Trade-off between Reliability and Energy Cost for Content-Rich Data Transmission in Wireless Sensor Networks (WSN)

Y. Charfi, N. Wakamiya and M. Murata
Graduate school of Information Science and Technology
Osaka University

Outline

- Issues and techniques of reliable transmission in WSN
- Link-layer versus end-to-end error control
- Description of the multi-path transmission system
- End-to-end error control using path diversification
- Formulation of reliability and energy cost
- Energy-reliability trade-off optimization
- Results
- Conclusions and current work

Issues of reliable transmission over WSN

- Data transmission over WSN is unreliable due to
  - Unreliability of wireless links
  - Limited power sensor nodes can use for transmission
  - Node failure
- Data generated by sensor nodes can be sensitive to errors
  - E.g., few bit errors in a compressed image bit-stream can lead to the image decoding failure

Techniques for reliable transmission in WSN (1)

- Transmission power control
- Error control
  - Techniques
    - Automatic Repeat reQuest (ARQ)
    - Forward Error Correction (FEC)
  - Approaches
    - Link-layer error control
    - End-to-end error control

Techniques for reliable transmission over WSN (2)

- Transmission power control
  - Higher transmission power reduces packet error rate, but also increases energy consumption and interference
  - Estimates the optimal transmission power using the link distance and the channel characteristics
  - Requires a multi-power-level radio

Techniques for reliable transmission over WSN(3)

- Automatic Repeat reQuest (ARQ)
  - ARQ incurs significant retransmission cost and additional delay
  - WSN have stringent energy constraints
  - Attempts have been made to design energy-efficient ARQ schemes

Techniques for reliable transmission over WSN(4)

- Forward Error Correction (FEC)
  - FEC reduces the error rate for any given transmission power
  - It requires additional processing power for the FEC codec
  - Need to optimize the trade-off between the additional processing power and the error rate reduction

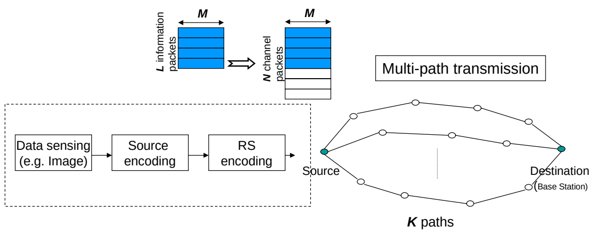
Link-layer error control for WSN

- Major issues of hop-by-hop link-layer error control
  - Typically implemented using a fixed number of retransmissions, or fixed-rate FEC codes
    - Can not be adapted to the reliability requirements of the transmitted bit-stream
  - Sensor nodes may fail or switch to a sleeping state and, thus, break any link-layer recovery mechanism
    - Unsuitable for applications that require end-to-end reliability guarantees
  - Alternative: End-to-end error control using path diversification

End-to-end error control using path diversification

- We consider the transmission of an information bit-stream of size *LM* from a source node to a destination over *K* available disjoint paths in a wireless sensor network
- Every path is characterized by
  - Probability of successful packet delivery
  - Energy consumption per transmitted bit
  - The number of packets that can still be transmitted over the path (this depends on the residual energy)

Illustration of the multi-path transmission system



End-to-end error control using path diversity: Problem statement

- To provide error recovery, the source node
  1. splits the data stream into *L* packets of size *M*
  2. appends (*N* – *L*) redundancy packets of size *M* using RS codes
  3. sends the *N* packets through the *K* paths
- Let α be the required reliability: probability of the successful transmission of the data stream
  - Optimization problem: For a given reliability α, find the transmission scheme, i.e., number of channel packets *N* and the path each packet should take, that will result in a minimal use of energy

Wireless channel model

- For sensor nodes that use fixed transmission power, the bit error rate (BER) is a function on the link distance.
- Using the BPSK modulation scheme, the BER is given by

$$\bar{p}_{j,j+1} = 0.5\, erfc\left(\sqrt{\frac{P_t}{D_{j,j+1}{}^2\, \eta\, f}}\right)$$

- Packet error rate of a packet of size *M*

$$p_{j,j+1} = 1-(1-\bar{p}_{j,j+1})^M$$

- Probability of successful packet transmission over path *k*, *k*=1, …, *K*

$$P^{(k)} = \prod_{j=0}^{n_k} (1-p^{(k)}_{j,j+1})$$

Reliability

- X_N : r. v. whose value is the number of successfully transmitted packets out of N sent packets
- $E(X_N)$: expected number of successfully transmitted packets
- S : a transmission strategy $S=(N,k_1,k_2,\ldots,k_N), k_i \in [1,K]$
- Reliability $R(S)$: probability of the successful transmission of a bitstream of N packets over K paths using strategy S

$$R(S)=\mathrm{Prob}\left[\mathrm{E}(X_N)\geq L\right]$$

- $R(S)$ can be approximated by the Poisson cumulative distribution :

$$\tilde{R}(S)=\sum_{l=0}^{N-L}\frac{e^{-\gamma(S)}\gamma(S)^l}{l!} \qquad \gamma(S)=-\sum_{i=1}^{N}\ln\left(P^{(k_i)}\right)$$

