Hindawi Publishing Corporation
Advances in Multimedia
Volume 2007, Article ID 19860, 9 pages
doi:10.1155/2007/19860

Research Article

Cross-Layer Path Configuration for Energy-Efficient Communication over Wireless Ad Hoc Networks

Hong-Chuan Yang,[1] Kui Wu,[2] and Wu-Sheng Lu[1]

[1] *Department of Electrical and Computer Engineering, University of Victoria, BC, Canada V8W 3P6*
[2] *Department of Computer Science, University of Victoria, BC, Canada V8W 3P6*

Received 27 December 2006; Revised 12 April 2007; Accepted 12 April 2007

Recommended by Jianwei Huang

We study the energy-efficient configuration of multihop paths with automatic repeat request (ARQ) mechanism in wireless ad hoc networks. We adopt a cross-layer design approach and take both the quality of each radio hop and the battery capacity of each transmitting node into consideration. Under certain constraints on the maximum tolerable transmission delay and the required packet delivery ratio, we solve optimization problems to jointly schedule the transmitting power of each transmitting node and the retransmission limit over each hop. Numerical results demonstrate that the path configuration methods can either significantly reduce the average energy consumption per packet delivery or considerably extend the average lifetime of the multihop route.

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1. INTRODUCTION

There have been considerable interests in selforganizing, fast deployable wireless ad hoc networks within both academic society [1, 2] and industry [3]. Since these networks consist of a group of battery operated wireless devices, they are ideal for providing instantaneous wireless services without deploying access points or wired infrastructure. On the other hand, limited battery lifetime greatly affects the usefulness of wireless ad hoc networks. Therefore, it is of great importance to develop energy-efficient communication techniques for such networks. Recently, there have been substantial research efforts in developing energy-efficient routing protocols for wireless ad hoc networks (see, e.g., [4–9]). The basic idea of these energy-efficient routing protocols is to integrate energy metrics into the route search or maintenance process. While saving considerable amount of energy compared to traditional routing protocols, these energy-aware routing algorithms become more complex and very difficult to implement. *Decoupling routing algorithms and other add-on features, for example, energy saving in our case, is of great importance from the point of view of protocol engineering and has become a broadly accepted industrial practice.*

In this paper, we follow the above philosophy to improve energy efficiency of wireless ad hoc networks. Our objective is to develop energy-efficient configuration algorithms for a multihop path that has been obtained through traditional routing protocols. The rationale behind this approach is that if the path obtained is not properly configured, the battery energy at some intermediate nodes may be quickly depleted and the whole path becomes unusable. The resulting route recovery operations [10, 11] will lead to extra energy cost for the whole network. In addition, since the path configuration is decoupled with any routing protocols or transport layer protocols, *it can serve as an add-on feature to existing routing or transport protocols with low implementation complexity*. Specifically, we consider a multihop path with hop-by-hop automatic repeat request (ARQ) mechanism. With hop-by-hop ARQ, a data packet must be acknowledged in the current hop before it could be transmitted over the next hop. Otherwise, packet retransmission occurs. Traditionally, this transmission/retransmission process is continued until either the packet arrives at the destination node correctly or the packet is dropped because the maximum number of allowed retransmissions is exceeded for that packet. This retransmission limit usually stems from the delay constraint of the data traffic, especially those generated by voice and/or video applications (in this work, we focus on the transmission delay while assume queuing delay due to multiple flow has been subtracted from the total delay budget). Obviously, this best-effort transmission strategy will lead to the best end-to-end path reliability, that is, the lowest packet loss rate. The energy cost for packet delivery with this strategy, however, will be large. Moreover, we can intuitively expect that if the number of retransmissions performed over an intermediate hop is large, the probability that the packet can successfully reach its final destination within the delay constraint will be small. It will be more energy efficient if we drop the packets immediately when the probability for the packet to reach its ultimate destination within a given delay constraint becomes very small.

With this observation in mind, we propose an energy-efficient hop-by-hop retransmission strategy for multiple-hop transmission. In particular, we allocate each hop along the path of a number of permitted retransmissions in advance.[1] If the number of performed retransmissions over a hop reaches its prespecified limit, then the transmitting node of that hop will drop the packet. To determine the number of allowed retransmissions for each hop as well as select the transmitting power for each transmitting node, we formulate optimization problems which take into account the delay constraint of the data packets, the channel quality of each hop, and the available energy supply of each transmitting node. These optimization problems are solved at the destination node where the channel quality and energy resource information of each hop have been collected during the route discovery process and the solution are then used to configure the multihop path.

Specifically, we develop two path configuration algorithms. The first algorithm, termed as *minimum-energy configuration*, targets at reducing the average energy consumption per packet delivery over the multihop path. We show through numerical examples that the minimum-energy algorithm can save considerable energy for packet delivery, compared with the traditional best-effort retransmission strategy, while guaranteeing a given quality of service (QoS) level in terms of the packet delivery ratio within a given delay constraint. While the minimum-energy configuration can reduce the average energy cost per packet transmission, it does not take into account the available energy resources of intermediate nodes along the path. We then develop another path configuration algorithm, termed as *maximum-lifetime configuration*, that tries to extends the lifetime of the multihop path by taking into consideration both the link quality of each hop and the battery resource of the transmitting nodes. Numerical examples also show that the maximum-lifetime configuration algorithm can prolong the lifetime of the multihop path at the cost of slightly increased average power consumption per packet delivery, compared to minimum-energy path configuration.

