FAULT TOLERANCE OF MULTIHOP WIRELESS NETWORKS

N. Eva Wu†, Xiaohua Li†, and Timothy Busch‡

†ECE Dept., Binghamton Univ., Binghamton, NY 13902, USA
‡AFRL/IFSB, 525 Brooks Road, Rome, NY 13441, USA

Abstract: This paper analyzes fault-tolerance over the entire design life of a class of multiple-hop wireless networks subject to both node failure and random channel fadings. It also examines the benefit and cost of feedback in network operations. A node lifetime distribution is modeled with an increasing failure rate, where the node power consumption level enters the parameters of the distribution. A method for assessing both link and network reliabilities projected at the network's design life is developed. The link reliability is then used to allocate active nodes to clusters using dynamic programming for maximizing the network's fault-tolerance, and to establish a re-transmission control policy that minimizes an expected cost involving power, bandwidth expenditures, and packet loss.

Keywords: reliability, fault-tolerance, wireless networks, dynamic programming, Markov decision problem.

1. INTRODUCTION

The class of wireless networks under consideration is the class of multiple-hop, distributed networks consisting of a large number of nodes. Each node has a limited energy supply that cannot be replenished, and is capable of packet transmission, reception, and processing that involves detection, fusion, coding and decoding. Our goal is to maximize the network reliability at its *design life* T_D [1]. Our main challenge is to develop a power covariate network reliability model [2]. As a result, the network reliability becomes the overarching measure that encompasses aspects of symbol error rate, energy efficiency, bandwidth efficiency, the effect of clustering, and the effect of feedback.

Many algorithms have been developed for the computation of node-pair reliability of networks, which is the probability that at least one route exists between a source node and a terminal node (Torrieri, 1994). Unlike any other networks, however, each route in our network itself forms a sub-network with an additional structure bound by the cooperative transmission scheme used. Therefore, we confine ourselves to the sub-network of a K-cluster route through which packets hop from cluster 1 to cluster K. The restriction to the single-route problem is entirely due to our intention to capitalize on some new physical layer transmission schemes (Li and Wu 2003; Li 2003, 2004). Our interest is not in devising routing protocols (Ordonez et al., 2004) that enhance the network connectivity evaluated using the knowledge of the spacial distribution of the wireless nodes (Xue and Kumar, 2004), or prolong network lifetime assessed using the deterministic knowledge of energy expenditure at each node (Bhardwaj et al., 2002). Instead, we are seeking to understand and to optimize the temporal evolution of network reliability and to utilize this information in the network operation with little supervising activity.

Existing schemes for enhancing the network fault-tolerance all carry significant overhead in terms of energy consumption. Examples of such schemes include multiple-path routing (Ganesan et al., 2002), packet replication (De et al., 2003), or

⋆ The first author acknowledges the support by the US Air Force Research Laboratory (F30602-020-C-0225), and by NASA (NCC-1-02009).

[1] A design life is defined as the maximum time by which a prescribed network reliability R^D is maintained, i.e.,$F^{net}(t)|_{t=T_D} = 1 - R^D$. where $F^{net}(t)$ is the cumulative distribution function of the network time to failure.

[2] The network reliability is given by $R^{net}(t) = 1-F^{net}(t)$, which is defined as the probability that the network performs successfully its required function over a period of t time units under the stated operating conditions.

feedback between neighboring nodes that either acknowledges a successful reception or requests a re-transmission of a packet (Kumar, 2001). Unlike more traditional networks, such as the Internet, where highly reliable links contribute little to the transmission failures, the links of wireless networks are much less reliable as a result of, for example, severe channel fading, or limited standalone reliability of low-cost nodes, or energy depletion of nodes. On the other hand, redundancy is abundant in such networks. Therefore, opportunities exist to address the issues of fault-tolerance and energy efficiency simultaneously. Of particular interest is the question on how much feedback is needed at a certain level of redundancy usage for a prescribed network design life.

