The Emergence of a Networking Primitive in Wireless Sensor Networks

P. Levis, E. Brewer, D. Culler, D. Gay, S. Madden,
N. Patel, J. Polastre, S. Shenker, R. Szewczyk and A. Woo

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Presenter - Bob Kinicki

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Introduction

- Sensors are normally on a mote platform with a low-power CMOS radio.
- Mote constraints include:
  - Power supply
  - Limited memory (a few kilobytes of RAM)
  - Unattended operation
  - Lossy and transient wireless communications
- WSNs (a collection of motes) are typically embedded in physical environment associated with their application.

Wireless Sensor Networks

- Physical device location often dictated by application and physical constraints.
- Any retransmission, response or ACK contributes to contention, interference and loss.
- Redundancy is essential to reliability!
- The variety of WSN topologies and densities calls for a polite, density-aware, local retransmission policy.

Networking Protocols

- Network protocols focus on minimizing transmissions and providing reliability (namely, making sure transmitted packets arrive successfully).
- Most sensor networks rely on two multi-hop protocols:
- a collection protocol for pulling data out of a network.
- A dissemination protocol for pushing data into a network.

Dissemination

- WSN administrators need to adjust how the network collects data by changing the sampled sensors, the sampling rate or the code running on the nodes.

- Administrator needs to disseminate these changes to every node in the network.

Dissemination

- Early systems used flooding to disseminate.
- Flooding can be unreliable and many, concurrent packet broadcasts yield a broadcast storm.
- Adaptive flooding uses an estimate of node density to limit the flooding rate.
  - Getting this to work across network densities is tricky!

Dissemination Protocols

- Another view – dissemination protocols ensure every node eventually has a consistent version of a shared state.
- Casting dissemination as a data consistency problem means it does not provide full reliability.
- Eventual consistency only implies delivery of the most recent version to connected nodes.

Dissemination Protocols

- An effective dissemination protocol needs to bring nodes up to date quickly while sending few packets when every node has the most recent version.

- Hence, this is a requirement for the underlying consistency mechanism.

Collection Protocols

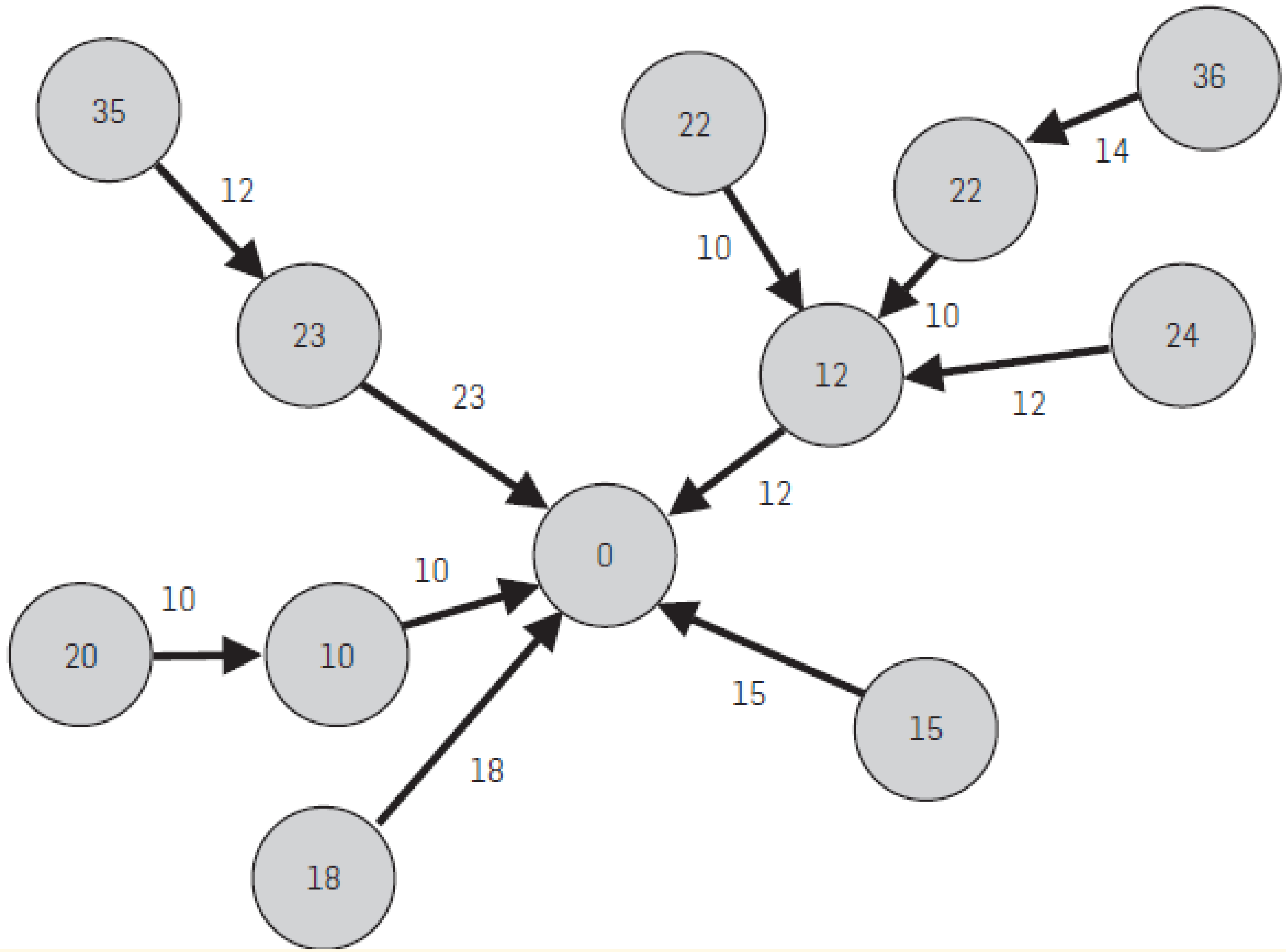
- WSNs report observations on a remote environment and thereby need a collection protocol.
- Collection protocols provide unreliable datagram delivery to a collection point using a minimum-cost routing tree.
- Typically cost measured in ETX (expected number of transmissions) which is related to packet delivery rate.
  - Nodes send packets on the route that requires the fewest transmissions to reach a collection point.