The rest of the paper is organized as follows. Section 2 introduces the system and channel model under consideration. In Section 3, we study the packet delivery ratio and average energy consumption with the best-effort transmission strategy as a benchmark. In Section 4, the minimum-energy configuration problem is formulated and solved. The optimization problem for the maximum-lifetime configuration is then presented in Section 5. Selected numerical example is presented and discussed in Section 6. In Section 7, we explain in detail how to incorporate our path configuration algorithms with existing routing/transport protocols. Finally, we conclude the paper in Section 8.

[1] Alternatively, we can set a limit for the total number of allowed retransmissions up to the current hop. In this case, the packet dropping decision will depend on the number of retransmissions performed in the previous hops, which will lead to a more complicated configuration algorithm and will be addressed in a different paper.

2. SYSTEM AND CHANNEL MODELS

2.1. Multihop path with fading

We consider a multihop path obtained via a certain routing protocol, where there are L hops between the source node, S, and the destination node, D. Let R_k denote the kth intermediate node for $k = 1, \ldots, L-1$. We can represent the ith hop as $R_{i-1}R_i$, $1 \le i \le L$, with the notation $R_0 = S$ and $R_L = D$. The radio link for each hop is assumed to be subject to independent Rayleigh block fading. In particular, the amplitude of the fading signal during a packet transmission can be considered constant and varies independently for the next transmission. The cumulative distribution function (CDF) $P_{\gamma_i}(x)$ of the instantaneous received signal-to-noise ratio (SNR) γ_i at R_i for the ith hop is given by

$$P_{\gamma_i}(x) = 1 - \exp\left(-\frac{x}{\overline{\gamma}_i}\right), \tag{1}$$

where $\overline{\gamma}_i$ is the average received SNR of the ith hop, which is proportional to the transmitting power of the transmitting node R_{i-1}, denoted by p_i. Specifically, we have $\overline{\gamma}_i = G_i \cdot p_i$, where G_i is a parameter depending on the antenna gain, the distance between the two nodes, and the shadowing effect, and so forth. We assume that G_i remains constant for the time duration of interest. We also assume that each transmitting node can select its transmitting power within the range of $(0, p_{\max}]$, where $p_{\max}$ is the common maximum transmitting power for all transmitting nodes.

The packet error rate over a radio hop is in general a complex function of the instantaneous received SNR of that hop. Simultaneous transmission over other hops will also cause interference to current hop. Note that since nodes cannot simultaneously transmit and receive packets, interference will only come from nonneighboring hops and therefore is small. In this paper, we treat the interference from other hops as background noise and approximate the packet error rate for the ith hop with the probability that the instantaneous received SNR γ_i is smaller than a fixed threshold γ_T [12–14]. Mathematically, the packet error probability of the ith hop $R_{i-1}R_i$, $1 \le i \le L$, denoted by P_i, is approximated by

$$P_i = P_{\gamma_i}(\gamma_T) = 1 - \exp\left(-\frac{\gamma_T}{G_i \cdot p_i}\right). \tag{2}$$

Note that the above equation associates the packet error rate for the ith hop with the transmitting power of its transmitting node R_{i-1}.

2.2. Hop-by-hop ARQ for delay sensitive traffics

We assume that the multihop path employs hop-by-hop ARQ mechanism. With hop-by-hop ARQ, the transmitting node of a certain hop waits for a positive acknowledgment before advancing to the transmission of the next data packet. If the positive acknowledgment is not received within a given threshold time, the transmitting node will retransmit the packet until the packet is positively acknowledged. Then the next node along the path will transmit the packet to the subsequent nodes in the same fashion. Traditionally, this process is continued until either the packet arrives at the destination correctly or the packet is dropped because the maximum number of allowed retransmissions is exceeded for that packet. This retransmission limit usually stems from the delay constraint of the data traffic, especially those generated by voice and/or video applications. In this paper, we propose to optimally select the retransmission limit as well as the transmitting power for each hop for energy saving purpose.

We consider the transmission of delay sensitive traffic over the multihop radio path. More specifically, the traffic has the QoS requirement that packets must be delivered to the destination node without error within T_D seconds with a required probability P_{req}. Note that we focus on the allowed transmission delay while assume queuing delay due to multiple flow has been taken into account during the routing process and subtracted from the total delay budget. The common round-trip time of each individual hop is assumed to be T_R and, as such, the total number of allowed transmissions/retransmissions[2] is $N = \lfloor T_D/T_R \rfloor$. The QoS requirement for the traffic can then be rephrased as follows: the packets must arrive at the destination correctly within N total transmission/retransmissions, or equivalently within $N - L$ retransmissions, with the probability of P_{req}. Finally, while there may be multiple packet traveling along the path at the same time, we ignore the interference between different packet transmissions. Note that if a node cannot transmit and receive at the same time, simultaneous transmission on adjacent hops will not occur.

3. ANALYSIS ON UNCONFIGURED BEST-EFFORT TRANSMISSION

In this section, we consider the best-effort transmission strategy for packet transmission over a multihop path. With best-effort transmission, every node along the path tries to deliver the packet to the next node without error by performing as many retransmissions as necessary with maximum transmitting power $p_{\max}$, that is, $p_i = p_{\max}$ for $i = 1, 2, \ldots, L$. A packet is dropped only if the maximum number of allowed retransmissions is exceeded. We derive closed-form expressions for the packet delivery ratio and average energy consumption for a single packet delivery with best-effort transmission.

