Fault-Aware Flow Control and Multi-path Routing in Wireless Sensor Networks

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Outline

- Motivation
- Challenges and opportunities
- Model and problem formulation
- $(FC)^2R$ algorithm
- Simulation results
- Related work
- Conclusion

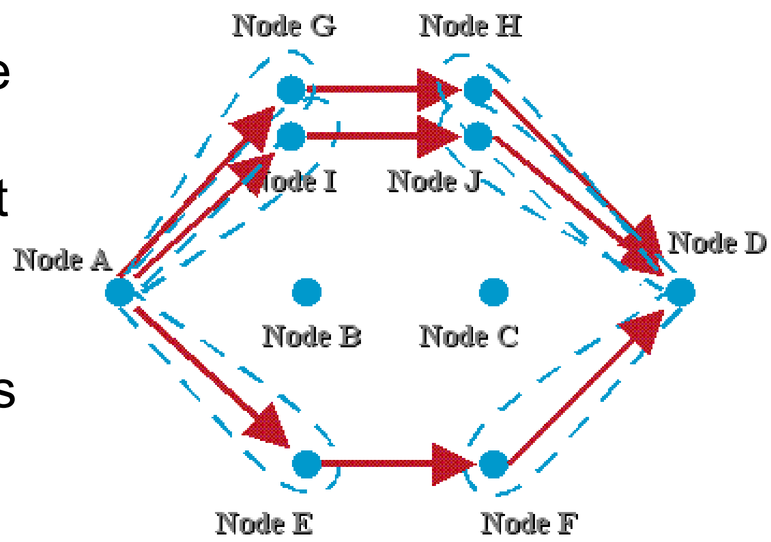
Motivation

- Wireless sensor networks are
  - capable of communicating with each other and cooperating to relay traffic throughout the network via multiple hops;
  - vulnerable to channel impairments, failure, interference and fading, etc.
- Some nodes may become misbehaving nodes / faulty nodes.
- The performance of the entire network will significantly degrade:
  - Effective network throughput (receive-throughput at the destination nodes);
  - Fairness among different users.

Challenges and Opportunities

- Wireless sensor networks are highly redundant – there exist multiple paths between source and destination.

- Multi-Path Routing
  - Each source node chooses multiple paths;
  - Each path is allocated with different traffic amount (how to control the rate of each flow?)
  - Each path has different probabilities to be affected by faulty nodes(how to measure this?)



Goal: Efficiently allocate the traffic to maximize the overall throughput.

Challenges and Opportunities

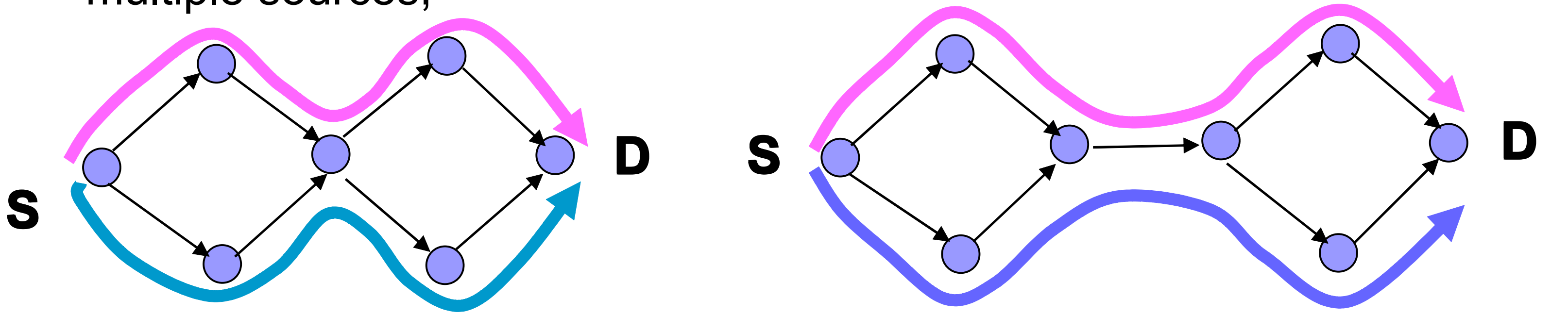
--Misbehavior Assumptions

- Nodes in WSNs are prone to be failure due to various unknown causes
  - hardware failure, communication link errors, malicious attacks, energy depletions and so on ;
  - outsider / insider ;
  - static / dynamic .
- nondeterministic and dynamic
- Misbehavior Assumptions
  - Byzantine faulty behavior in routing and forwarding ;
  - The impact of fault links can be characterized as probabilistic from the perspective of the network.