With a proper formulation of a cooperative transmission problem employing multiple nodes, transmission diversity can be provided to combat deep-fading suffered by the near-ground communications (Laneman and Wornell, 2003; Sendonaris et al., 2003). The existing cooperative diversity schemes, though efficient in transmission power, increase the circuit energy consumption associated with, for example, static current in transceivers and encoding/decoding circuity, when multiple nodes must be kept on for listening and reception (Ganesan et al., 2002). We are developing new *cooperative transmission* schemes to address power efficiency, bandwidth efficiency, and fault-tolerance simultaneously. Our preliminary simulation results (Li and Wu, 2003) indicated a 6-fold reduction in power consumption at an enhanced level of network reliability with a two-node cluster that achieves a $15dB$ signal to noise ratio at the receiving cluster. This can be implemented using a new space-time block coding technique (Li, 2003 and 2004) with no loss of bandwidth efficiency.

Little has been discussed at the physical-layer in terms of network fault-tolerance (Hoblos et al., 2000) up to this point. Our basic idea is to determine the level of redundancy appropriate for our cooperative transmission scheme that also maximizes the network reliability at its design life. Since high cross-correlation among packets exists under this scheme, a certain packet loss rate could be tolerated without having to incur energy loss associated with frequent feedback and re-transmission.

The paper is organized as follows. In section 2, a re-transmission chain is formed that serves to motivate the quest for understanding the impact of loop-closure on the network reliability. Section 3 discusses modeling the life time distribution of a node, and deriving the network level reliability and its lower bound as a function of link reliabilities. Section 4 applies the link reliabilities for the assignment of active nodes to clusters to maximize the network fault-tolerance up to its design life. It also tackles the re-transmission issue as a Markov decision problem with partial information feedback.

2. A MOTIVATING EXAMPLE

The Markov chain in Fig.1 describes a K-cluster packet transmission process where state name i stands for the ith cluster within which a packet hopping from the source through the network to the destination is residing. This chain is non-homogeneous due to the deteriorating link reliability p_i^l as the network ages. The link reliability, to be evaluated in the next section, is the probability that a packet reaching the i^{th} cluster is successfully relayed to the $i+1^{th}$ cluster with a required power level.

c_i, called a supervisory coverage, in Fig.1 is the conditional probability that upon the failure of the first transmission attempt, a re-transmission command is successfully issued to cluster i. In an unsupervised environment, $c_i = 1$ for the first transmission attempt, and $c_i = 0$ for any re-transmissions. In a supervised environment, on the other hand, $0 < c_i < 1$ in general (Wu, 2004). The factors affecting c_i include lack of observability of state, or erroneous state estimation, failure of a supervising node or cluster, fading channel linking the supervising cluster and cluster i, and collision among packets in which case a more elaborate queuing network model becomes appropriate. Therefore, in a truly distributed environment, it is reasonable to assume that $c_i \le p_i^l$. $u(i)$in Fig.1 is the re-transmission control action when state i is entered. For the moment, $u(i) \equiv 1$ and time-invariant p_i^l are assumed.

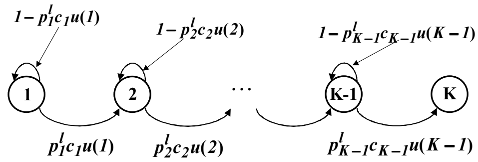

Fig.1 Packet transmission process in a K-cluster route

With the Markov chain established, the state probability p_i^c, i.e., the probability that a packet is in cluster i, can be calculated by solving recursively for $\pi_i(k) = [p_1^c(k) \ \cdots \ p_K^c(k)]$ from $\pi_{k+1} = \pi_k \mathcal{P}_{k,k+1}$, where $\mathcal{P}_{k,k+1}$ transition probability matrix (Cassandras and Lafortune, 1999) as a function of $p_i^l c_i$.
Assume each transmission attempt consumes power P_i The average number of transmissions needed to reach state $i+1$ can be shown to be $\bar{N}_i = 1/p_i^l c_i, \quad i = 1, \cdots, K-1$. Then the power usage per packet transmission through the network, or power efficiency can be estimated by $\bar{P} = \sum_{i=1}^{K} p_i^c(\bar{N}_i P_i)$, and $E = \sum_{t=0}^{T_D} \bar{P}$ is an estimate of the network energy efficiency over its life time.

Here the notion of the network age t is specialized to the number of packet transmissions that the network has carried out so far with the assumption all clusters age uniformly and the number of redundant nodes in each cluster is large.

Let us consider two simple but representative cases. In the first case there are no feedback and no supervisory activity, i.e., $c_i = 0$ for all re-transmissions, while the cluster transmission with multiple nodes is used. In the second case a supervisory scheme is in place to issue re-transmission whenever needed, while only a single node in a cluster is used at a time for each transmission attempt.