Let x_i denote the number of transmissions and retransmissions that are actually performed over the ith hop. We note that with the best-effort strategy, a packet can arrive at the destination without error after $k = \sum_{i=1}^{L} x_i$ transmissions/retransmissions, where $L \le k \le N$. The probability of each realization of vector $\mathbf{x} = [x_1, x_2, \ldots, x_L]$, satisfying (i) $k = \sum_{i=1}^{L} x_i$, (ii) $1 \le x_i < k$, and (iii) $L \le k \le N$, can be calculated as

$$P_{\text{succ}}(\mathbf{x}) = \prod_{l=1}^{L} P_l^{x_l - 1}(1 - P_l), \tag{3}$$

where P_l is the packet error probability for the lth hop. Note that P_l was given in (2) with p_l now equal to $p_{\max}$ for all l. Summing up the probabilities for all possible vectors, we obtain the packet delivery ratio P_{succ} with best-effort transmission strategy as

$$P_{\text{succ}} = \sum_{k=L}^{N} \left[\sum_{\substack{\sum_{i=1}^{L} x_i = k \\ 1 \le x_i < k}} \left(\prod_{l=1}^{L} P_l^{x_l - 1}(1 - P_l) \right) \right]. \tag{4}$$

We now determine the average energy consumption for a single data packet delivery, regardless of whether the packet arrives at the destination node correctly within the delay constraint. Note that if a packet fails to arrive at the destination within the maximum number of retransmissions, it may be dropped on any one of the L hops. In this case, all $N - L$ allowed retransmissions must have been performed. Note that if the packet is dropped on the jth hop, then the vector $\mathbf{x}$ satisfies (i) $x_i = 0$ for $j < i \le L$; (ii) $\sum_{i=1}^{j} x_i = N - (L - j)$; and (iii) $1 \le x_i \le N - (L - j)$ for $1 \le i \le j$ and the probability for each such vector is equal to

$$P_{\text{drop}}^{(j)}(\mathbf{x}) = \left(\prod_{l=1}^{j-1} P_l^{x_l - 1}(1 - P_l) \right) P_j^{x_j}. \tag{5}$$

Therefore, the probability that the packet is dropped on the jth hop $P_{\text{drop}}^{(j)}$ is obtained as

$$P_{\text{drop}}^{(j)} = \sum_{\substack{\sum_{i=1}^{j} x_i = N-(L-j) \\ 1 \le x_i \le N-(L-j)}} \left(\prod_{l=1}^{j-1} P_l^{x_l - 1}(1 - P_l) \right) P_j^{x_j}. \tag{6}$$

For a particular realization of vector $[x_1, x_2, \ldots, x_L]$, the corresponding energy consumption $\mathcal{E}$ is equal to $T \cdot \sum_{i=1}^{L} x_i p_{\max}$, where T is the time duration required for transmitting a data packet. For simplicity, in the rest of the paper, we set $T = 1$ without loss of generality. Therefore, we obtain the following

[2] Since the receiving node may transmit to the next node once it correctly receives the packet, without waiting for the positive acknowledgment to reach the transmitting node, the actual value of N may be slightly greater than $\lfloor T_D/T_R \rfloor$. We ignore those extra transmissions for the sake of brevity here.

analytical expression for the average energy consumption per packet delivery with best-effort transmission strategy as

$$\mathbf{E}[\mathcal{E}] = \sum_{k=L}^{N}\left[\sum_{\substack{\sum_{i=1}^{L} x_i=k\\ 1\le x_i<k}}\left(\sum_{i=1}^{L} x_i p_{\max}\right)\left(\prod_{l=1}^{L} P_l^{x_l-1}(1-P_l)\right)\right] + \sum_{j=1}^{L}\left[\sum_{\substack{\sum_{i=1}^{j} x_i=N-(L-j)\\ 1\le x_i\le N-(L-j)}}\left(\sum_{i=1}^{j} x_i p_{\max}\right) \times\left(\prod_{l=1}^{j-1} P_l^{x_l-1}(1-P_l)\right)P_j^{x_j}\right], \tag{7}$$

where $\mathbf{E}[\cdot]$ denotes the statistical expectation.

4. MINIMUM-ENERGY CONFIGURATION

In this section, we consider the minimum-energy configuration of a multihop link for energy-efficient packet delivery. We assign a maximum retransmission limit to each individual hop, denoted by $\hat{x}_i$, in advance. As such, packet drop may occur in any hop when the retransmission limit for that hop is reached. We first derive closed-form expressions for the message delivery ratio and average energy consumption with an arbitrary transmitting power and retransmission limit configuration. Then, we formulate and solve an optimization problem to configure the path through jointly setting the transmitting power for each transmitting node and the number of allowed transmissions/retransmissions over each hop.

4.1. Packet delivery ratio and energy consumption analysis

Let $\hat{\mathbf{x}}$ and $\mathbf{p}$ denote the vector of the number of permitted transmissions/retransmissions and the transmitting power over the ith hop, respectively, that is, $\hat{\mathbf{x}} = [\hat{x}_1, \hat{x}_2, \ldots, \hat{x}_L]$ and $\mathbf{p} = [p_1, p_2, \ldots, p_L]$. We first determine the probability of successful packet transmission over the multihop link for a particular choice of the vectors $\hat{\mathbf{x}}$ and $\mathbf{p}$. Note that node R_{i-1} will drop a packet if the data packet has been transmitted $\hat{x}_i$ times over the ith hop $R_{i-1}R_i$ without being correctly received by R_i. It can be shown that the packet delivery ratio $P_{\text{succ}}(\hat{\mathbf{x}}, \mathbf{p})$ is given by

$$P_{\text{succ}}(\hat{\mathbf{x}}, \mathbf{p}) = \prod_{i=1}^{L}\left(1 - P_i^{\hat{x}_i}\right), \tag{8}$$

where P_i is the packet error probability for the ith hop, which is given in (2) as a function of p_i.

