Energy Efficient Link Assessment in Wireless Sensor Networks

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What is link assessment?

- Given N nodes capable of transmission and reception, placed in an area
- Goal of link assessment process:
  - Each node discovers all its neighbors
  - Assess the quality of links to neighbors
    - i.e. Packet success rate on each link

Motivation

- Link Assessment combines two goals:
  - Neighbor discovery
  - Link grading
- Knowledge of one hop neighbors is required in many routing, time scheduling, topology control algorithms
- Information about quality of links can lead to more energy-efficient routes, topologies

Assumptions

- Nodes are stationary
- Nodes have single transmission power
- Each node knows the maximum number of neighbors, n
- Slotted, Synchronous system
- At each slot, a node can either transmit or receive or sleep

Problem Definition

- A slot is "collision-free" for link (i,j) if:
  - i is in transmit mode
  - j is in listen mode
  - All neighbors of j are in listen or sleep mode
- Goal : finding a protocol that ensures that each link in the network gets at least C collision-free time slots, given a total of F time slots

A Random Protocol

- At each slot a node transmits or listens, sleeps with probabilities pt, pl respectively.
- For link (i,j) : probability that a time slot is collision free:
  - $P_c = p_t.p_l.(1-p_t)^(n-1)$
- Number of collision-free time slots for link (i,j) :
  - $C_{i,j}$ ~ Binomial(F,P_c)

Optimization Problem

- Total average energy consumption in entire network :
  - $E_{tot} = N.F(p_t.E_{tx} + p_l E_l)$
- Problem : Find F, p_t, p_l that minimize E_{tot} such that $P(C_{i,j} < C)$ is very small
- Optimal $p_t = 1/n$ and $p_l = 1 - 1/n$

Energy Efficiency of random protocol

- $E_{tot,min}$ – minimum total energy consumed by all nodes in network (irrespective of link assessment protocol)
  - $E_{tot,min} = N(C.E_{tx} + n_a C E_l)$
- Energy Efficiency, $E_{eff} = E_{tot}/E_{tot,min}$
- For random protocol :
  - $E_{eff} = 9.76$, $C=30$, $F=4834$
  - $E_{eff} = 103.2$, $C = 1$

A Deterministic Protocol

- (F,W,d) "constant-weight codes" are binary codes with:
  - length F (total number of time slots),
  - weight W, (W 1's and F-W 0's) and
  - minimum hamming distance d
- A node transmits when the next bit in its codeword is 1 and listens when it is 0

Conditions for successful assessment

- Link assessment is successful, i.e. each link in the network gets at least C collision-free time slots if:
  - $C \le W \le (n.d/2 - C)/(n-1)$
- By selecting code words properly, link assessment can be done very efficiently
- Since pre-computation of codewords may not be possible, nodes must construct them post-installation
  - Can be done using optical-orthogonal codes (OOCs)

Optical Orthogonal Codes

- Let **a** denote the maximum number of bit positions in which any 2 code words have 1
- (F,W,**a**) OOC is a family of codes of length F and weight W, that have cross-correlation and auto correlation not exceeding **a**

Example of OOCs

- (5,2,1) OOC code with the following 10 codewords:
  - 10100, 01010, 00101, 10010, 01001
    11000, 01100, 00110, 00011, 10001
- Any codeword can be cyclically shifted to obtain another valid codeword
- Each node needs to store only one codeword from a group
  - Based on its own id it can unambiguously determine what its codeword should be

Optimization Problem

- Total Energy Consumption using deterministic protocol :
  - $E_{tot} = N (W.E_{tx} + (F - W) E_l)$
- Find F,W,**a** such that E_{tot} is minimized subject to the constraints that :
  - Each node is assigned a unique codeword
  - W >= C + **a**.n
- <u>Optimal design</u> : **a** = 1, W = C+n, F = W^2

Energy Efficiency of Deterministic Protocol

- C=30, n = 25 :
  - Deterministic : E_{eff} = 7.7, F=4000
  - Random : E_{eff} = 9.76, F = 4834
- C = 1, n=25:
  - Deterministic : E_{eff} = 39.9, F = 660
  - Random : E_{eff} = 104.2, F = 1704

Under-Weight OOCs

- The condition W >= a.n + C is used to achieve 100% guarantee of success
- By using smaller W, we can tradeoff guarantee of success for higher energy efficiency
- Assume (F,W,1) OOCs are used and randomly assigned among nodes s.t. each node has a unique codeword

Under-Weight OOCs

- Prob. that packets from two neighboring nodes collide at one of the F slots is less than W^2/F
- Number of neighbors that a node collides with, m ~ Binomial (n, W^2/F)
- The probability, $p_m(e)$, that a node gets e collision-free time slots, given m collided time slots and weight W:

$$p_m(e) = (W-e)/W \; p_{m-1}(e) + (e+1)/W \; p_{m-1}(e+1)$$

Under-Weight Codes

- Unconditioning on m, we get the probability, p(e), of obtaining e collision free time slots, given weight W of codes
- $P_L = P(e<C)$ – probability that a node gets less than C collision-free time slots
  - $P_L = p(0) + p(1) + \ldots + p(C-1)$
- By appropriately choosing W for a given value of P_L we can reduce F and E_{eff}

