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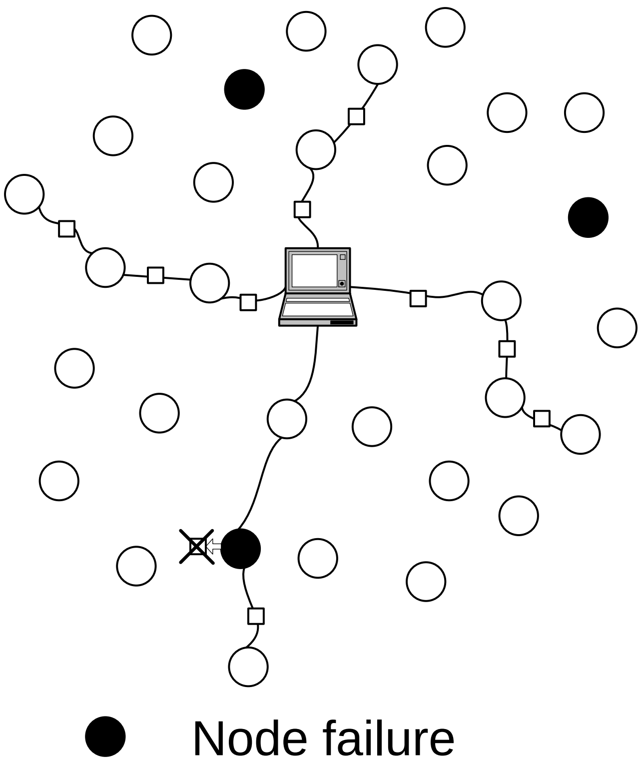
Reliable Packet Transmission in Sensor Networks

Sensor Networks

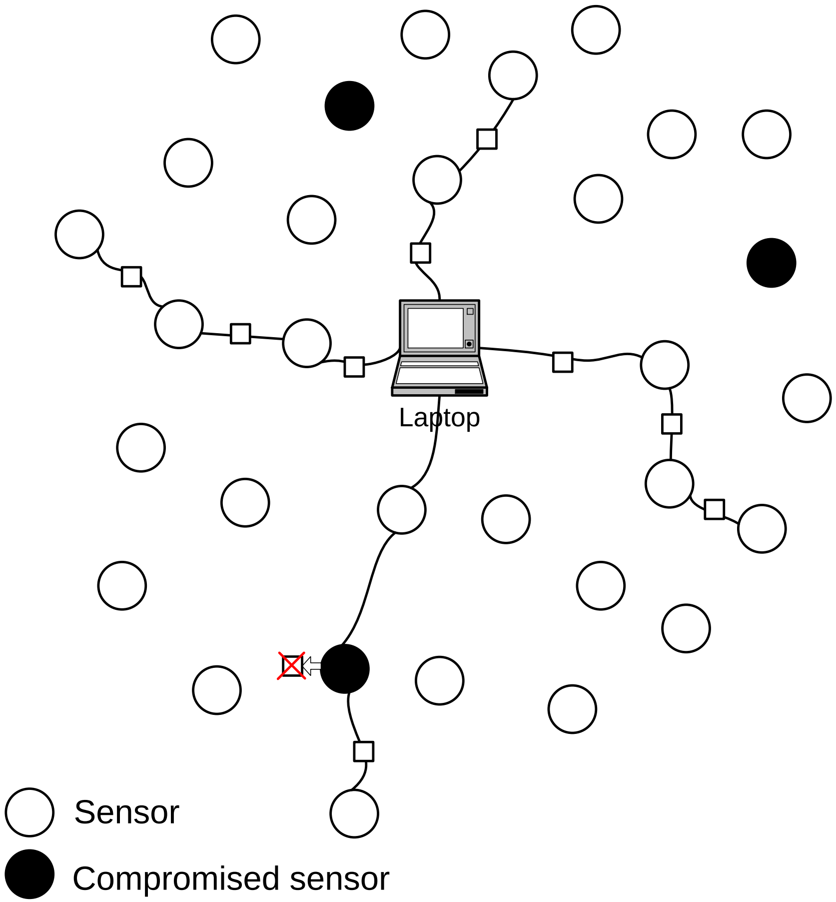
1. Sensor Network
   - Base station (BS)
   - Set of nodes
2. Node (sensor)
   - **Limited power resource (10^6 packets)**
   - Small memory size (8 Kbytes)
   - Restricted CPU (4 Mhz, 8-bit)
   - Wireless interface of limited range (15 meters)

Problem Statement

1. Packet is retransmitted by sensors over route
2. **Node failure**: node receives packet , but does not retransmit it
3. **Task**: develop algorithm for packet forwarding
   - Resistant to failures
   - Taking in account energy consumption and transmission time