We now calculate the average energy consumption for a single packet transmission regardless of whether it is successfully delivered to the destination within the delay constraint. For a particular realization of $\hat{\mathbf{x}}$ and $\mathbf{p}$, the average power consumption per packet delivery over the configured multihop link is given by

$$\mathbf{E}[\mathcal{E}(\hat{\mathbf{x}}, \mathbf{p})] = \sum_{i=1}^{L}\mathbf{E}[x_i]p_i, \tag{9}$$

where x_i denotes the actual number of transmissions and retransmissions performed over the ith hop, which becomes a discrete random variable (RV) taking integer values from 0 to $\hat{x}$. Note that the distribution of x_i depends on the values of $\hat{x}_j$ and p_j for $1 \le j \le i$. For the first hop, the source node R_0 would repeatedly transmit a data packet until either it is successfully received by R_1 or the number of maximum retransmissions for the first hop $\hat{x}_i$ is exceeded. Conditioning on the number of retransmissions used in a successful delivery and applying the total probability theorem, it can be shown that the probability that a data packet is correctly received by R_1 is $(1 - P_1)\cdot\sum_{k=1}^{\hat{x}_1} {P_1}^{k-1}$. Moreover, we can easily obtain the probability that a packet is dropped in the first hop is ${P_1}^{\hat{x}_1}$. Combining the two mutually exclusive cases, we can write $\mathbf{E}[x_1]$ as

$$\mathbf{E}[x_1] = (1 - P_1)\sum_{k=1}^{\hat{x}_1} {P_1}^{k-1}\cdot k + P_1^{\hat{x}_1}\cdot\hat{x}_1. \tag{10}$$

After similar algebraic manipulations as in [15, page 36], we have

$$\mathbf{E}[x_1] = \frac{1 - P_1^{\hat{x}_1}}{1 - P_1}. \tag{11}$$

For the second hop R_1R_2, x_2 may be either zero or a positive integer depending on whether the packet can reach R_1 or not. If the packet is successfully delivered to R_1, we can follow the similar approach for deriving (11) to calculate the average number of transmission/retransmissions performed by R_1. Therefore, noting that the probability that a data packet can reach R_1 correctly is equal to $1 - P_1^{\hat{x}_1}$, it can be shown that

$$\begin{aligned}\mathbf{E}[x_2] &= P_1^{\hat{x}_1}\times 0 + \left(1 - P_1^{\hat{x}_1}\right)\\ &\quad\times\left[(1 - P_2)\sum_{k=1}^{\hat{x}_2} {P_2}^{k-1}\cdot k + P_2^{\hat{x}_2}\cdot\hat{x}_2\right]\\ &= \left(1 - P_1^{\hat{x}_1}\right)\cdot\frac{1 - P_2^{\hat{x}_2}}{1 - P_2}.\end{aligned} \tag{12}$$

With the above derivation in mind, we now develop a general expression for $\mathbf{E}[x_i]$, $i \ge 2$. Note that x_i is nonzero if and only if the packet is successfully delivered over the first $i - 1$ hops and finally received by R_{i-1}, the probability of which is given by $\prod_{j=1}^{i-1}(1 - P_j^{\hat{x}_j})$. Also note that the average number of transmissions/retransmissions conducted in the ith hop is $(1 - P_i^{\hat{x}_i})/(1 - P_i)$, after the packet arrives at R_{i-1} correctly. Therefore, we have

$$\mathbf{E}[x_i] = \prod_{j=1}^{i-1}\left(1 - P_j^{\hat{x}_j}\right)\cdot\frac{1 - P_i^{\hat{x}_i}}{1 - P_i}, \quad i \ge 2. \tag{13}$$

Combining (9), (10), and (13), we obtain a closed-form expression for the average energy consumption per packet delivery over a configured L-hop path as

$$\mathbf{E}\left[\mathcal{E}(\hat{\mathbf{x}},\mathbf{p})\right]=\frac{1-P_1^{\hat{x}_1}}{1-P_1}\cdot p_1+\sum_{i=2}^{L}\prod_{j=1}^{i-1}\left(1-P_j^{\hat{x}_j}\right)\cdot\frac{1-P_i^{\hat{x}_i}}{1-P_i}\cdot p_i. \tag{14}$$

4.2. Minimum-energy optimization

Based on the closed-form expressions for the packet delivery ratio and average energy consumption of a multihop wireless path, we are now in a position to formulate an optimization problem for the multihop route configuration. In particular, we seek to select vectors $\hat{\mathbf{x}}$ and $\mathbf{p}$ so that the average energy consumption for packet delivery is minimized and the packet can arrive at the destination node within $N-L$ retransmissions with probability at least P_{req}. This leads to the following optimization problem:

$$\underset{\hat{\mathbf{x}},\mathbf{p}}{\text{minimize}}\ \mathbf{E}\left[\mathcal{E}(\hat{\mathbf{x}},\mathbf{p})\right] \tag{15a}$$

$$\text{subject to } P_{\text{succ}}(\hat{\mathbf{x}},\mathbf{p})\geq P_{\text{req}}, \tag{15b}$$

$$p_{\max}>p_i>0 \quad \text{for } 1\leq i\leq L, \tag{15c}$$

$$\sum_{i=1}^{L}\hat{x}_i=N,\quad \hat{x}_i\in\{1,2,\ldots,N\}, \tag{15d}$$

where in this case the packet delivery ratio $P_{\text{succ}}(\hat{\mathbf{x}},\mathbf{p})$ becomes a function of both power configuration vector $\mathbf{p}$ and retransmission configuration vector $\hat{\mathbf{x}}$.