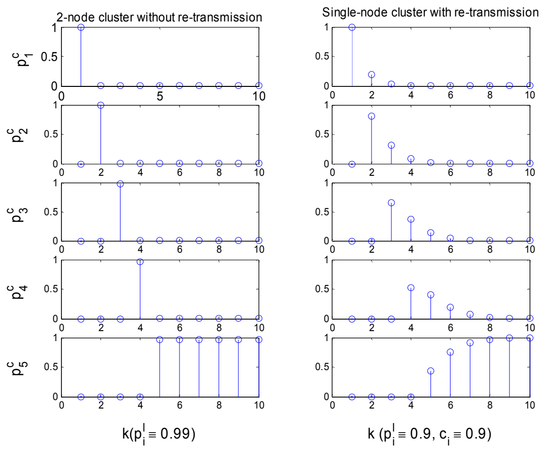

Fig.2 Cooperative transmission using 2-node without feedback v.s. using 1-node with feedback

Fig. 2 shows 10 snapshots of state probabilities for a 5-cluster route when a packet transmission is initiated at $k = 1$ for the above mentioned two representative cases. The five rows of the plots are p_1^c through p_5^c at 10 consecutive instants of packet transmissions. The left column of plots is for the unsupervised case, where the link reliability $p_i^l \equiv 0.99$ for all i at the current network age, resulting from a 2-node cooperative transmission with a reliability of 0.9 for each node. For the moment perfect channels are assumed, in which case a link reliability is the same as a cluster reliability. The right column of plots is for the supervised case, where the current link reliability $p_i^l \equiv 0.9$ for all i, resulting from a 1-node/transmission scheme with a node reliability also 0.9, and a supervisory coverage $c_i = 0.9$.

The following can be observed. (i) Without feedback, the network reliability $\prod_{i=1}^{K-1} p_i^l$ depends solely on the individual link reliabilities. Therefore, high link reliability is crucial, especially for a route with a large number of hops. Given the limited standalone node reliability and channel fading phenomena, high link reliability is not possible without using a multiple-node cooperative transmission scheme. (ii) Feedback enables the network to eventually settle in its absorbing state at the expense of power and bandwidth expenditures. More specifically, it takes an average of 1.23 transmissions to send a packet to the next cluster in this example, which leads to less power efficiency, and more delay. In conclusion, it is most desirable to have a supervisory scheme that is, however, rarely called for under high coverage and high link reliability conditions.

Our remaining tasks have become obvious: to assess and maximize link reliabilities, and to devise a re-transmission stopping rule that abandons a route when it becomes a liability to the network.

3. NETWORK RELIABILITY

3.1 Node and channel reliability models

Due to dependence on power consumption, time to failure distribution of a node must be of increasing failure rate (IFR), i.e., a node that is found to be good after some usage must have a shorter residual life than a brand new node. Weibull IFR distribution

$$F^n(t) = 1 - r^n(t) = 1 - e^{-\left(\frac{t}{\theta(P(J))}\right)^{\beta(P(J))}} \quad (1)$$

is used as an example in this paper, where $\beta(P(J)) > 1$ is called a shape parameter and $\theta(P(J)) > 0$ is called a characteristic life. The Weibull model is deemed covariate because of its explicit dependence of the parameters on power $P(J)$ joules/packet/node involving an J-node cooperative transmission. For simplicity $P(J)$ will be suppressed in the following discussion. t is now the identified with the number of packets the node has relayed. The characteristic life can be scaled by $1/\bar{N}_i$ to reflect the additional life expenditure due to the need of re-transmission at the i^{th} cluster.

For a given type of node and a family of distributions, the parameters of the distribution can be determined statistically (Casella,2002). Suppose at a fixed power level, an n-unit concurrent test is performed. The test terminates at the arrival the rth node failure, i.e., upon the observation of failure times $\{t_1, \cdots, t_r\}$. The maximum likelihood estimates of the Weibull parameters can be solved from

$$\frac{n}{\hat{\beta}} + \sum_{i=1}^{r} \log t_i - \frac{1}{\hat{\theta}} \sum_{i=1}^{r} t_i^{\hat{\beta}} \log t_i + (n-r) t_r^{\hat{\beta}} \log t_r = 0$$

$$\frac{n}{\hat{\beta}} + \frac{1}{\hat{\theta}^2} \sum_{i=1}^{r} t_i^{\hat{\beta}} + (n-r) t_r^{\hat{\beta}} = 0.$$

In addition, Mann's two-parameter F-test can be performed to determine whether to reject the hypothesized Weibull with a specified significance level (Zacks,1992). The empirical dependence of β and θ on $P(J)$ can be established by repeating the experiments for many power levels.