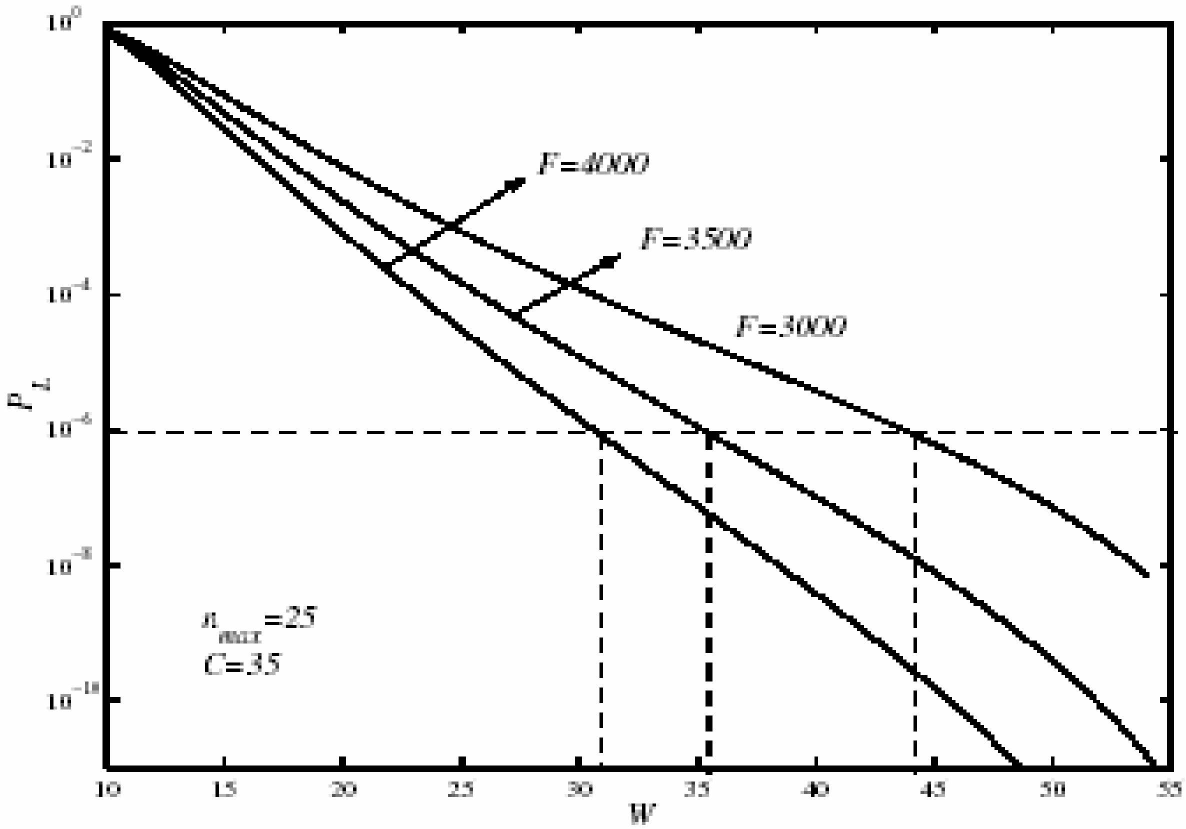

Fig. 1. Loss probability versus code weight, W for different values of code length F, with $n_{max} = 25, C = 35$.

Energy Efficiency

- For F=3000, W>44 can be used to maintain $P(e < C) < 10^{-6}$
- Similarly, for F=3500 W > 35 and for F=4000 W > 32 is sufficient
- For (3000,45,1) *OOC* set is used, total time reduces from 3600 to 3000 time slots while E_{eff} reduces from 3.83 to 3.18

Some Protocol Enhancements

- Using sparse OOCs further energy gains are possible
- An OOC with length F and weight W is sparse if the W ones are evenly distributed among F positions
- All nodes execute the same protocol as before for F/2 time slots
- In this time, a node has discovered all its neighbors with high probability
- Using neighbor ids, construct the OOCs of all neighboring nodes
- For the remaining F/2 time slots, wake up only when there is a need to transmit or when only one of its neighbors transmitting

Conclusions

- This paper considers the problem of link assessment – joint link discovery and grading
- First a randomized protocol is considered
- Subsequently, a deterministic scheme based on constant-weight codes is proposed, which improves upon the randomized protocol
- Using OOCs code assignment can be done very easily
- Several enhancements to the deterministic scheme are considered, i.e. sparse codes

Critique/Possible Future Work

- The proposed scheme works only for a synchronous system
  - No obvious way to extend to asynchronous case
- How does F scale with the number of nodes?
- Works well in a static environment, but what happens as new nodes are added?
- How about if nodes have directional antennas?
- Other criticisms/questions?