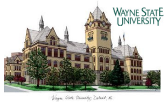

Unraveling the Subtleties of Link Estimation and Routing in Wireless Sensor Networks

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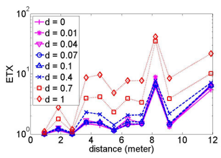
Question #1: Basis of link estimation: broadcast beacon vs. data?

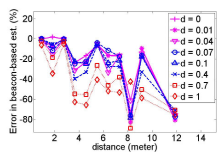
- Inherent errors in beacon-based estimation due to
  - ✓ impact of traffic-induced interference, and
  - ✓ temporal link correlation and link layer retransmission
- Estimation error in beacon-based link estimation leads to worse routing performance

Impact of Traffic-induced Interference

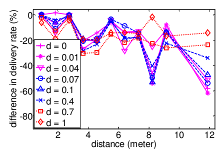


Unicast ETX in different interference scenarios

Errors in Beacon-based Estimation

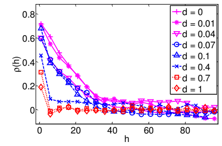


Errors in estimating unicast ETX via broadcast reliability

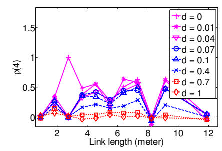


Mean reliability of each unicast-physical-transmission minus that of broadcast

Complex Correlation (unicast phy. tx)

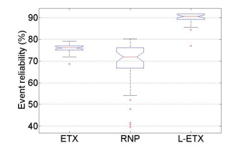


ρ(h) for a link 9.15 meters long

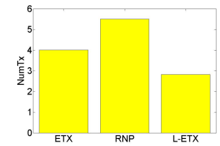


ρ(4) for different links

Data-driven vs. Beacon-based Routing



Event reliability



#. Tx per packet received

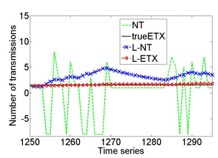
Question #2: How to use MAC feedback in data-driven link estimation and routing?

- *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 {PDRj} 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(PDRj), because

$$COV(NT_i) = \frac{\sqrt{P_0}}{(1-P_0)^2},\quad COV(PDR_j) = \frac{1}{\sqrt{W}}\frac{\sqrt{P_0}}{\sqrt{1-P_0}}$$

where P_0 is the average reliability of unicast-physical-transmission, and is the window size W for calculating PDR_j

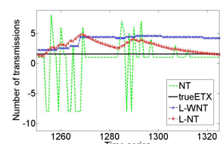
L-NT vs. L-ETX



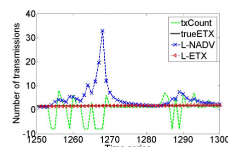
Estimated ETX values in L-NT and L-ETX for a link 9.15 meters long

Method	Forwarder	Percentage(%)	Cost ratio
L-NT	5	0.1	2.3
	6	4.14	1.3
	7	7.17	1.5
	8	21.26	1.3
	10	67.33	1
L-ETX	6	5.91	1.3
	7	0.2	1.5
	8	5.1	1.3
	10	88.79	1

Variants of L-NT and L-ETX

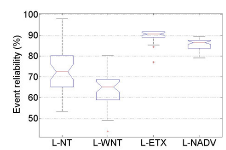


Variant/stabilized L-NT: L-WNT

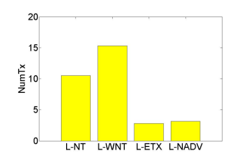


L-NADV (variant of L-ETX): estimate PER instead of PDR

Routing Performance



Event reliability



#. Tx per packet received

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.

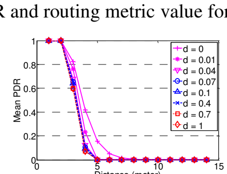
Dynamics of Best Forwarders

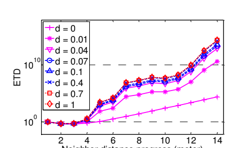
Model B-MAC and IEEE 802.15.4 using a Markov chain where the state i is the set S_i of nodes that are transmitting concurrently at a certain time moment. Given a link (t, s), then, the SINR at receiver s is

$$\frac{Pow(t,s)}{N_0 + \sum_{i:t\in S_i}\ \sum_{j:\, j\in S_i,\, j\neq t} \pi_i Pow(j,s)}$$

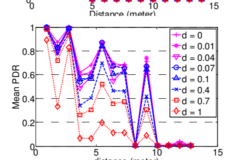
where $Pow(x, y)$ is the received signal strength at y for signals coming from x, N0 is the background noise, and π_i is the stationary probability of state i. Accordingly, we can compute the PDR and routing metric value for each link and forwarder candidates.

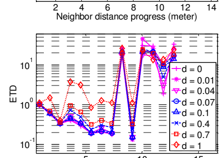
Analysis, outdoor:





Measurement, indoor:

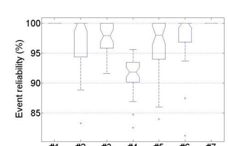


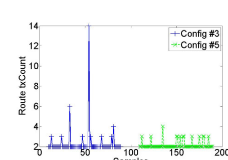


Routing with dynamic traffic patterns

Dynamic events:

1×1→3×3→5×5→7×7→5×5→3×3→1×1





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