: Figure 9 shows a similar normalized energy consumption plot for TCP flows. The costs match very closely with the results for UDP flows.

Foe TCP flows, it is interesting to observe the behavior of the effective reliable throughput metric for the different schemes. This is shown in Figure 10. The number of packets transmitted reliably over a fixed duration for the EA scheme falls rapidly with increase in spectral noise. This is expected because the EA scheme does not consider channel properties in choosing routes. In contrast, the number of packets reliably transferred by the RA scheme falls in a more gradual fashion. The decreasing trend in both these schemes is due to the increasing link error rates with the increase in spectral noise. As the link error rates increase, packets sees an increase in end-to-end delays, due to the delays spent in increased number of retransmissions necessary to ensure reliability.

However, the same metric stays relatively constant for the RA-Opt case. This is because, the RA-Opt scheme aggressively adapts the transmission power so as to minimize the energy costs for reliable packet delivery across a link. *The corresponding transmission power to achieve this optimal cost is such that the link error rate stays fairly stable across the entire range of spectral noise.*

D. *High noise Environment for Grid Topologies*

Now we present results for the higher noise environment. Note that in this environment, the value of N_{min} is significantly larger than its corresponding value in the low noise environment.

UDP flows: In Figure 11, we plot the normalized energy required per packet in the high noise environment for UDP flows. For example, when N_{max} is set to $3.375 \times 10^{-11} W$ the relative energy requirements of RA-Opt, RA and EA schemes are 0.21, 0.40 (i.e. 90% more than RA-Opt) and 0.56 (i.e. 167% more than RA-Opt) respectively. The benefits of the RA-Opt scheme is significantly higher than in the low noise environment (note that the scale of the Y-axis is much larger than the corresponding plots for low noise environments). The RA scheme consumes between 60% to 120% more energy per packet in this environment than the RA-Opt scheme, while the EA scheme consumes four times more energy in the worst case.

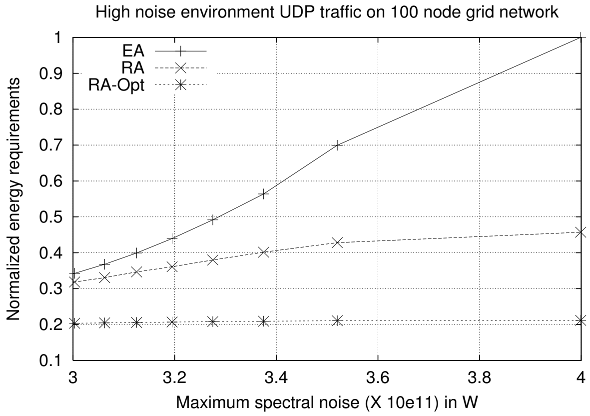

Fig. 11. Normalized energy costs for UDP flows (High Noise Grid Topology).

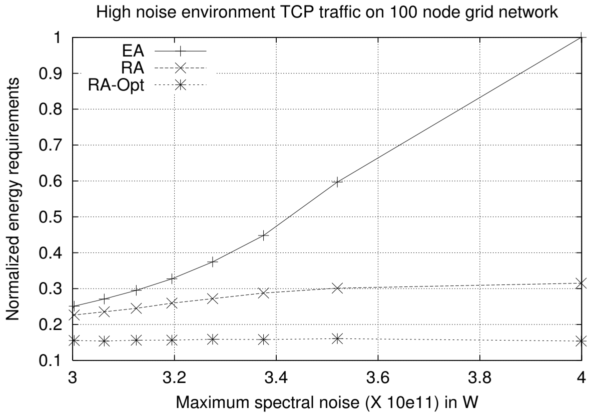

Fig. 12. Normalized energy costs for TCP flows (High Noise Grid Topology).

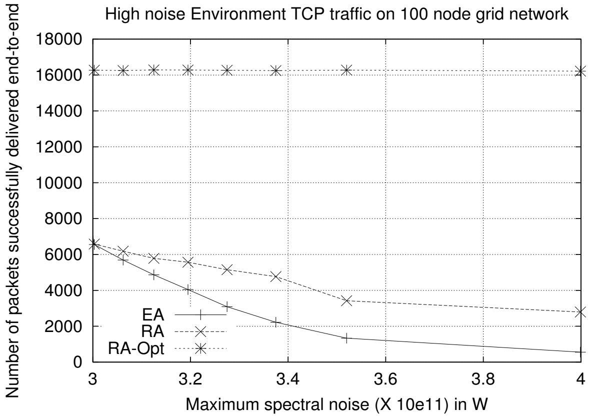

Fig. 13. Comparison of throughput for TCP flows (High Noise Grid Topology).

TCP flows: The energy consumption for TCP flows (see Figure 12) is again similar to the UDP counterparts.

It is interesting to observe the behavior of the throughput achieved by TCP flows in this high noise environment. In trying to optimize the energy consumption, the RA-Opt scheme adapts the transmission power which suitably drives down the channel error rates in all environments. Therefore, the throughput achieved by the RA-Opt scheme is largely unaffected by the noise characteristics. In Figure 13 we plot the throughput for TCP flows in the high noise environment. We can observe that the RA-Opt scheme achieves the same throughput both in the low and high noise environments. Both the EA and RA schemes suffer in the high noise environment, as can be seen in the significant drop in their throughputs achieved.

Both the EA and RA schemes achieve similar throughputs when the maximum spectral noise is $3 \times 10^{-11} W$ with the minimum spectral noise being $2.8 \times 10^{-11} W$. This is because the range of error rates between different links are similar in this scenario, and so RA is unable to choose significantly better paths than EA. RA-Opt is able to make such a choice by increasing the transmission power at nodes to drive down the error rates significantly.