Let T_{lc} denote the period of loop closure, indicating how often a node is checked out to determine whether it has failed. Assuming a uniform aging process, the residual life distribution $F_k(t) \equiv P[T \leq t | T > (k-1)T_{lc}]$ of a node follows

$$F_k(t) = 1 - \frac{r_i^n(t)}{r_i^n((k-1)T_{lc})}, \ \ t \geq (k-1)T_{lc}, \ \ k = 1, 2, \cdots.$$

Single channel failure distribution is assumed to be time independent, and identical for all channels in the network, i.e., $r_i^c = r^c$, unless some a priori information is available, which can be easily incorporated. The randomness is associated with the fading phenomena (Rappaport,2002).

3.2 Link and network reliability

Suppose the i^{th} cluster of the K-cluster network contains a total of I_i nodes. Suppose for every sequence of I_i requests of packet transmission that arrive at the i^{th} cluster, a node responds to a set of J_i consecutive requests. In such an arrangement which will be called a participating/non-participating protocol hereafter, the burden of packet transmission for every node is effectively reduced to a fraction J_i/I_i, and the single node characteristic life θ_i is increased effectively to $\theta_i I_i / J_i$. Note again that the current age of a node is the number of packet transmissions the node has carried out so far. This protocol unifies the node ages across a cluster.

The reliability of the K-cluster network is now considered. The example in Fig.3(a) depicts a portion of an interconnection containing two nodes in each cluster, where S_j^i denotes the j^{th} node in the i^{th} cluster, and $C_{j,k}^i$ denotes the channel linking the j^{th} node in the i^{th} cluster to the k^{th} node in the $i+1^{th}$ cluster. The consideration of channel failures turns the interconnection into a nested structure rather than a cascade structure.

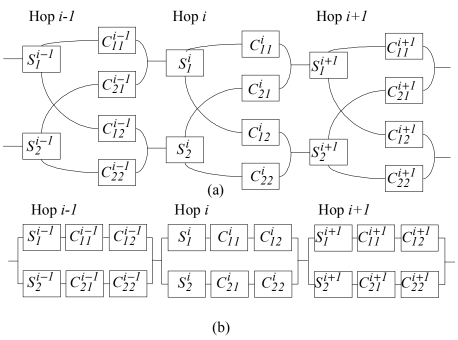

Fig.3 (a) Interdependence diagram of a 2-node/hop multiple-hop network, and (b) a conservative simplification of the interdependence

The nested structure in Fig.3a can be decomposed into logic stages for which the output signal availability can be computed when conditioned on the input signal availability using a combinatorial method. More specifically, one may write for the ith hop in Fig.3(a)

$$y_1^i = C_{11}^i S_1^i u_1^i + C_{21}^i S_2^i u_2^i, \ \ y_2^i = C_{12}^i S_1^i u_1^i + C_{22}^i S_2^i u_2^i,$$

for which sixteen conditional probabilities

$$P(y_1^i y_2^i = ab | u_1^i u_2^i = cd), \ \ a, b, c, d \in \{0, 1\}$$

can be computed with a '1' representing availability of a signal and a '0' unavailability. For example, with t suppressed, it can be shown that

$$\begin{aligned}
&P(y_1^i y_2^i = 00 | u_1^i u_2^i = 11) \\
&= (1 - r_i^n)^2 + 2(1 - r^c)^2 r_i^n (1 - r_i^n) + (1 - r^c)^4 (r_i^n)^2 \\
&P(y_1^i y_2^i = 01 | u_1^i u_2^i = 11) \\
&= 2r^c(1 - r^c) r_i^n (1 - r_i^n) + (2r_c - (r^c)^2)(1 - r^c)^2 (r_i^n)^2 \quad (2) \\
&P(y_1^i y_2^i = 10 | u_1^i u_2^i = 11) = P(y_1^i y_2^i = 01 | u_1^i u_2^i = 11) \\
&P(y_1^i y_2^i = 11 | u_1^i u_2^i = 11) \\
&= 2(r^c)^2 r_i^n (1 - r_i^n) + (r^c)^2 (1 - r^c)^2 (r_i^n)^2
\end{aligned}$$

The stages are linked by $u_1^{i+1} = y_1^i$, $u_1^i = y_1^{i-1}$, $u_2^{i+1} = y_2^i$, and $u_2^i = y_2^{i-1}$.