Attacks on Transmission



- Black Hole or Selected Forwarding
- Intermediate node could drop packets

Agenda

1. Part 1
   - Survey of reliable packet transmission algorithms
   - Algorithm of Adaptive Redundant Transmission (ART)

2. Part 2
   - Optimization of ART parameters for one-packet messages

3. Part 3
   - Optimization of ART parameters for multi-packet messages

4. Part 4
   - Comparison of algorithms for reliable transmission
   - Control of survivability in sensor network

Existing Solutions

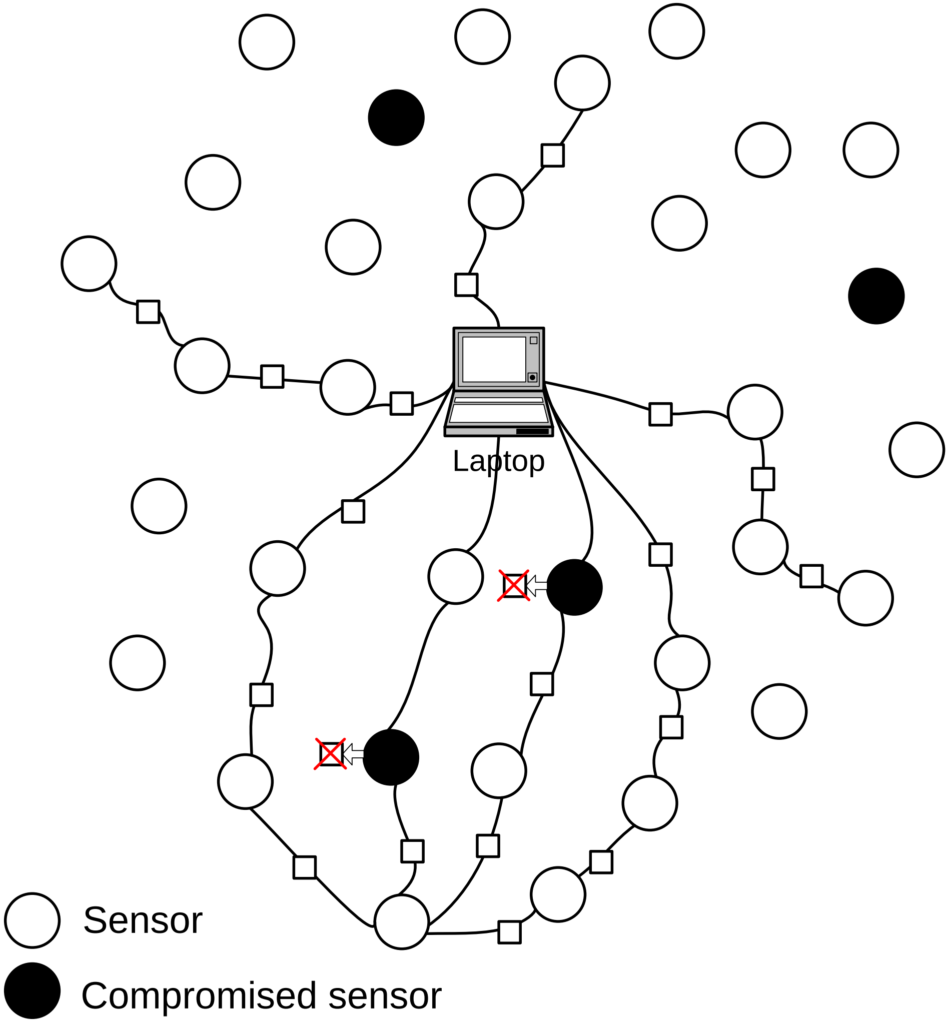
General idea

Usage of several routes from node to BS

1. Arbitrary transmission (AT) [e.g. Perrig'02]
   - Randomly choose one route and send packet over it
   - Low reliability of transmission

2. Redundant transmission (RT) [e.g. Kabatyansky-Krouk'93]
   - Packet copies are sent over each route
   - High energy consumption of transmission

Reliable Transmission



- Forward data using multiple disjoint routes

Network model

- Centralized network management
- Several types of messages
  - Standard one-packet messages
  - Urgent one-packet messages
  - Multi-packet messages
- Set of routes from node to BS is constructed by BS
- The independent events are
  - Packet losses on node
  - Packet losses on route
  - Packet losses on different routes

Adaptive Redundant Transmission (ART)

- Over i-th route $n_i \geq 0$ copies are sent
  - The number of copies are calculated using route characteristics
  - For calculating number of copies the optimization problem is formulated
- Each route has the following characteristics
  - p_i – probability to lose packet
  - E_i – energy consumption to transmit one packet
  - T_i – time for transmission of one packet
- Algorithms for creating of redundant packets
  - One-packet messages – duplication of packets
  - Multi-packet messages – transport layer encoding

Optimization Problem

- Given
  - N routes, for each route the following characteristics are given (p_i, E_i, T_i)
  - P – required probability for receiving message at BS
  - r_i – delay between packets sent over route
- Find such ($n_1, \ldots , n_N$), that

$$P(k,N) = p(n_1,\ldots,n_N) \leq P$$

$$E(n_1,\ldots,n_N) = \sum_{i=1}^{N} E_i n_i \rightarrow \min$$

or

$$T(n_1,\ldots,n_N) = \max_{i=1\ldots N}(T_i + r_i n_i) \rightarrow \min$$

- The problem is computationally hard

Packets duplication

For standard messages

$$\begin{cases} \prod_{i=1}^{N} p_i^{n_i} \le P \\ E = \sum_{i=1}^{N} E_i n_i \to \min \end{cases}$$