Challenges and Opportunities

--Misbehavior Assumptions

- Fully disjoint multi-path routing
  - A theoretical limit on the security-performance tradeoff of fully disjoint multi-path routing in the presence of fault nodes [1];
  - Lack of scalability;
  - High overhead.
- Some works relax the disjointness requirement [2] [3];
- Assume that some non-disjoint nodes exist on the paths from one source or multiple sources;



How to measure the impact of the correlation of these paths on the effective throughput ?

Network Model

- The set of all the available paths of source s : $R_s = [R_{s,1}, R_{s,2}, ..., R_{s,k_s}]$
- The rate of source s on the path $R_{s,n}$: $x_{(s,n)}$
- The total source rate $x_s = \sum_{n=1}^{k_s} x_{s,n}$
- The path rate vectors of source s : $X_s = [x_{s,1}, ..., x_{s,n_s}]$
- Users contend for the channel
- Random access protocols
- The set of links in the ωth contention clique consisting of link l : $\mathcal{L}(\omega_l)$
- The sum of all transmission probabilities in a clique must be less than 1 : $\sum_{l \in \mathcal{L}(\omega_l)} p_l \leq 1$

Faulty Node Model

- The impact of faults is probabilistic from the perspective of the network;
- The behavior of node v is formulated as a random variable H(v):

$$H(v) = \begin{cases} 1 & \text{if } v \text{ forwards the observed data packet correctly} \\ 0 & \text{otherwise} \end{cases}$$

- The effective throughput received at the destination node is lower than the throughput at the source node;
- A path $p = [v_1, v_2, ..., v_p]$ can also be formulated as a random variable $T(p)$:

$$T(p) = \begin{cases} 1 & \text{if } p \text{ successfully delivers the observed data packet} \\ 0 & \text{otherwise} \end{cases}$$

Flow Control for Multipath Routing

- Link l transmits data with a persistence probability p_l to contend for the channel resource in its clique;
- The total flow rate over link l should be no more than the average capacity;
- NUM for cross-layer rate control with the MAC resource constraint :

$$\text{Problem: } \max \sum_{s\in S}(U_s(\sum_{n=1}^{k_s} x_{s,n}))$$

$$s.t.: \sum_{s\in S(l)} A_{s,l}X_s \le c_l p_l \prod_{d\in\mathcal{L}(\omega_l)} (1-p_d)$$

$$x_s^{min} \le \sum_{n=1}^{k_s} x_{s,n} \le x_s^{max}$$

$$0 \le \sum_{l\in\mathcal{L}(\omega_l)} p_l \le 1$$

- Appealing to the Lagrangian dual method, update form for flow control :

$$x_{s,n}(t+1) = [x_{s,n}(t) + \gamma L_{x_{s,n}}(x(t),\lambda(t))]_{x_s^{min}}^{x_s^{max}}$$

$$\lambda_l(t+1) = [\lambda_l(t) - \gamma L_{\lambda_l}(x(t),\lambda(t))]^+$$

$(FC)^2R$ Algorithm
– Estimate Local Packet Success Ratios

- The ratio of packets successfully delivered over link *l*(*i*, *j*) : $h_l = Pr\{H(i) = 1\}$
- Each node estimates the packet delivery probability : $\hat{h}_l = \frac{m}{n}$
- Updates the estimation through iterations :

$$\hat{h}_l^t = (1 - \frac{1}{t}) \times \hat{h}_l^{t-1} + \frac{1}{t} \times \frac{m}{n}$$

- The end-to-end packet success ratio for the path l : $g_{s,n} = \prod_{l \in R_{s,n}} h_l$
- The mean of random variable $g_{s,n}$: $\theta_{s,n} = \prod_{l \in R_{s,n}} \hat{h}_l$
- The capacity constraint on the average data rate, imposed by faults

$$\sum_{Q_s} g_{s,n}^{(i)} x_{s,n} \leq c_{(i,j)} p_{(i,j)} \prod_{d \in \mathcal{L}(\omega_{(i,j)})} (1 - p_d)$$

the correctly received data ratio at the intermediate node *i*

$(FC)^2R$ Algorithm

– Fault-Correlation between multiple Paths

- How to measure the correlation between non-disjoint routing paths ?
  - There are common nodes between paths, the random variable $g_{s,n}$ may not be independent.