- $\tilde{R}(S)$ is monotonically decreasing with $\gamma(S)$

Energy cost

- The total expected energy consumption could be written as

$$E(S)=E_s(N)+\sum_{i=1}^{N}\mathrm{E}_{\mathrm{p}}^{(k_i)}$$

- $E_s(N)$: energy spent by the source node for RS coding and the transmission of the data bit-stream to the nearest node of each transmission path

$$E_s(N)=E_c(N)+E_t(N)$$
$$E_c(N)=C_c\frac{ML(N-L)}{s}$$
$$E_t(N)=NMP_t$$

- $\mathrm{E}_{\mathrm{p}}^{(\mathrm{k})}$: expected energy consumed by the intermediate nodes of a path *k* during packet transmission

$$\mathrm{E}_{\mathrm{p}}^{(\mathrm{k})}=\sum_{l=0}^{n_k-2}\left[\prod_{j=0}^{l}\left(1-p_{j,j+1}^{(k)}\right)p_{l+1,l+2}^{(k)}\sum_{j=0}^{l}e_{j+1}^{(k)}\right]+\prod_{j=0}^{n_k-1}\left(1-p_{j,j+1}^{(k)}\right)\sum_{j=0}^{n_k-1}e_{j+1}^{(k)}$$

Definition of transmission strategies

- For a given N, the set of possible transmission strategies

$$\Omega_N=\{(N,k_1,\ldots,k_N)\mid k_i\in[1,K] \text{ for } i=1,\ldots,N,$$
$$\text{and } \sum_{i=1}^{N}\delta_i^{(k)}\leq a^{(k)} \text{ for } k=1,\ldots,K\}.$$

$$\delta_i^{(k)}=\begin{cases}1 & \text{for } k_i=k\\ 0 & \text{otherwise}\end{cases}$$

- For $L\leq N\leq N_{\max}$ $\quad \Omega=\bigcup_{N=L,\ldots,Nmax}\Omega_N$

Energy-reliability trade-off (1)
Optimization problem

- Constrained minimization

$$\min_{S\in\Omega}E(S) \quad \text{subject to} \quad R(S)\geq\alpha$$

  - Unconstrained minimization using the Lagrange Multiplier

$$\min_{S\in\Omega}L(S,\lambda), \quad L(S,\lambda)=E(S)-\lambda R(S)$$

Energy-reliability trade-off (2)
Speed-up technique

- Simplifying the minimization problem by decomposing it as follows :

$$\min_{N\in[L,N_{max}]}\left[E_s(N)+\min_{S\in\Omega_N}L_N(S,\lambda)\right]$$

where $L_N(S,\lambda)=\sum_{i=1}^{N}E_p^{(k_i)}+\lambda\gamma(S)$

Energy-reliability trade-off (3)
Minimization for a given N

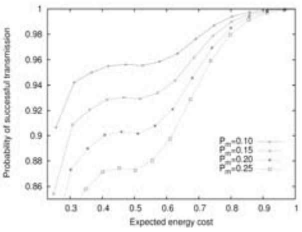
$$L_N(S,\lambda)=\sum_{i=1}^{N}E_p^{(k_i)}-\lambda\sum_{i=1}^{N}ln\left(P^{(k_i)}\right)$$

$$L_N(S,\lambda)=\sum_{i=1}^{N}L^{(i)}(k_i,\lambda) \qquad L^{(i)}(k_i,\lambda)=E_p^{(k_i)}-\lambda\ln\left(P^{(k_i)}\right)$$

- Minimizing $L_N(S,\lambda)$ is equivalent to minimizing $L^{(i)}(k_i,\lambda)$ for *i = 1, … , N*
  - It follows that the choice of the transmission path can be made independently for each packet
- Based on this result, Lagrange minimization can be done with a computational complexity linear with the number of packets *N*

Results (1)

Probability of successful packet transmission over a path versus its energy cost. Curves are displayed for various maximum link error rates P_m.

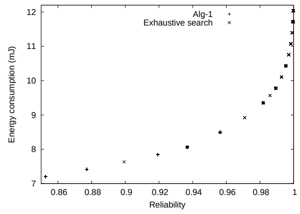


Results (2)

Alg-1 versus exhaustive search

N=20, L=10, K=8, P_m=0.20

- Alg-1 denotes the proposed Lagrange minimization algorithm for a given number of channel packets *N*



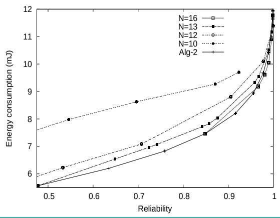
Results (3)

Alg-2 versus Alg-1

Alg-1 was run for different values of N

P_m = 0.20, L = 10, K = 8, N_{max}=20

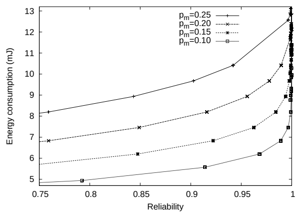
- Alg-2 denotes the proposed Lagrange minimization algorithm for $L \leq N \leq N_{max}$



Results (4)

Minimal energy cost versus reliability using Alg-2 for different maximum link error rates

L = 10, K = 8, N_{max}=20



Conclusions

- We proposed an algorithm that finds energy-efficient transmission strategies for multi-path data transmission under given reliability constraints
- This work is part of our research project on adaptive and reliable data communications in wireless visual sensor networks
- Currently, we are investigating a hybrid mechanism based on FEC and feedback to improve the trade-off between reliability and energy cost
- Practical experiments are also required to test the proposed algorithms and confirm the obtained results