Note that in the optimization problem (15), $\hat{x}_i$ can only take integer values whereas p_i are continuous variables, and that both the objective function and the constraints given in (19b) are nonlinear functions of $\hat{x}_i$ and p_i. Therefore, the optimal configuration problem of a multihop link is actually a mixed integer nonlinear programming (MINP) problem [16]. In general, optimization problems of this kind are NP-hard and few algorithms guarantee to find the global minimum. However, in practical systems, the number of hops in a multihop wireless link is usually small. In this case, (15) can be efficiently solved by using small scale MINP algorithms such as the branch-and-bound algorithm [17]. Because of space limitation, we omit the details of applying the branch-and-bound algorithm to solve the optimization problem. Obviously, the calculation of the solution to the optimization problem will incur additional energy consumption to the destination node. However, as we will observe in the later numerical examples, the average energy saving for packet transmissions with route configuration based on the possibly local-minimum solution is significant compared to the unconfigured best-effort approach, which justifies the energy cost spent in solving the optimization problem.

5. MAXIMUM LIFETIME CONFIGURATION

While the minimum-energy configuration in the previous section can reduce the average energy cost per packet transmission, it does not take into account the available energy resources of intermediate nodes along the path. Consider, as an example, a transmitting node with low battery supply and sending data packets over an unfavorable radio hop. With the minimum-energy configuration, this node will be configured with high transmitting power and a large number of retransmissions. This configuration will quickly deplete the battery resource of this node and leave the whole path unusable, which will not only cause the interruption of the data transmission but also lead to extra route recovery operations. In this section, we develop a maximum-lifetime configuration algorithm for multihop paths in wireless ad hoc networks. In particular, we take into consideration both the link quality of each hop and the battery capacity of the transmitting nodes in determining the transmitting power for each transmitting node and the maximum number of allowed retransmissions for each hop to extend the lifetime of the multihop, in terms of the average number of packets that can be transmitted.

Note that for a particular pair of path configuration vectors $\hat{\mathbf{x}}=[\hat{x}_1,\hat{x}_2,\ldots,\hat{x}_L]$ and $\mathbf{p}=[p_1,p_2,\ldots,p_L]$, the average packet delivery ratio of that multihop path is given in (8). We assume that the multihop path reaches its lifetime when the battery supply of any intermediate node becomes too little to support a single packet transmission. Let B_i, $1\leq i\leq L$, denote the remaining battery resource of the ith node for packet transmission. The average path lifetime is defined as

$$T(\hat{\mathbf{x}},\mathbf{p})=\min_i\left\{\frac{B_i}{\mathbf{E}[x_i]p_i}\right\}, \tag{16}$$

where $\mathbf{E}[x_i]$ is the average energy consumption per packet delivery over the ith hop, which is given in (13).

Based on the closed-form expressions for the packet delivery ratio and the average path lifetime, we can formulate another optimization problem to configure the multihop path. In particular, we seek to select vectors $\hat{\mathbf{x}}$ and $\mathbf{p}$ so that the average path lifetime is maximized under the constraint that the packet can arrive at the destination node within $N-L$ retransmissions with probability at least P_{req}. This leads to the following optimization problem:

$$\underset{\hat{\mathbf{x}},\mathbf{p}}{\text{maximize}}\ T(\hat{\mathbf{x}},\mathbf{p}) \tag{17a}$$

$$\text{subject to } P_{\text{succ}}(\hat{\mathbf{x}},\mathbf{p})\geq P_{\text{req}}, \tag{17b}$$

$$p_{\max}>p_i>0 \quad \text{for } 1\leq i\leq L, \tag{17c}$$

$$\sum_{i=1}^{L}\hat{x}_i=N,\quad \hat{x}_i\in\{1,2,\ldots,N\}. \tag{17d}$$

From (16) and (17), we see that (17) is a constrained optimization problem with a minimax-type objective function to which few optimization algorithms are directly applicable. To deal with this problem, let δ be a lower bound of $B_i/\mathbf{E}[x_i]p_i$, $i=1,\ldots,L$, for vectors $\hat{\mathbf{x}}$ and $\mathbf{p}$ satisfying constraints in (17), that is,

$$\frac{B_i}{\mathbf{E}[x_i]p_i}\geq\delta \quad \text{for } 1\leq i\leq L. \tag{18}$$

It follows from (16) and (18) that $T(\hat{\mathbf{x}},\mathbf{p})\geq\delta$. Hence, maximizing $T(\hat{\mathbf{x}},\mathbf{p})$ subject to the constraints in (17) amounts to

Table 1: Results of minimum-energy path configuration.

$\mathbf{c}$	$\mathbf{p}$	$\hat{\mathbf{x}}$
[0.158, 0.06, 0.158]	[0.338, 0.214, 0.354]	[4, 3, 4]
[0.158, 0.06, 0.05]	[0.319, 0.154, 0.175]	[4, 4, 3]
[0.05, 0.06, 0.158]	[0.166, 0.152, 0.326]	[3, 4, 4]

maximizing the lower bound δ subject to the constraints in (17) and (18). In this way, the optimization problem in (17) is reformulated as

$$\underset{\hat{\mathbf{x}},\mathbf{p},\delta}{\text{maximize}}\ \delta \tag{19a}$$

$$\text{subject to } \frac{B_i}{\mathbf{E}[x_i]p_i} \geq \delta, \quad 1 \leq i \leq L, \tag{19b}$$

$$P_{\text{succ}}(\hat{\mathbf{x}}, \mathbf{p}) \geq P_{\text{req}}, \tag{19c}$$

$$p_{\max} > p_i > 0, \quad 1 \leq i \leq L, \tag{19d}$$

$$\sum_{i=1}^{L} \hat{x}_i = N, \quad \hat{x}_i \in \{1, 2, \ldots, N\}, \tag{19e}$$

where lower bound δ is treated as an additional variable. Note that the maximum-lifetime configuration of a multihop path is again an MINP problem [16]. Since the number of hops in a multihop wireless link is usually not large, (19) can also be efficiently solved by using small scale MINP algorithms such as the branch-and-bound algorithm [17]. As we will see in the next section, even with possibly local-minimum solution, the maximum-life configuration can extend path lifetime and save considerable energy, compared to the unconfigured best-effort case.