- The variance of two paths $R_{s,n}$ and $R_{s,m}$

$$\phi_{s,n,m} = E[g_{s,n}g_{s,m}] - E[g_{s,n}]E[g_{s,m}]$$

- This correlation means that any packet loss in a set of correlated paths sharing the faulty nodes may decrease the effective throughput.

- The cost function

$$Cost_s = X_s \Phi_s X_s^T$$

(FC)²R Algorithm

– (FC)²R Approach with Multiple paths

- Each flow *s* has a utility function associated with the effective rate and the cost from the variance between correlated paths;
- The principle objective is to maximize the overall effective network utility

$$\text{Problem: } \max \textstyle\sum_{s\in S}(U_s(\sum_{n=1}^{k_s}\theta_{s,n}x_{s,n})) - k_s X_s \Phi_s X_s^T$$

$$s.t.: \sum_{Q_s} g_{s,n}^{(i)} x_{s,n} \le c_{(i,j)} p_{(i,j)} \prod_{d\in\mathcal{L}(\omega_{(i,j)})} (1-p_d)$$

$$x_s^{min} \le \sum_{n=1}^{k_s} x_{s,n} \le x_s^{max}$$

$$0 \le \sum_{l\in\mathcal{L}(\omega_l)} p_l \le 1$$

(FC)²R Algorithm

– Change of Variables

- Let $\tilde{x}_{s,n} = log(x_{s,n})$

Problem: $\tilde{U}_s(\tilde{x}_{s,n})$

$$s.t. :log \sum_{Q_s} g_{s,n}^{(i)} e^{\tilde{x}_{s,n}} - \log c_{(i,j)} - \log p_{(i,j)} - \sum_{d \in \mathcal{L}(\omega_{(i,j)})} \log(1 - p_d) \leq 0$$

$$x_s^{min} \leq \sum_{n=1}^{k_s} e^{\tilde{x}_{s,n}} \leq x_s^{max}$$

$$0 \leq \sum_{l \in \mathcal{L}(\omega_l)} p_l \leq 1$$

where $\tilde{U}_s(\tilde{x}_{s,n}) = \sum_{s \in S}(U_s(\sum_{n=1}^{k_s} \theta_{s,n} e^{\tilde{x}_{s,n}})) - k_s \tilde{X}_s \Phi_s \tilde{X}_s^T$

Lemma 1: The function $\tilde{U}_s(\tilde{x}_{s,n})$ is strictly concave with $k \geq 1$.

(FC)²R Algorithm

– Lagrange Dual Approach

- The Lagrangian function is

$$L(\tilde{X}, f, \lambda, \underline{\lambda}, \bar{\lambda}) = \sum_{s \in S} (U(\sum_{n=1}^{k_s} \theta_{s,n} e^{\tilde{x}_{s,n}}) + \bar{\lambda}(x_s^{max} - \sum_{n=1}^{k_s} e^{\tilde{x}_{s,n}}) - \underline{\lambda}(x_s^{min} - \sum_{n=1}^{k_s} e^{\tilde{x}^{s,n}}))$$
$$- \sum_{(i,j)} \lambda_{(i,j)} (\log(\sum_{Q_s} g_{s,n}^{(i)} e^{\tilde{x}_{s,n}}) - \log c_{(i,j)} - \log p_{(i,j)} - \sum_{d \in \mathcal{L}(\omega_{(i,j)})} \log(1 - p_d))$$

- Then, the Lagrange dual function is

$$D(\lambda, \overline{\lambda}, \underline{\lambda}) = max_{\{\tilde{x}\}} L(\tilde{x}, \lambda, \overline{\lambda}, \underline{\lambda})$$

- The dual problem is given by

$$min_{\{\lambda, \overline{\lambda}, \underline{\lambda}\}} D(\lambda, \overline{\lambda}, \underline{\lambda})$$

(FC)²R Algorithm

– Distributed Primal-dual Alg.