Extension of the above result from a 2-node clusters to a J_i-node cluster is straightforward, and can be carried out in a systematic manner. Nevertheless, reliability evaluation of the nested structure is a major hurdle for optimization, especially in real-time. It is therefore desirable to work with simpler network reliability models that provide bounds on the nested network reliability. For example, with a k_i-out-of-J_i (Zacks,1992) requirement based on cooperative transmission considerations, where k_i is the required minimal number of operative nodes and J_i is the number participating nodes in the ith cluster, R^{net} is bounded below by

$$\prod_{i=1}^{K} \sum_{r=k_i}^{J_i} \binom{J_i}{r} [(r^c)^{J_{i+1}} r_i^n]^r [1 - (r^c)^{J_{i+1}} r_i^n]^{J_i - r}, \quad (3)$$

which comes from the decomposed cascade of functional units as shown in Fig.3(b). Note that $J_{K+1} = 0$ because no further transmission is needed at cluster K. The lower bound is equivalent to the configuration of Fig.3(a) in that signals initiated from node S_j^i can reach every participating node in hop $i+1$ if and only if every channel C_{jk}^i is intact for the given i, j, and for all $k \in \{1, \ 2, \cdots, J_{i+1}\}$. This implies a channel reliability $r_c^{J_{i+1}}$. It is, however, not necessary that every channel must work to guarantee the information flow through the network, hence the conservativeness. Let $R_i^{J_j}$ be the probability that a packet reaches at least k_{i+1} nodes among the J_{i+1} participating nodes in cluster $i+1$ with the required power level, given that the packet is transmitted at cluster i from at least k_i nodes among J_i participating nodes. Denote by the i^{th} term in the product in (3) as $\underline{R}_i^{J_i}$.It can be shown that $0 < R_i^{J_j} - \underline{R}_i^{J_i} < 1 - (r^c)^{J_{i+1}}$. The error bound is tight as long as channel reliability is high, and the number of participating node in cooperative transmissions is not excessively large. Many of the analyses from this point on will use the lower bound (3), including the definition of link reliability, i.e., $p_i^l \equiv \underline{R}_i^{J_i}$, and composite network reliability $\underline{R}^{net} = p_1^l \times \cdots \times p_K^l$. Now, the participating node allocation problem becomes amendable to solutions using dynamic programming (Bellman, 1957).

4. OPTIMIZATION AND CONTROL

This section discusses two applications of the derived link reliabilities.

4.1 Participating node allocation

Our task is to determine the values of $J_1,\ J_2,\ \cdots, J_K$ so that the network reliability is the largest at T_D without violating a bandwidth constraint. In cluster i, $J_{i,min}$ is imposed by the particular transmission scheme, while $J_{i,max} \leq I_i$ is mainly imposed by the available bandwidth. Bounding model (3) converts the network level decision into a series of coupled cluster level decisions. In this case, channel failures introduce only local coupling which can be resolved by an ordered selection process starting from J_K at the last cluster and ending at J_1. The solution $\{J_1^*,\ \cdots, J_K^*\}$ can then be inserted to the staged conditional probability formulae (2) to calculate the true network reliability.

To illustrate the basic idea, consider a 3-cluster network with 10 nodes in each cluster. A tree structure shown in Fig.4 can be created to represent all possible solutions at T_D, where all branches violating the constraints have been trimmed. Constrains particular to the cooperative transmission scheme (Li and Wu, 2003) are $\sum_{i=1}^{3} J_i \leq 12$ and $J_{i,min} = 2$. Each joint of the tree at a given cluster index represents a possible cumulative number of nodes. Each branch leading to the joint carries a cost equal to $\underline{R}_i^{J_i}(T_D)$ for a particular J_i. The accumulated reliability for each passage from the root to a leaf can be computed using Bellman's principle of optimality (Bellman, 1957). The principle is applied at every unit index i by comparing all the accumulated reliabilities leading to the same joint. Only the solution of the highest reliability is retained at each joint, and the rest are removed. Once the set $\{J_1^*, J_2^*, \cdots, J_K^*\}$ is obtained, the link reliabilities are set to $p_i^l = \underline{R}_i^{J_i^*}, i = 1, 2, \cdots, K-1$. Suppose unit reliabilities $\underline{R}_i^2(T_D)$ through $\underline{R}_i^8(T_D)$ have been found to be 0.85, 0.90, 0.95, 0.99, 0.995, 0.999, and 0.9995, respectively, for the network in Fig.4, the optimal node allocation derived using dynamic programming is: $J_i = 4$ for $i = 1, 2, 3$.