6. NUMERICAL EXAMPLES AND DISCUSSION

In this section, we illustrate the effectiveness of the path configuration algorithms over multihop paths through numerical examples. In particular, we consider a 3-hop path, that is, $L = 3$, while noting that most of observations hold for paths with a larger number of hops. To simplify the following presentation, we define a channel coefficient vector $\mathbf{c}$, whose ith entry c_i is given by

$$c_i = \frac{\gamma_T}{G_i}, \quad i = 1, 2, 3. \tag{20}$$

It can be seen that the channel condition of the ith hop becomes worse as the corresponding coefficient c_i increases. The QoS requirement of the traffic is assumed to be that packets should reach its destination after $N = 11$ transmission/retransmission with probability of at least $P_{\text{req}} = 0.95$. The maximum transmitting power $p_{\max}$ is set to 0.56 W. For the maximum-lifetime configuration, we assume that the battery capacities of the three transmitting nodes are set as $B_1 = 600$ J, $B_2 = 500$ J, and $B_3 = 400$ J, respectively.

6.1. Minimum-energy configuration

In Table 1, we present the solutions of the minimum-energy configuration problem given in (15) for three different choices of channel coefficient vector $\mathbf{c}$. As we can see, the path configuration algorithm selects a higher transmission power and allocates a larger number of retransmissions to a hop experiencing poor channel condition, as one can expect by intuition. We also notice that this bias in route configuration towards poorer hops is not inversely proportional to the channel quality. In particular, we note that $p_i/p_j < c_i/c_j$ for $c_i > c_j$. Finally, we observe from the first choice of vector $\mathbf{c}$ that although the first and the last hops experience the same poor channel condition, the configuration algorithm allocates more power to the last hop and the same retransmission limit for both hops. This is because once a packet arrives at the last hop, less energy will be wasted if the packet is successfully transmitted to the destination than if the packet is lost eventually.

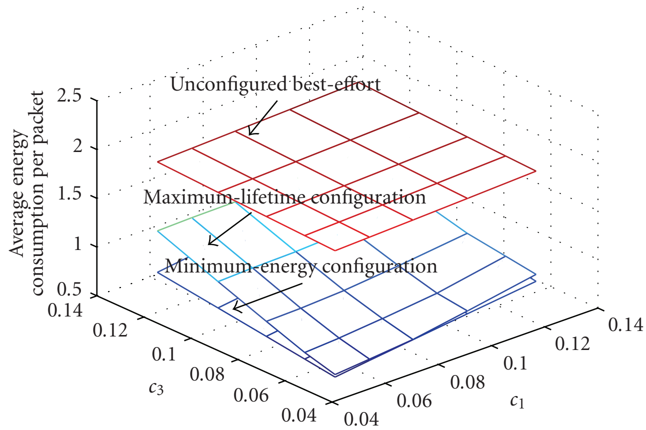

Figure 1: Average power consumption per packet with the maximum-lifetime configuration, minimum-energy configuration, and unconfigured best-effort strategies ($P_{\text{req}} = 0.95$, $N = 11$, $p_{\max} = 0.56$ W).

The energy saving offered by the minimum-energy configuration algorithm is illustrated in Figure 1. In generating the numerical results, we fix the channel coefficient of the second hop c_2 to be 0.06 while varying c_1 and c_3 from 0.05 to 0.158.[3] We first compare the average energy consumption for a single packet delivery in the 3-hop wireless link with minimum-energy configuration and unconfigured best-effort case (i.e., each node always uses the maximum transmitting power $p_{\max}$ for each transmission/retransmission). It can be observed that route configuration can save considerable amount of energy compared to the traditional best-effort strategy. For example, when c_1 and c_3 are equal to 0.0998 and 0.0792, respectively, the average power consumption required for a packet delivery with minimum-energy configuration is only 36.38% of that of the unconfigured best-effort case. It can also be seen that both strategies consume less energy on average as the channel

[3] This range for the channel coefficients and the choice of 0.7 W for $p_{\max}$ guarantee that even the worst hop, that is, the hop with channel coefficient 0.158, has a packet loss rate less than 20%.

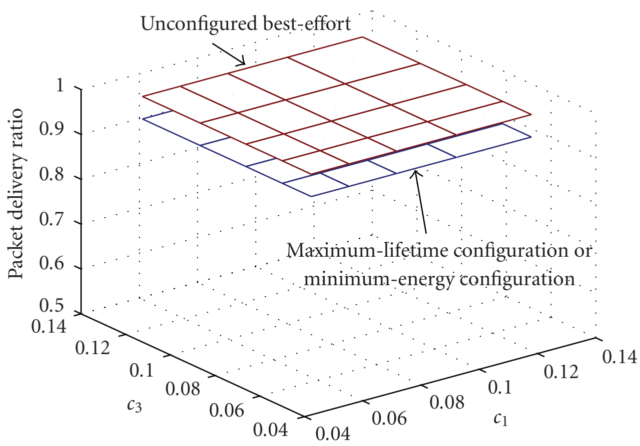

Figure 2: Packet delivery ratio with the maximum-lifetime configuration, minimum-energy configuration, and unconfigured best-effort strategies ($P_{\text{req}} = 0.95$, $N = 11$, $p_{\max} = 0.56$ W).