For urgent messages

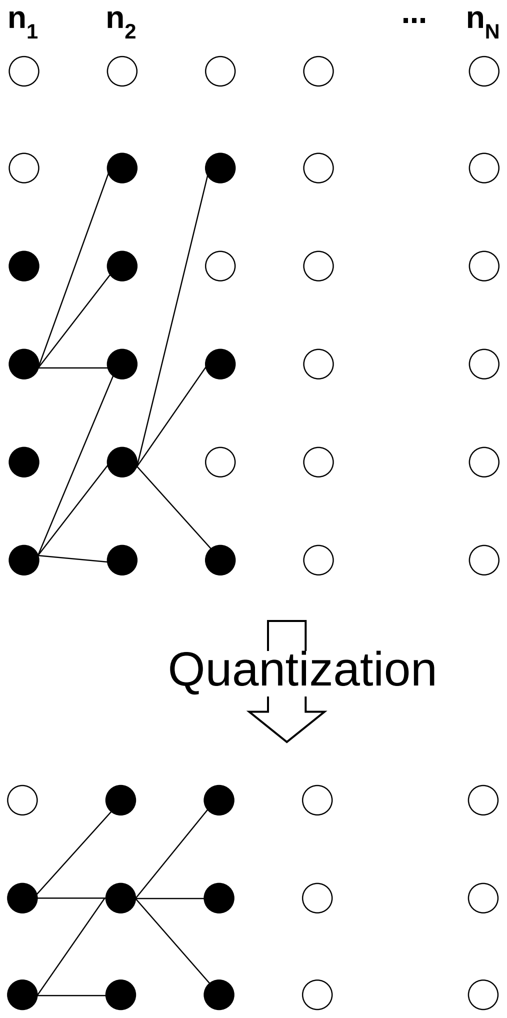
$$\begin{cases} \prod_{i=1}^{N} p_i^{n_i} \le P \\ T = \max_{i=1\ldots N}(T_i + r_i n_i) \to \min \end{cases}$$

- Used for one-packet messages
  - Over i-th route $n_i \ge 0$ copies are sent
  - For reconstruction it is required to receive at least 1 packet
- Known methods
  - Dynamic programming
  - Branches-and-bound (or divide-and-conquer) method

Dynamic programming (DP)

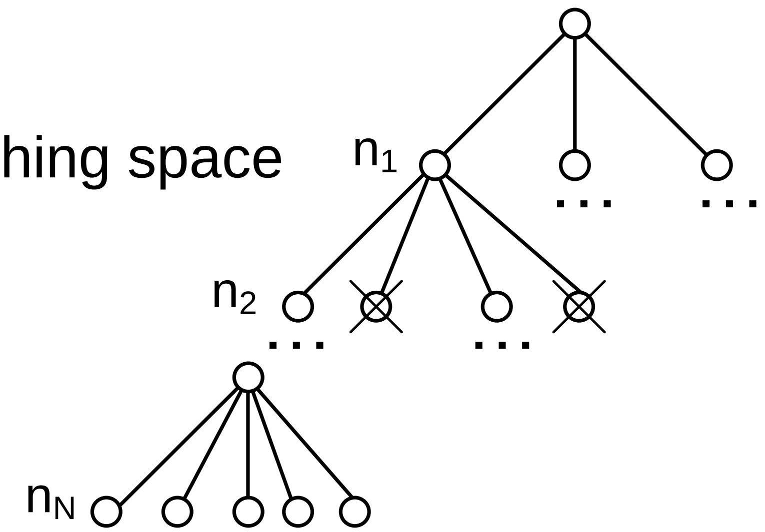
$$S=\sum_{i=1}^{N} n_i \frac{\ln p_i}{\ln P} \geq 1$$

- Search is ordered over the grid
  - *S* is quantified with some step
- It is required to estimate upper bounds for n_i
- **Accuracy:** some loss of accuracy is caused by quantization
- **Complexity:** changing inversely to quantization step



Branches and bounds (BB)

- Search is ordered over tree
- It is required to define
  - Method for partitioning of the searching space
  - Methods for estimating of upper and lower bounds