- The source rates are updated by

$$\tilde{x}_{s,n}(t+1) = [\tilde{x}_{s,n}(t) + \gamma L_{\tilde{x}_{s,n}}(\tilde{x}(t), \lambda(t))]^+$$

$$L_{\tilde{x}_{s,n}}(\tilde{x}(t), \lambda(t)) = U'(\sum^{k_s} \theta_{s,n} e^{\tilde{x}_{s,n}(t)}) - \bar{\lambda}_s(t) e^{\tilde{x}_{s,n}(t)} + \underline{\lambda}_s(t) e^{\tilde{x}_{s,n}(t)}$$

$$- g_{s,n}^{(i)} e^{\tilde{x}_{s,n}(t)} \sum_{(i,j)\in\mathcal{L}(s)} (\frac{\lambda_{(i,j)}(t)}{\sum_{Q_k} g_{k,n}^{(i)} e^{\tilde{x}_{k,n}(t)}}) - (2\sum_{i=1}^{n_s} \phi_{s,n,i} e^{2\tilde{x}_{s,n}} + \sum_{i=1}^{n_s} (\phi_{s,i,n} + \phi_{s,n,i}) e^{\tilde{x}_{s,i} + \tilde{x}_{s,n}})$$

- The shadow prices are updated by

$$\lambda_{(i,j)}(t+1) = [\lambda_{(i,j)}(t) - \gamma(\sum_{d\in\mathcal{L}(\omega_{(i,j)})} \log(1 - p_d(t)) + \log p_{(i,j)}(t) + \log c_{(i,j)} - \log(\sum_{Q_s} g_{s,n}^{(i)} e^{\tilde{x}_{s,n}(t)})]^+$$

$$\bar{\lambda}_s(t+1) = [\bar{\lambda}_s(t) + \gamma(x_s^{max} - \sum_{n=1}^{k_s} e^{\tilde{x}_{s,n}(t)})]^+ \qquad \underline{\lambda}_s(t+1) = [\underline{\lambda}_s(t) - \gamma(x_s^{min} - \sum_{n=1}^{k_s} e^{\tilde{x}_{s,n}(t)})]^+$$

- The persistence probabilities are updated by

$$p_{(i,j)}(t) = \frac{\lambda_{(i,j)}(t)}{\sum_{k\in\mathcal{L}(\omega_{(i,j)})} \lambda_k(t)}$$

(FC)^{2}R Algorithm

– Prevent Oscillations

- To improve the convergence speed and eliminate the effect of oscillation

$$\max \sum_{s \in S} (U_s(\tilde{\theta}_s \sum_{n=1}^{k_s} e^{\tilde{x}_{s,n}}))$$

$$\downarrow$$

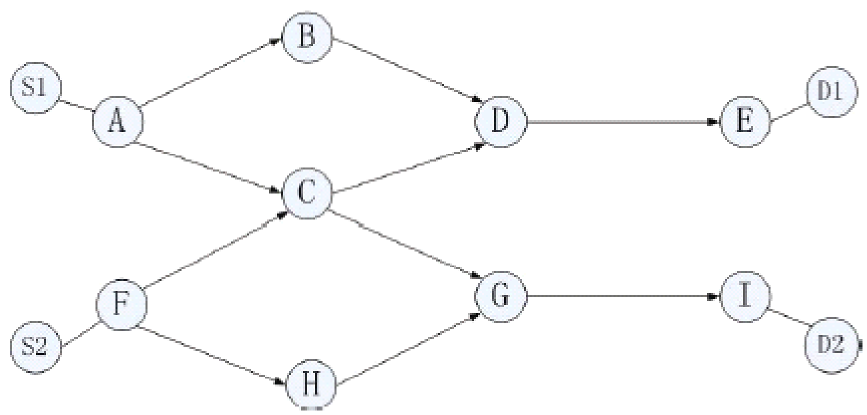
$$\max \sum_{s \in S} (U_s(\tilde{\theta}_s \sum_{n=1}^{k_s} e^{\tilde{x}_{s,n}})) - \sum_{s \in S} \sum_{n=1}^{k_s} \frac{1}{2} (\tilde{x}_{s,n} - f_{s,n})^2$$