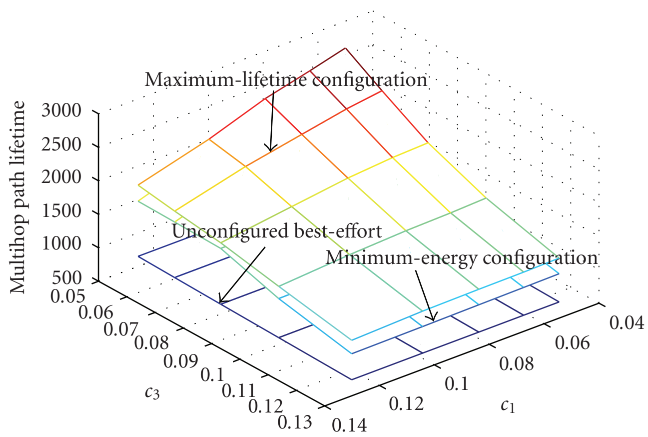

Figure 3: Path lifetime with the maximum-lifetime configuration, minimum-energy configuration, and unconfigured best-effort strategies for a 3-hop path ($P_{\text{req}} = 0.95$, $N = 11$, $p_{\max} = 0.56$ W).

Table 2: Results of maximum-lifetime path configuration.

$\mathbf{c}$	$\mathbf{p}$	$\hat{\mathbf{x}}$
$[0.05, 0.05, 0.126]$	$[0.443, 0.367, 0.143]$	$[2, 2, 7]$
Minimum-energy case	$[0.159, 0.128, 0.247]$	$[3, 4, 4]$
$[0.126, 0.05, 0.05]$	$[0.180, 0.248, 0.188]$	$[5, 3, 3]$
Minimum-energy case	$[0.254, 0.165, 0.132]$	$[4, 3, 4]$

coefficients c_1 and c_3 decrease. That is because smaller values of the channel coefficients represent better channel conditions.

Figure 2 plots the packet delivery ratio with the minimum-energy configuration and unconfigured best-effort case as the functions of c_1 and c_3. It can be observed that for all value pairs of c_1 and c_3, the minimum-energy configured path can always provide a packet delivery ratio greater or equal to P_{req}, which satisfies the QoS requirement. Note also that the application of traditional best-effort strategy leads to a slightly higher packet delivery ratio compared to the case with minimum-energy configuration, as expected. However, considering Figures 1 and 2 together, we can observe that the minimum-energy path configuration achieves the appealing property of maintaining acceptable path reliability while significantly reducing the average energy consumption.

6.2. *Maximum lifetime configuration*

In Table 2, we present the solutions of the maximum-lifetime path configuration problem given in (19) for two different choices of channel coefficient vector. For comparison, we also present the results of the same path with minimum-energy configuration in the italic format. As we can see, the maximum-lifetime configuration algorithm selects a smaller transmitting power and allocates a larger number of retransmissions to transmitting node with less battery resource, compared with the minimum-energy configuration. As such, the average energy consumption over the corresponding hop decreases to achieve a longer path lifetime. For example, for the first choice of channel coefficient vector, the average energy consumption of the third hop with maximum-lifetime configuration is 0.327, while a value of 0.41 is observed with minimum-energy configuration.

We now compare the maximum-lifetime configuration with the minimum-energy configuration and the unconfigured best-effort case. In Figure 3, we plot the path lifetime with the three strategies. It can be seen that with maximum-lifetime configuration, the multihop route achieves the largest lifetime. For example, when $c_1 = 0.063$ and $c_3 = 0.0998$, there is a 23.1% and a 150% increase in the path lifetime with the maximum-lifetime configuration, compared with minimum-energy configuration and traditional best-effort case, respectively. It can also be seen that as c_1 and c_3 decrease, that is, the channel conditions improve, all three schemes would lead to an increased path lifetime, as expected.

For comparison purpose, we have also plotted the average energy consumption with maximum-lifetime configuration in Figure 1 and the corresponding packet delivery ratio in Figure 2. As we can see, the maximum-lifetime configuration can also save considerable amount of energy per packet delivery compared to the unconfigured best-effort case. We also notice that the maximum-lifetime configuration will lead to a slightly larger average power consumption than minimum-energy configuration for the same selection of channel coefficients. From Figure 2, we observe that, similar to the minimum-energy configuration, the maximum-lifetime configuration can always provide a packet delivery ratio greater or equal to 0.95 for all value pairs of c_1 and c_3. Considering Figures 1, 2, and 3 together, we can observe that the maximum-lifetime configuration achieves the property of maintaining acceptable path reliability and considerably low energy consumption while significantly improving the lifetime of an existing path.

7. IMPLEMENTATION CONSIDERATION

The route configuration algorithm presented in this paper targets at the efficient usage of existing paths obtained by routing protocols. As such, our route configuration algorithm could become an optional but a desired feature of any existing routing protocol of wireless ad hoc network for improved energy efficiency. In this section, we adopt a commonly used routing protocol, dynamic source routing (DSR) [10], as an example to illustrate how our route configuration algorithm can be utilized. The principle discussed in this section is applicable to most routing protocols.

The DSR protocol [10] uses the source routing approach (i.e., every data packet carries the whole path information in its header) to forward packets. When a source node wants to send messages to a destination node but does not know a path to the destination, the source node initiates the route discovery process by broadcasting a Route REQuest (RREQ) message. Each node, once receiving the RREQ message, puts its node ID in the RREQ message and rebroadcasts the message. When the RREQ message reaches the destination node, the destination node replies with a Route REPly (RREP) message to the source node, using the reversed path that the RREQ message just traversed. The source node can obtain the complete path information after it receives the RREP message.