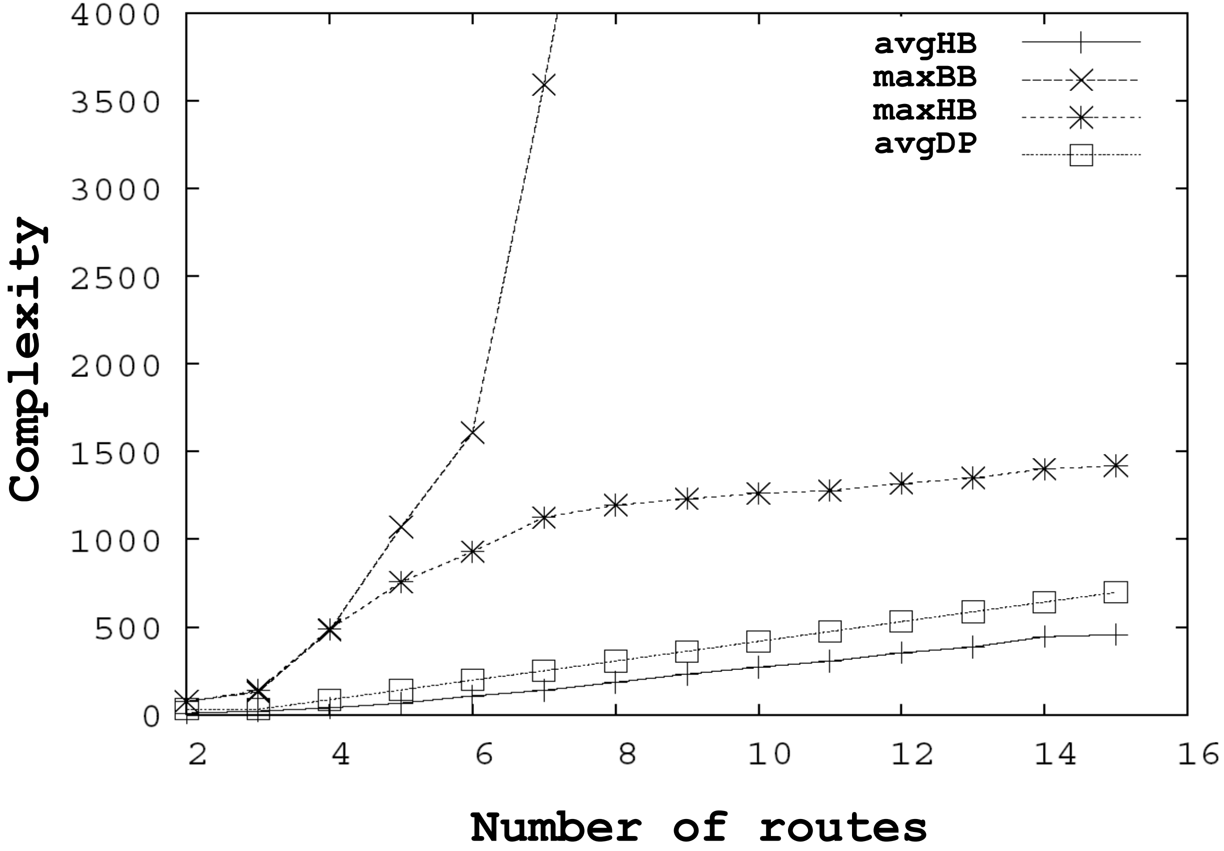


- **Accuracy:** no loss of accuracy
- **Complexity:**
  - Average complexity is smaller than in DP algorithm
  - Maximum complexity is equal to complexity of exhaustive search

Hybrid algorithm (HB)

- Dynamic programming (DP)
  - Acceptable maximum complexity
  - Loss of accuracy
- Branches and bounds (BB)
  - Maximum complexity is equal to complexity of exhaustive search
  - Average complexity is less than DP complexity (caused by cutting using upper and lower bounds)
  - No loss of accuracy
- Hybrid algorithm (HB)
  - Search using BB
  - If the defined threshold on number of operations is reached --- use DP

Comparison of algorithms complexities **Duplication**



- $$\frac{E_{optim}}{E_{suboptim}} \geq 0.98$$

Comparison of transmission algorithms over energy consumption

- Arbitrary transmission (AT)

$$\begin{cases} (\frac{1}{N}\sum_{i=1}^{N} p_i)^n \le p \\ E_I = \frac{n}{N}\sum_{i=1}^{N} E_i \to \min \end{cases}$$