- The update formulation of source rate is slightly modified

$$\tilde{x}_{s,n}(t+1) = [(1-\gamma)\tilde{x}_{s,n}(t) + \gamma f_{s,n}(t) + \gamma(L_{\tilde{x}_{s,n}}(\tilde{x}(t), \lambda(t)))]^+$$
$$f_{s,n}(t+1) = (1-\gamma) f_{s,n}(t) + \gamma \tilde{x}_{s,n}(t)$$

Simulation Setup

- The average data rate of each link : 1 Mbps
- The step size γ : 0.01
- Each fault parameter $h_{i,j}$: independent beta random variables
- $\alpha = 1$, $x_s^{min} = 0$ and $x_s^{max} = 1$



Simulation Results

- $(FC)^2R$ yields higher effective rates
- $(FC)^2R$ yields better fairness

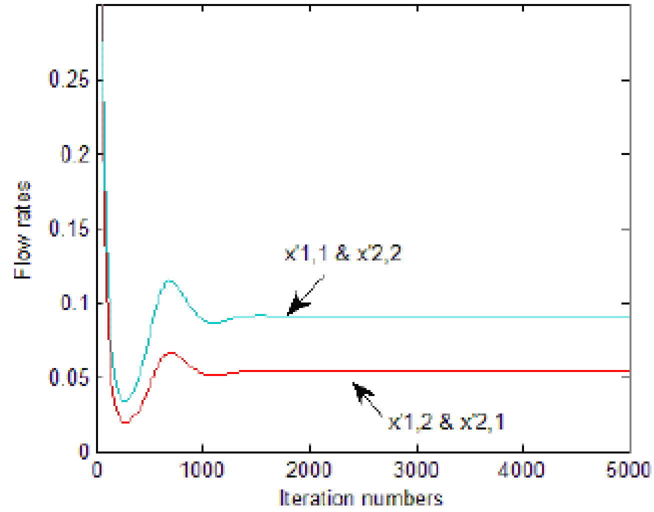


Fig. 2. The flow rates at the source nodes of OFC

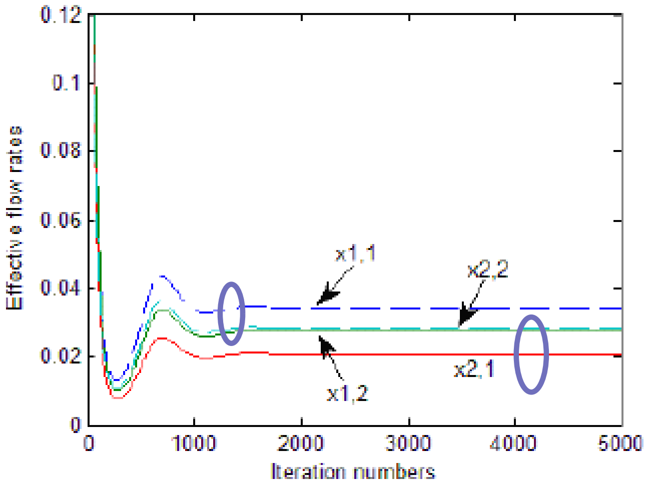


Fig. 3. The effective flow rates at the destination nodes of OFC

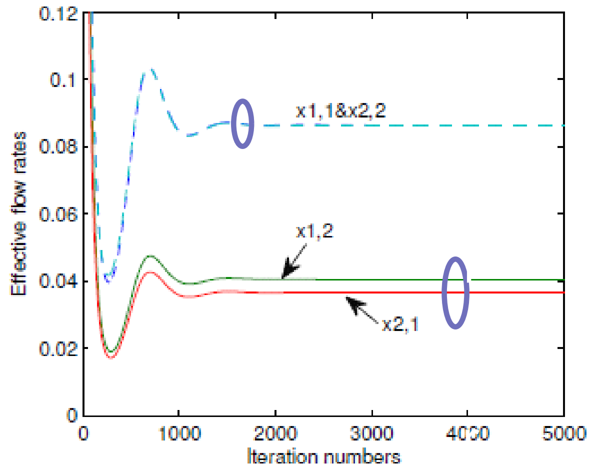
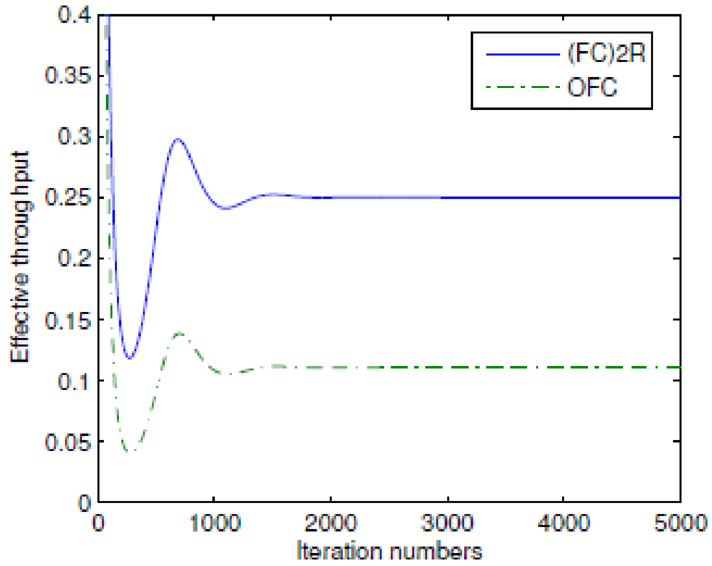


Fig. 4. The effective flow rates at the destination nodes of $(FC)^2R$

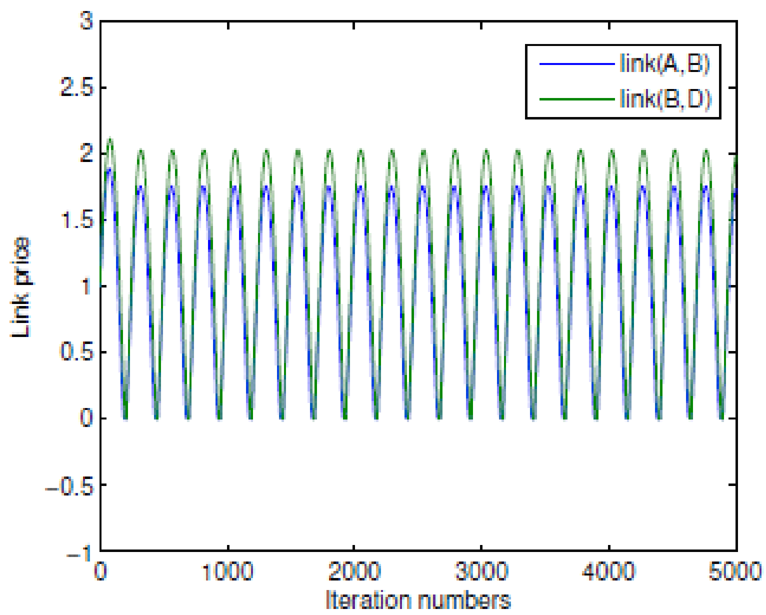
Simulation Results

- Higher effective throughput



Simulation Results

- The oscillation is observed



Related work

- [1] L. Chen and J. Leneutre, “On multipath routing in multihop wireless networks: security, performance, and their tradeoff”.
- [2] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin, “Highly-resilient, energy-efficient multipath routing in wireless sensor networks”.
- [3] Y. Yang, C. Zhong, Y. Sun, and J. Yang, “Network coding based reliable disjoint and braided multipath routing for sensor networks”.

Conclusion

- We formulate the problem of flow control for multipath routing in MSNs in the presence of faulty links as the optimization of wireless flows along leaky paths. We measure the degree of packet loss on leaky paths, according to the probabilistic characterization of faulty links.
- We design a cost function to describe the uncertainty and variation failure-correlation between non-disjoint routing paths. The function is used in our solution to the above optimization problem.
- We propose a novel distributed algorithm, $(FC)^2R$, which generates the optimal effective rate allocation across multiple wireless paths. The numerical results indicate that higher effective throughput and better fairness among effective flow rates can be achieved by the $(FC)^2R$ algorithm than the standard OFC with multipath routing.

Thank you!