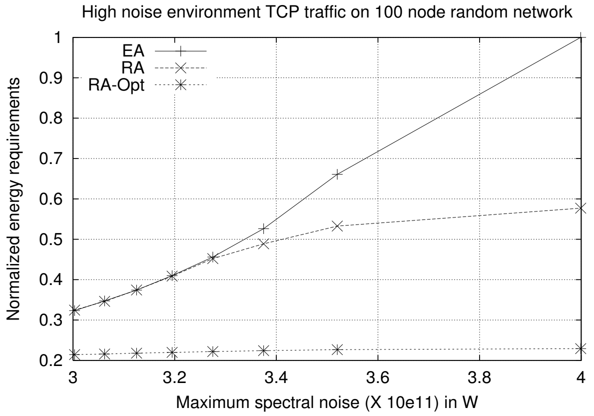

Fig. 14. Normalized energy costs for TCP flows (High Noise Random Topology).

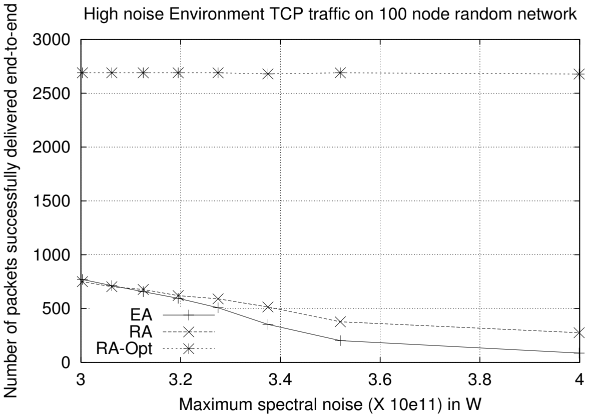

Fig. 15. Comparison of throughput for TCP flows (High Noise Random Topology).

E. Random Topologies

We now present results of our studies with randomly generated topologies. Observing that the relative energy requirements for both TCP and UDP flows are similar in nature, we only present the results for the TCP flows in a high noise environment.

In Figure 14, we plot the energy requirements for the different schemes in the high noise environment. The benefits of the RA-Opt scheme is apparent in the plot. The relative energy costs of the RA-Opt, RA and EA schemes are 0.22, 0.49 (i.e. 123% more than RA-Opt) and 0.53 (i.e. 141% more than RA-Opt) respectively. At low noise levels (less than $3.28 \times 10^{-11} W$) the RA scheme and the EA scheme performs equally. However, by adapting the transmission power at the nodes, the RA-Opt scheme performs significantly better than these schemes.

In Figure 15 we show the throughput of the different schemes. Like before, the RA-Opt scheme maintains a stable throughput, while the other schemes see a significant degradation in performance.

VI. CONCLUSIONS

We have defined an optimal energy routing scheme for reliable data transfer on a multi-hop wireless network. This scheme outperforms well-known existing routing schemes for a wide range of channel characteristics. This improvement in energy efficiency is achieved by explicitly considering the impact of receiver noise on packet errors, and by adjusting the transmission power to minimize the total energy spent in reliably forwarding a single bit. The scheme is general across different modulation techniques that can be employed for data delivery on wireless networks.

We investigated the issue existence of an optimal transmission energy for a given link. By employing information-theoretic bounds, we have shown how any link is associated with a fundamental lower bound on energy efficient reliable communication. Moreover, this fundamental bound is directly proportional to the channel attenuation rate ($\propto D^{\alpha}$), and is achieved by choosing arbitrary low transmission power. In contrast, practical communication systems are associated with a well-defined optimal transmission power, such that any decrease or increase from this optimal value results in a sharp increase in the total transmission energy spent in reliable data transfer. Moreover, an increase in the link distance

D causes the optimal communication cost to rise less sharply than D^{α}; accordingly, existing energy-aware routing protocols impose a much stiffer penalty on longer distance hops than warranted.

We have studied the applicability of this technique in choosing optimal energy paths. By appropriately choosing the cost metric, it is possible to optimize other objective functions, e.g. end-to-end latencies, data delivery throughput, etc. We, therefore, believe that our scheme has a wider applicability to a range of operating modes depending on the the optimization objectives. Simulation studies indicate that performing adaptive power control based on the individual link conditions (error rates) can provide energy savings of $\approx 10\%$ in low-noise environments, and as much as $\approx 40\%$ in high-noise environments.

The analysis in this paper assumed that the use of retransmissions as the sole means of providing a reliable link layer. As discussed earlier, the fundamental technique can, however, also be applied to alternate reliability schemes such as forward error correcting codes through appropriate changes to the relationships in Equations 10 and 12. Since our power adaptation mechanism implicitly relies on relative stable variations in the packet error-rate, this technique is especially useful in static, or low-mobility, multi-hop networks, where link parameters such as distance or attenuation coefficients do not exhibit very rapid changes. (Of course, our formulation is applicable in the presence of typical wireless environment effects such as fading; the average bit error rate at the link-layer is typically a more stable statistical metric obtained by averaging over such physical layer variations). We have also assumed the existence of appropriate MAC-layer contention resolution mechanisms for common-channel networks, which present an abstraction of zero-interference to the higher layers. Such an abstraction is also provided by the use of distinct physical channels based on TDMA/FDMA/CDMA techniques. Finally, our approach to energy optimization is useful not just for forming energy-efficient routing paths, but also for independently optimizing the transmission energy on each individual link. The routing algorithm and individual link-layer power control techniques can operate on different time scales; while routes can be re-computed over longer time periods, individual transmitters can adjust their link transmission power over shorter time-scales.

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