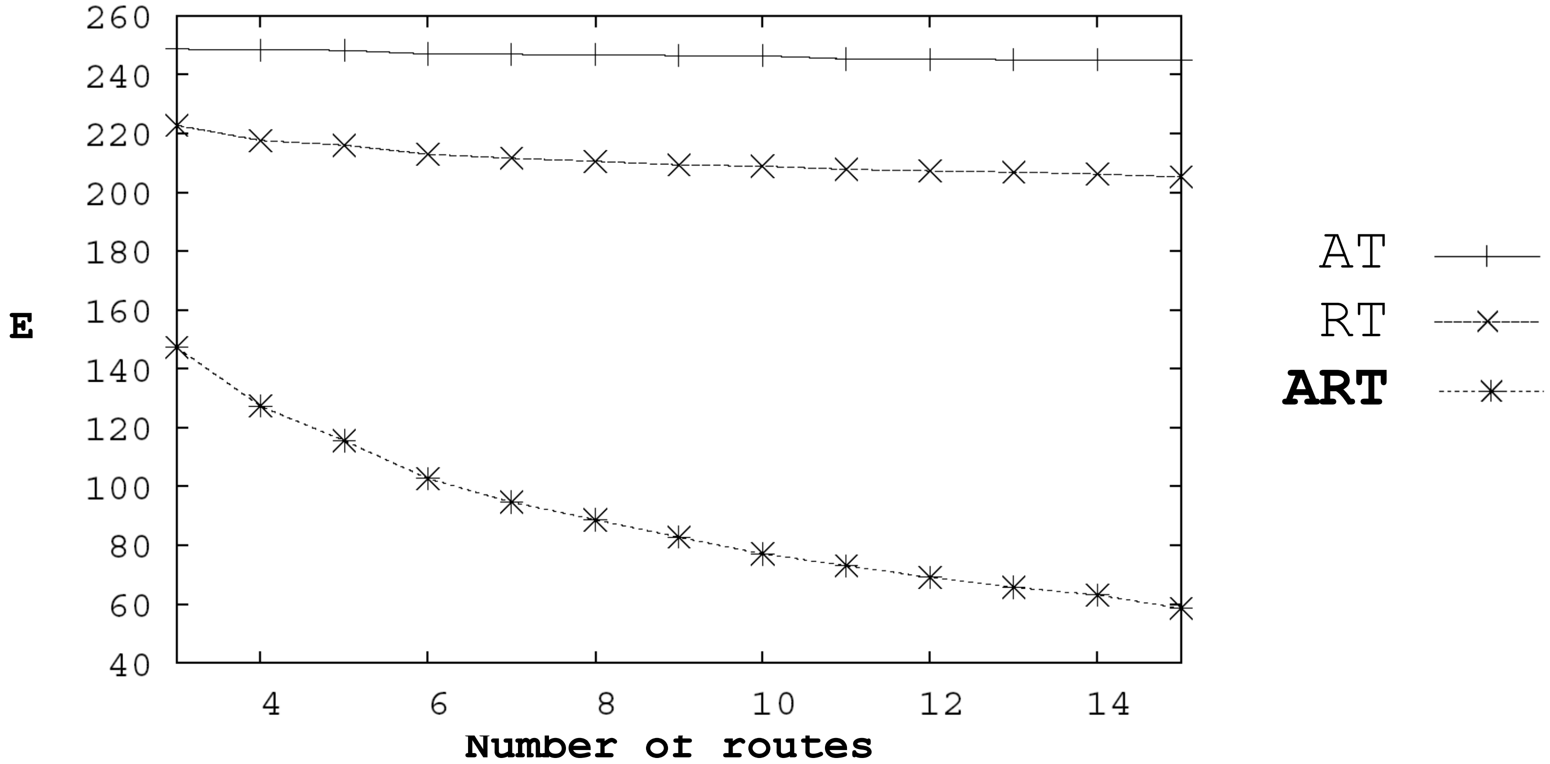
- Redundant transmission (RT)

$$\begin{cases} (\prod_{i=1}^{N} p_i)^n \le p \\ E_{II} = n\sum_{i=1}^{N} E_i \to \min \end{cases}$$

- **Adaptive redundant transmission (ART)**

$$\begin{cases} \prod_{i=1}^{N} p_i^{n_i} \le p \\ E_{III} = \sum_{i=1}^{N} E_i n_i \to \min \end{cases}$$