Note that unit reliability is a complex function of J_i, which is determined by the methods discussed in Sections 3.1 and 3.2. The optimization in this section is carried out under the assumption that network is operating unsupervised. It is possible to re-optimize the network reliability projected at the network design life when supervisory exists that can report the actual rather than the predicted status of the nodes. A commonly used idea called a receding horizon optimal control in the control literature (Mayne, 1990) can be applied in this case. Though only limited data exchange is required to carry out dynamic programing, the main challenge with real time optimization in a distributed environment is that data exchange is not only expensive but unreliable. How frequently such a partial reorganization should be performed is currently under investigation.

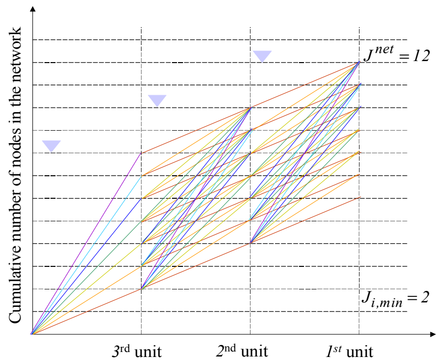

Fig.4 Trellis diagram for participating node allocation

4.2 Re-transmission control

In this section, the re-transmission chain of Section 2 is revisited. It is now assumed that the network is supervised to the extent that it can detect a cluster transmission failure but not the state of the nodes and channels, and the participating/nonparticipating protocol is effective to manage the large number of nodes available at each cluster. The decision regarding re-transmission in each of the clusters upon the detection of a cluster transmission failure can be made based on the solution of a Markov decision problem. The main purpose is to be able to terminate the service of the K-cluster route so that it does not turn into a black hole in the network.

Let $X_k \in \{1, 2, \cdots, K\}$ denote the random state variable at $t = k$ in the chain. Control action $u(x_k) = 1$ (or 0) indicates the network's decision to (or not to) re-transmit a packet. Let $C(x_k, u_k)$ be the cost incurred when control action u_k is taken based on x_k. Our goal is to determine a re-transmission policy π that minimizes the total expected cost $V_\pi(x_k = i) = E_\pi \sum_{k=0}^{\infty} C(X_k, u_k)$. It has been shown that under the condition $0 \leq C(j, u) < \infty$ for all j and all u that belongs to some finite admissible sets U_j, $j = 1, 2, \cdots, K-1$, the minimal cost $V^*(i)$ satisfies the following optimality equation (Cassandras and Lafortune, 1999)

$$V(i) = min_{u \in U_i} \{C(i,u) + \sum_{j=1}^{K} p_{i,j} V(j)\}.$$

In addition, policy π^* is optimal if and only if it yields $V^*(i)$ for all i.

Referring to the Markov chain in Fig.1, the optimality equation can be specialized to the following form.

$$V(i) = min_{u \in U_i} \{\underbrace{u(i)T_i + [1 - u(i)]L_i}_{C(i,u(i))} + \\ +u \underbrace{[p_{i,i}(u(i))V(i) + p_{i,i+1}(u(i))V(i+1)]}_{\sum_{j=1}^{K} p_{i,j}V(j)}\} \quad (4)$$

where $p_{i,i} = 1 - p_i^l c_i$, $p_{i,i+1} = p_i^l c_i$, where network age t is suppressed, T_i is the power and bandwidth cost incurred when the network chooses to re-transmit a packet, and L_i is the packet loss cost incurred when the network chooses not to re-transmit. (4) can be expressed as

$$V(i) = min\{T_i + p_{i,i}V(i) + p_{i,i+1}V(i+1), L_i\}$$

To gain some insight into the optimal policy, assume $T_i = T$, $L_i = L$, $p_{i,i+1} = r$, and $p_{i,i} = 1-r$ for $i = 1, \cdots, K-1$. Since

$$(1-r)V(j) + rV(j+1) < (1-r)V(i) + rV(i+1)$$

as long as $j > i$, the optimal policy is of the threshold type (Cassandras and Lafortune, 1999) with some threshold i^*, i.e.,

$$V(i) = \begin{cases} T/r + V(i+1), & i > i^*, \ (u(i) = 1) \\ L, & i \leq i^*, \ (u(i) = 0) \end{cases}.$$