Our path configuration algorithms could be applied to the route discovery process of DSR as follows. From implementation point of view, decoupling the routing protocol and energy saving means that the routing algorithm is irrelevant to energy metrics. Nevertheless, data structure of control messages may need to change to facilitate path configuration. Each RREQ message should piggyback parameters of the link status of intermediate hops, that is, the parameters G_i in Section 2, and the remaining battery resource, that is, B_i in Section 5. After receiving RREQ, the destination node uses the collected information to solve the optimization problem and determine the retransmission limit and the power level for each intermediate hop. Then, it piggybacks the configuration information in the RREP packet. Each intermediate node, once receiving the RREP packet, will configure itself accordingly.

Since our path configuration algorithms are essentially independent of routing protocols or transport layer protocols, our path configuration algorithms could also be used for an end-to-end data flow. For instance, when a source node wants to establish a TCP connection with a destination node, the TCP SYN message can piggyback the link status information to the destination node. The destination node, after it calculates the path configuration with our algorithms, can use the TCP ACK message to notify each intermediate node the path configuration instruction. Similar operations could be performed even during an on-going data flow, by piggybacking the control information in the end-to-end data and acknowledgment messages.

We stress that route configuration is not performed on a packet-by-packet basis. When the network topology and network link quality are stable, the frequency of path reconfiguration could be quite small. In mobile ad hoc networks, however, route reconfiguration should be performed when the network topology changes and new paths are searched for. Although the destination node may consume extra energy in calculating optimal path configuration, such cost is not prohibitive as long as the number of nodes remains small. On the other hand, the path configuration process has substantial benefits due to the fact that a properly configured path will last longer and also the fact that energy cost on calculation is negligible compared to that on message transmission. For instance, the energy cost for transmitting 1 bit could be equivalent to the energy cost of executing up to 800 instructions [18].

8. CONCLUSION

In this paper, we have proposed the minimum-energy and maximum lifetime configuration algorithms to configure an existing multihop path with ARQ mechanism under a given QoS requirement and delay constraint. Our algorithms could work as an add-on function with most existing routing and transport protocols. Numerical results clearly illustrate the benefit of the proposed methods. We observed that the new algorithms can prolong the lifetime of the multihop path while maintaining an acceptable packet delivery ratio and considerably low overall average energy consumption. We have also investigated the tradeoff of path lifetime versus average energy consumption between the minimum-energy and maximum-lifetime configuration schemes.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Le Yang for his help with the preparation of the figures and for some insightful discussions regarding these figures. This work was supported in part by startup funds from the University of Victoria and in part by Discovery Grant from NSERC. This is an expanded version of work which was presented in part at the 25th IEEE International Performance Computing and Communications Conference (IPCCC ’06), Phoenix, Arizona, USA, April 2006.

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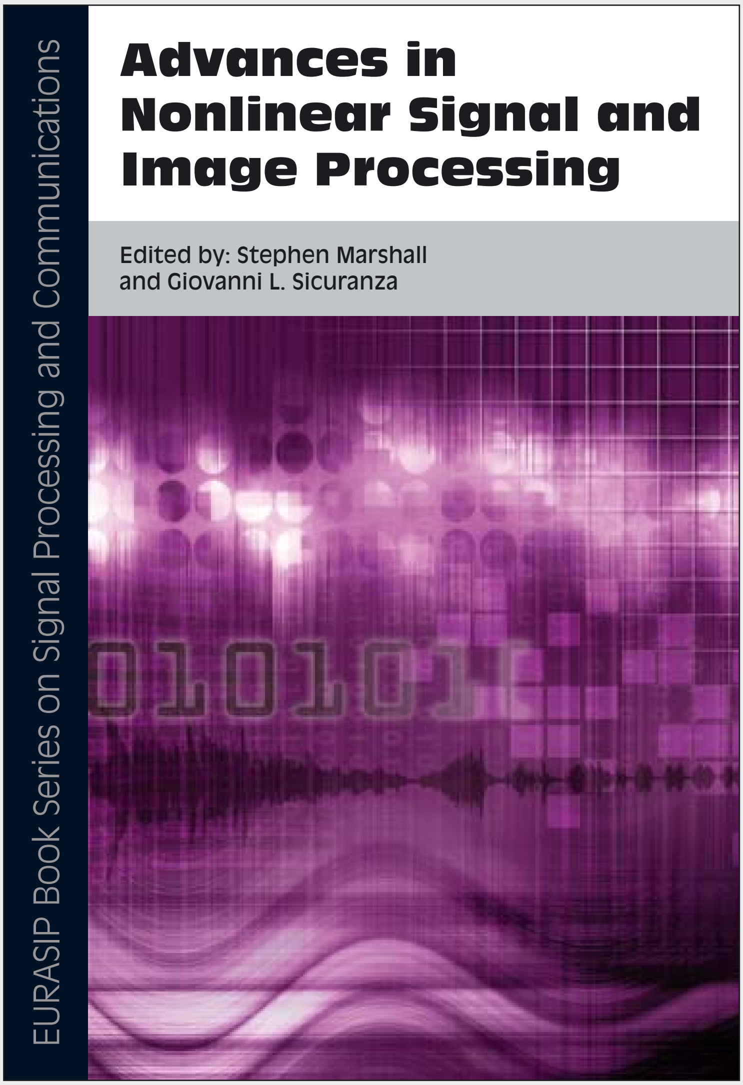

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