Duplication of packets



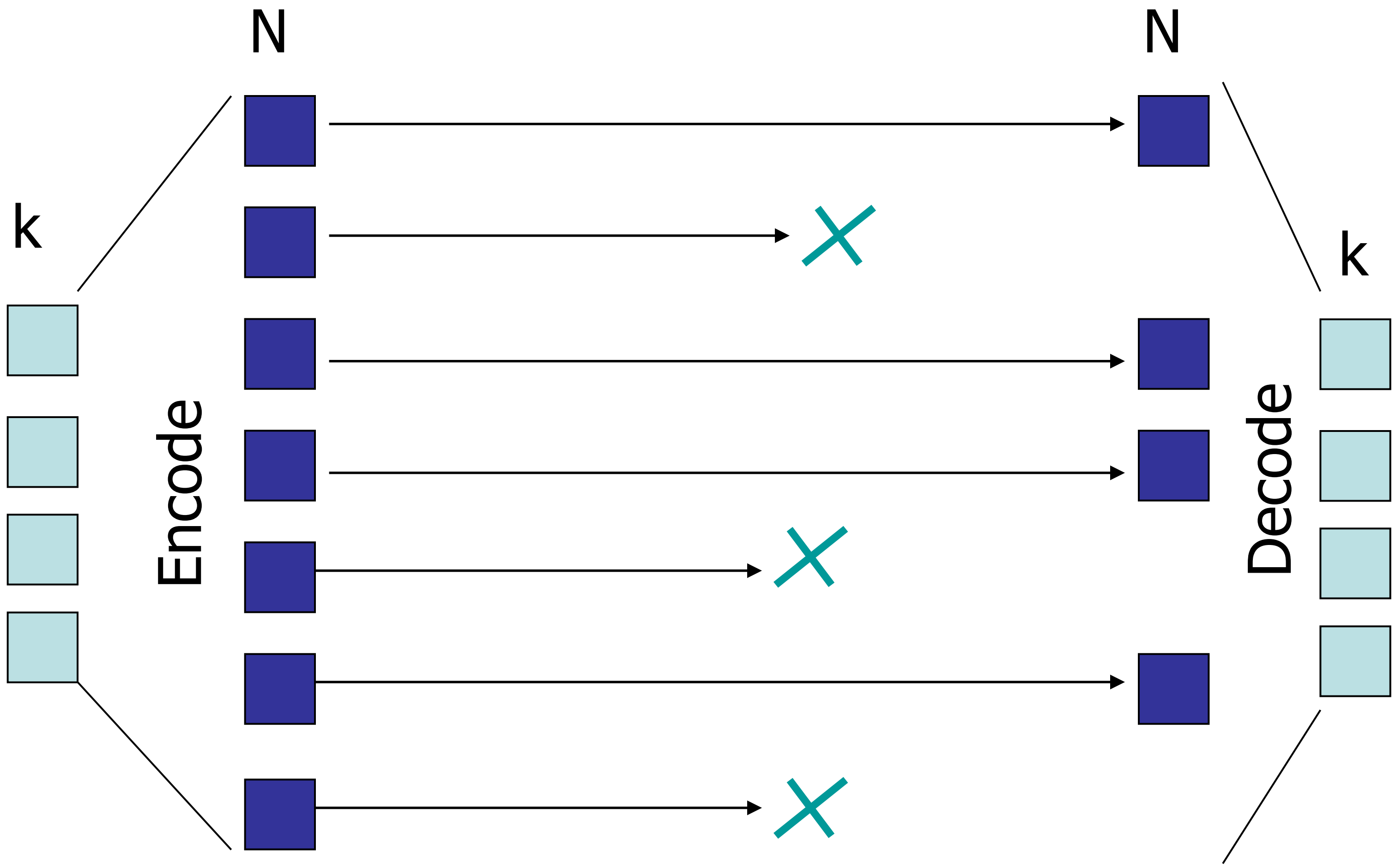
- ART usually uses only part of existing routes

Transport Layer Encoding

$$\begin{cases} \sum\limits_{k_1+\ldots+k_N \geq k} \prod\limits_{i=1}^{N} C_{k_i}^{n_i} (1-p_i)^{k_i} \, p_i^{n_i-k_i} \geq (1-P) \\ 1 \leq k_i \leq n_i, i \in [1..N] \\ E = \sum\limits_{i=1}^{N} E_i n_i \to \min \end{cases}$$

- Used for multi-packet messages
  - *k* packets are encoded using Reed-Solomon code into *n* packets ($n=n_1+\ldots+n_N$)
  - Over i-th route n_i packets are sent
  - For reconstruction any k out of n packets are required
- Known methods
  - Method of branches-and-bounds

K packet message



Branches and bounds (BB)

- Lower bound
  - The hypothetic route *best* with idealized characteristics is defined

$$p_{best} = \min(p_1, \ldots, p_N)$$
$$E_{best} = \min(E_1, \ldots, E_N)$$
$$T_{best} = \min(T_1, \ldots, T_N)$$

- Upper bound
  - “Greedy” algorithm: chose route, where transmission packet copies require minimal energy

Branches and bounds (BB)

- Calculation of criterion function in each node of search tree --- computationally hard task
- Optimization using recursion
  - In each node of search tree pre-calculated values are stored
  - The value of criterion function in child node is calculated using numbers saved in parent node
  - Without recursion – C_{n+N-1}^{N-1} basic operations
  - With recursion – n_i basic operations and k memory cells

