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)

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 $\alpha$ be the required reliability: probability of the successful transmission of the data stream
- Optimization problem: For a given reliability $\alpha$, 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
  \[
  p_{j,i+1} = 0.5 \text{erfc} \left( \frac{P}{D_{j,i+1} \eta f} \right)
  \]
- Packet error rate of a packet of size $M$
  \[
  p_{j,i} = 1 - (1 - p_{j,i+1})^M
  \]
- Probability of successful packet transmission over path $k$
  \[
  p_{k,j} = \prod_{i=1}^{L} (1 - p_{j,i+1})
  \]
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 \( S = (N, k_1, k_2, \ldots, k_N) \)

Reliability \( R(S) \): probability of the successful transmission of a bitstream of \( N \) packets over \( K \) paths using strategy \( S \)

\[ R(S) = \text{Prob}[E(X_n) \geq L] \]

- \( R(S) \) can be approximated by the Poisson cumulative distribution:
  \[ \tilde{R}(S) = \sum_{i=0}^{L-1} \frac{e^{-\lambda} \lambda^i}{i!} \]
- \( \tilde{R}(S) \) is monotonically decreasing with \( \gamma(S) \)

Energy cost

- The total expected energy consumption could be written as
  \[ E(S) = E_s(N) + \sum_{k=1}^{K} E_k(L) \]
  \[ E_s(N) = c_s N \]
  \[ E_k(L) = c_k L \]

Definition of transmission strategies

- For a given \( N \), the set of possible transmission strategies
  \[ \Omega_N = \{(N, k_1, \ldots, k_N) \mid \forall k \in [1, K] \text{ for } i = 1, \ldots, N, \]
  \[ \sum_{i=1}^{N} k_i = d \text{ for } k = 1, \ldots, K \}
- \( \delta(k) = \begin{cases} 1 & \text{for } k_i = k \\ 0 & \text{otherwise} \end{cases} \)
- For \( L \leq N \leq N_{\text{max}} \)
  \[ \Omega = \bigcup_{N = E_{\text{min}}}^{N_{\text{max}}} \Omega_N \]

Energy-reliability trade-off (1)

Optimization problem

- Constrained minimization

\[ \min_{S \in \Omega} E(S) \text{ subject to } R(S) \geq \alpha \]
- 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:
  \[ \min_{N \in [E_{\text{min}}, N_{\text{max}}]} \left[ E_s(N) + \min_{S \in \Omega_N} L_N(S, \lambda) \right] \]
  where \( L_N(S, \lambda) = \sum_{i=1}^{N} E_k(k_i, \lambda) + \lambda R(S) \)

Energy-reliability trade-off (3)

Minimization for a given \( N \)

\[ L_N(S, \lambda) = \sum_{i=1}^{N} E_k(k_i, \lambda) \]

Minimizing \( L_N(S, \lambda) \) is equivalent to minimizing \( L_k(k_i, \lambda) \) for \( i = 1, \ldots, N \)
- 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 $P_m$.

![Graph showing probability vs energy cost](image1)

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 $N$.

![Graph showing Alg-1 vs exhaustive search](image2)

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 $L \leq N \leq N_{max}$.

![Graph showing Alg-2 vs Alg-1](image3)

Results (4)
Minimal energy cost versus reliability using Alg-2 for different maximum link error rates
$L=10$, $K=8$, $N_{max}=20$

- $P_m=0.25$
- $P_m=0.20$
- $P_m=0.15$
- $P_m=0.10$

![Graph showing energy cost vs reliability](image4)

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.