Given that $V(K) = 0$, $V(i)$ can be solved

$$V(i) = \begin{cases} (K-i)T/r, & i > i^*, \ (u(i) = 1) \\ L, & i \leq i^*, \ (u(i) = 0) \end{cases},$$

from which the threshold is obtained

$$i^* = \lceil K - \frac{rL}{T} \rceil.$$

$\lceil . \rceil$ denotes the smallest nonnegative integer greater than $K - rL/T$. It can be seen that the optimal policy favors a re-transmission when a packet is near the end of the K-cluster route (large i), when a cluster is young (large r), when the cost of a packet loss is large (large L), when power & bandwidth are cheap (small T), when a route is short. (small K). A study without the simplifying assumptions along this direction is ongoing.

REFERENCES

Bellman, R. (1957). *Dynamic Programing,* Princeton University Press.

Bhardwaj, M., and A.P. Chandrakasan (2002) Bounding the lifetime of sensor networks via optimal role assignments. *Proc. IEEE Infocom.*

Cassandras, C. G., and S. Lafortune (1999). *Introduction to Discrete Event Systems*, Kluwer Academic Publishers.

Casella, G., and R. L. Berger (2002). *Statistical Inference*, 2nd Edition, Duxbury.

De, S., and C. Qiao (2003). Does packet replication along multipath really help, *Proc. ICC.*

Ganesan, D., R. Govinden, S. Shenker, and D. Estrin (2002). Highly-resilient, energy-efficient multipath routing in wireless sensor networks, *ACM Mobile Computing and Communications Review* , **1**, Issue 2.

Ordonez, F., and B. Krishnamachari (2004). Optimal information extraction in energy-limited wireless sensor networks, to appear in *IEEE Journal on Selected Areas in Communications, Special Issue on Fundamental Performance Limits of Wireless Sensor Networks.*

Hoblos, G., M. Staroswiecki and A. Aitouche (2000). Optimal design of fault tolerant sensor networks, *Proc. IEEE International Conference on Control Applications.*

Kumar, P.R. (2001). New technological vistas for systems and control, *IEEE Control Systems Magazine*, vol. pp. 24-37.

Laneman, J. N. and G. W. Wornell (2003). Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks, *IEEE Transactions on Information Theory*, **49**, pp. 2415-2425.

Li, X., and N. E. Wu (2003). Power efficient wireless sensor networks with distributed transmission-induced space spreading, *Proc. 37th Asilomar Conf. Signals., Syst., Comput..*

Li, X. (2003). Energy efficient wireless sensor networks with transmission diversity, *Electronics Letters*, **39**, pp.1753-1755.

Li, X., (2004). Space-time coded multi-transmission among distributed transmitter without perfect synchronization, to appear in *IEEE Signal Processing Letter*, **11**.

Mayne, D. Q., and H. Michalska, (1990). Receding horizon control of nonlinear systems, *IEEE Trans. Automatic Control*, **35**, pp.814824.

Rappaport, T.S., (2002). *Wireless Communications, Principle and Practice*, 2nd ed., Prentice Hall.

Sendonaris, A. E., Erkip and B. Aazhang, (2003). User cooperation diversity, Part I, II, *IEEE Transactions on Communications*, **51**, pp.1927-1948.

D. Torrieri, (1994). Calculation of node-pair reliability in large networks with unreliable nodes, *IEEE Transactions on Reliability,*, **43**, pp.375-377.

Wu, N. E., (2004). Coverage in fault-tolerant control, *Automatica*, **40**, pp.537-548.

Xue, F., and P. R. Kumar, (2004). The number of neighbors needed for connectivity of wireless networks, *ACM Journal of Wireless Networks*, **10**, pp.169-181.