Recursion

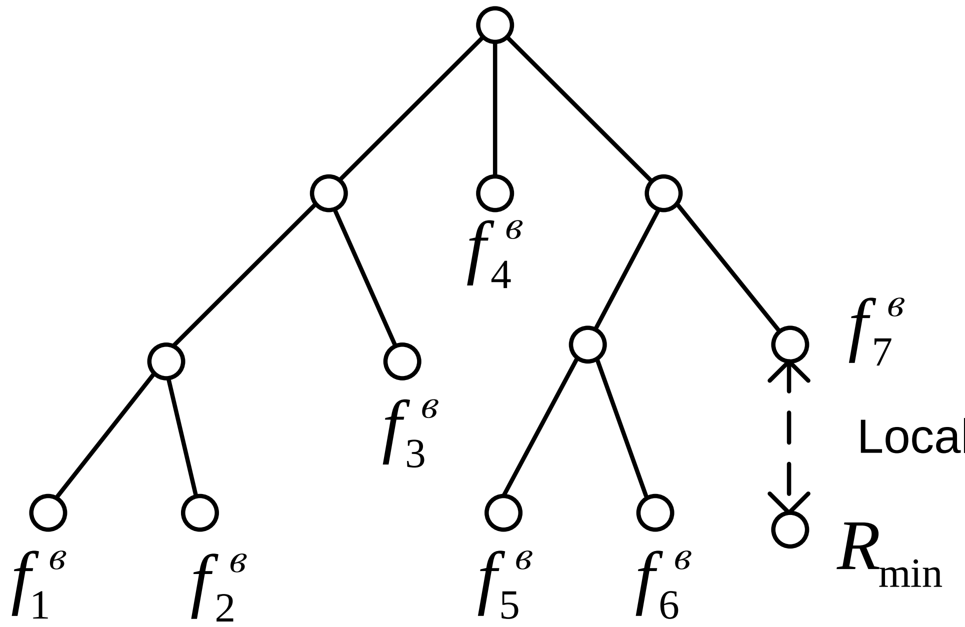
$$\sum_{k_1+\ldots+k_N\geq k}\prod_{i=1}^{N}C(n_i,k_i,p_i)=\sum_{k_N=1}^{n_N}C(n_N,k_N,p_N)\sum_{k_1+\ldots+k_{N-1}\geq k-k_N}\prod_{i=1}^{N-1}C(n_i,k_i,p_i)$$

Example

$$P(k,2)=\sum_{k_2=1}^{n_2}C(n_2,k_2,p_2)\sum_{k_1\geq k-k_2}^{n_N}C(n_1,k_1,p_1)$$

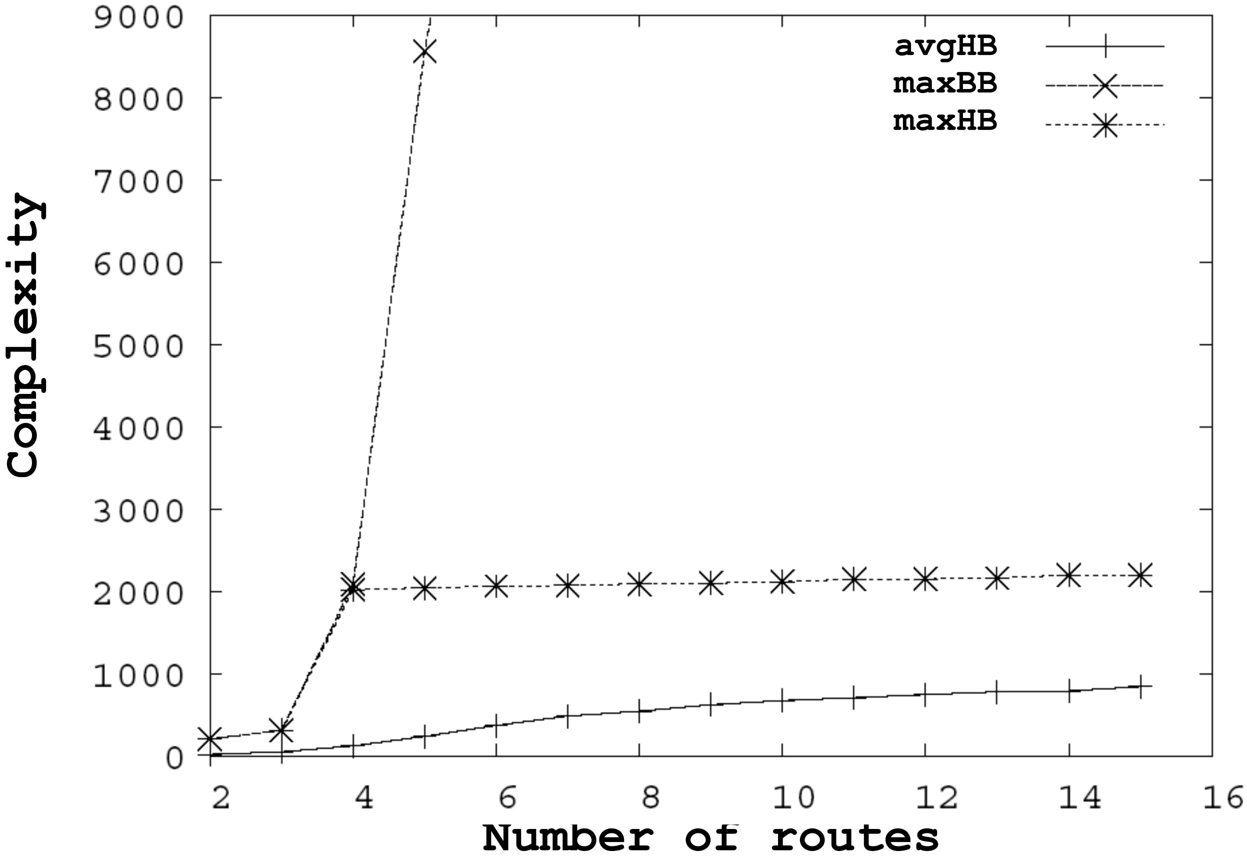
$$\sum_{k_1\geq 0}^{n_1}C(n_1,k_1,p_1),\ldots,\sum_{k_1\geq k}^{n_1}C(n_1,k_1,p_1)$$

