Unraveling the Subtleties of Link Estimation and Routing in Wireless Sensor Networks

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Question #1: Basis of link estimation: broadcast beacon vs. data?

- Inherent errors in beacon-based estimation due to
  - impact of traffic-induced interference, and
  - temporal link correlation and link layer retransmission
- Estimation error in beacon-based link estimation leads to worse routing performance

Impact of Traffic-induced Interference

Unicast ETX in different interference scenarios

Errors in estimating unicast ETX via broadcast reliability

Mean reliability of each unicast-physical-transmission minus that of broadcast

Question #2: How to use MAC feedback in data-driven link estimation and routing?

- Seemingly similar methods may differ significantly in routing behavior!
- Tow representative methods for estimating ETX:
  - L-NT: directly use feedback information on the number of physical transmissions, \(|NTi|\), to estimate ETX; represents MAC-latency based approach too.
  - L-ETX: first use transformed feedback information \(|PDR_i|\) to estimate the reliability \(PDR\) of individual unicast-physical-transmissions, then estimate ETX as \(1/PDR\).
- Proposition: for the commonly used EWMA estimator, L-NT introduces larger estimation error than L-ETX does.
  - For \(\{Xi\}\), estimation error of EWMA is approximately proportional to \(COV(Xi)\);
  - \(COV(NTi) > COV(PDR_i)\), because
    \[
    COV(NTi) = \frac{\mu^2}{0 - \mu^2}, \quad COV(PDR_i) = \frac{1}{W} \sqrt{\mu^2 - \mu^2}
    \]
  - where \(P_i\) is the average reliability of unicast-physical-transmission, and is the window size \(W\) for calculating \(PDR\).

L-NT vs. L-ETX

Estimated ETX values in L-NT and L-ETX for a link 9.15 meters long

Variants of L-NT and L-ETX

Routing Performance

Routing with dynamic traffic patterns

Dynamic of Best Forwarders

Dynamics of Best Forwarders

Model B-MAC and IEEE 802.15.4 using a Markov chain where the state \(i\) is the set \(S_i\) of nodes that are transmitting concurrently at a certain time moment. Given a link \((t, s)\), then, the SINR at receiver \(s\) is

\[
N_s = \sum_{j \neq s} \sum_{i} \pi_i \cdot P_{\text{Pow}}(t, j)
\]

where \(P_{\text{Pow}}(s, y)\) is the received signal strength at \(y\) for signals coming from \(s\), \(N_0\) is the background noise, and \(\pi_i\) is the stationary probability of state \(i\). Accordingly, we can compute the PDR and routing metric value for each link and forwarder candidates.

Analysis, outdoor:

Measurement, indoor:

Routing stability: 99.98% time with the same routes 0.02% time with decreased hop length

Question #3: Convergence and stability of data-driven link estimation and routing?

- Biased link sampling (BLS): the properties of a link is not sampled unless the link is currently used in data forwarding.
- For traffic-induced dynamics (in mostly static deployments, e.g., environmental monitoring),
  - the optimal routing structure in L-ETX remains quite stable even though the properties of individual links and routes vary significantly;
  - when the optimal routing structure does change, data-driven link estimation and routing is either guaranteed to converge or empirically shown to converge to a close-to-optimal structure.
- These findings provide the foundation for addressing the BLS issue and suggest simpler, lighter-weight approaches as compared to existing schemes.

Cost ratio Percentage(%) Forwarder Method

<table>
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<th>Method</th>
<th>Forwarder</th>
<th>Percentage(%)</th>
<th>Cost ratio</th>
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<td>L-ETX</td>
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</tbody>
</table>

L-NT: L-WNT (variant of L-ETX): estimate PER instead of PDR

L-NADV (variant of L-ETX): estimate PER instead of PDR

# Tx per packet received

Event reliability

L-NADV (variant of L-ETX): L-WNT

Estimated ETX values in L-NT and L-ETX for a link 9.15 meters long

# Tx per packet received

Event reliability