Hybrid Algorithm (HB)



$$f_7^{\epsilon} = \min(f_1^{\epsilon}, \ldots, f_7^{\epsilon})$$

Comparison of algorithms complexities Transport Layer Encoding

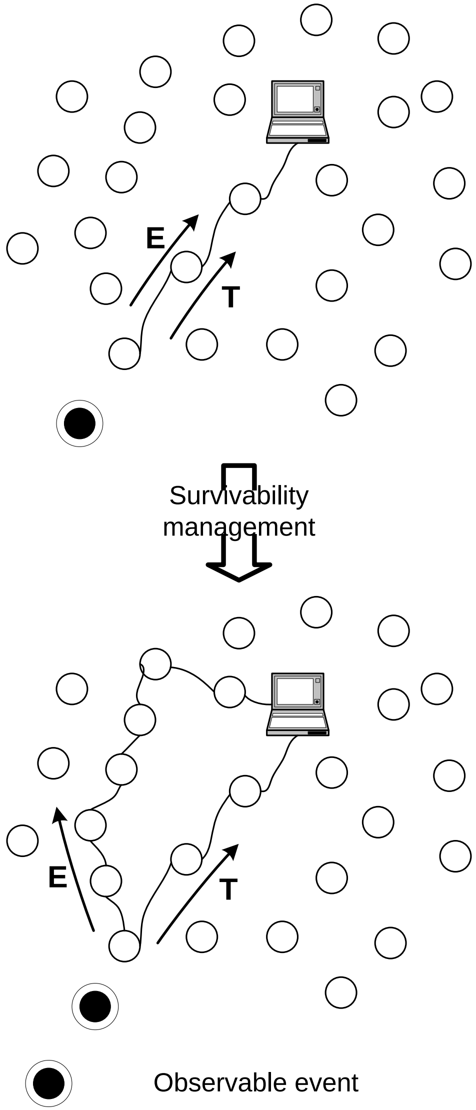


- $$\frac{E_{optim}}{E_{suboptim}} \geq 0.98$$

Survivability of Sensor Network

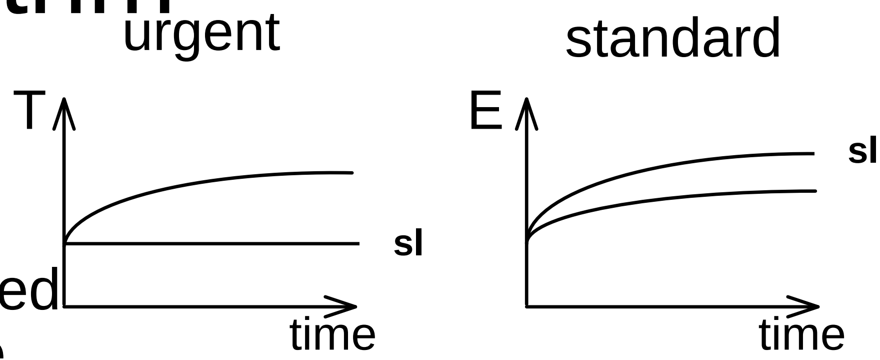
- Some nodes forwards more packets than others
  - Network topology, traffic pattern
- This leads to early depletion of power resources and increasing of urgent message delivery time

- Survivability – ability to preserve reserve of power resource for transmitting of urgent messages with maximal speed and required reliability



Survivability Management Algorithm

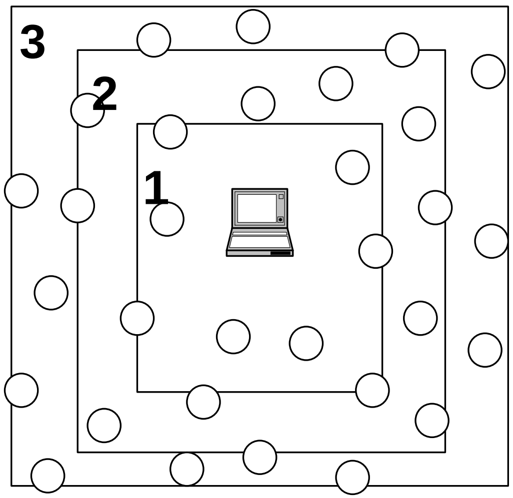
- BS could estimate current level of power resource of each node – v_i



- Nodes are divided into classes based on number of routes, in which node participates
  - n – number of nodes in class
  - $$M = \sum_{i=1}^{n} \frac{v_i}{n}$$
- For standard messages: all routes passing through this node are "switched off" if

$$\frac{|v_i - M|}{M} > threshold$$

Partitioning into classes



Summary

1. Algorithm of adaptive redundant transmission (ART)
2. Algorithms for finding optimal parameters of ART for one-packet and multi-packet messages
3. Algorithm for survivability management of the network