Collection Protocols

- An early collection protocol, directed diffusion, used collection trees based on data-specific node requests.
- Experiences with low-power wireless networks moved strategies towards a simpler approach where each node decides on a single next hop for all forwarded traffic.
  → creating routing trees to fixed collection points.
  - Tree built using a routing cost gradient.
  - Collection point has a cost of 0.

Figure 2: Collection Tree

Figure 2: Sample collection tree, showing per-link and node costs. The cost of a node is its next hop's cost plus the cost of the link.



Collection Protocols

- Collection variation includes:
  - How to quantify and calculate link costs.
  - The number of links in the tree.
  - How link state changes are propagated.
  - How frequently to re-evaluate link costs and switch parents.

Collection Protocols

- Early collection protocols used link costs.
- Second generation (similar to AODV and DSDV) used periodic broadcasts to estimate transmissions per delivery.
- Third generation added physical layer quality data.
- Current generation (e.g., Collection Tree Protocol (CTP)) gets information from multiple layers.

Collection Protocols

- Newer protocols reduce control traffic to increase efficiency.
- However, they need to send link-layer broadcasts to their local neighbors to advertise their presence and routing cost.
- Transmission frequency of routing advertisements causes design tension.
- Protocols reduce this tension by converting routing gradient to a data consistency problem.

Data Consistency Mechanism

- To address both dissemination and collection protocols as a problem of maintaining data consistency, the data consistency requirements are:
  - Resolve inconsistencies quickly.
  - Send few packet when data is consistent.
  - Require very little state.
- Trickle meets these three requirements.

Trickle

- Trickle algorithm establishes a density-aware local broadcast with an underlying consistency model that guides when a node communicates.
- The algorithm controls the send rate such that each node hears a trickle of packets (enough to stay consistent).
- Trickle relies only on local broadcasts and its basic mechanism is a randomized suppressive broadcast.

Trickle Algorithm [Bjamaa 15]

Trickle variables:

- c consistency counter
- I Trickle interval
- t transmission time

Trickle configuration parameters:

- I_{min} minimum interval size (time units)
- I_{max} determines maximum interval size as: $I_{min} \times 2^{I_{max}}$
- k redundancy constant

Trickle Algorithm

0. Initialization:

   I ← random value in range [$Imin$, $Imin \times 2^{Imax}$];

1. c ← 0;

   Pick t uniformly at random from range [I/2, I];

   start timer;

   {anytime during interval, if node hears a consistent message increment c;}

2. Once timer reaches t

   iff c < k node transmits message;   suppression possible!

3. When I expires, double interval length until I reaches $Imin \times 2^{Imax}$; go to 1.

   {anytime during interval, if node hears an inconsistent message and if I > $Imin$ then (I ← $Imin$; go to 1) }

Message Suppression

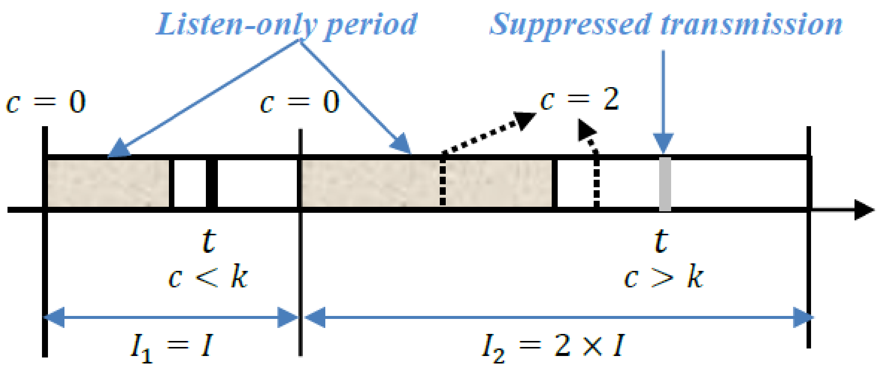


Figure 1 Trickle algorithm over two intervals with $k = 1$. Black line is a transmission, grey one is a suppressed transmission and dotted lines are receptions

- **Listen-only period addresses short-listen problem.**
- **When c > k , state is consistent and other transmissions are suppressed.**

Short-listen Problem

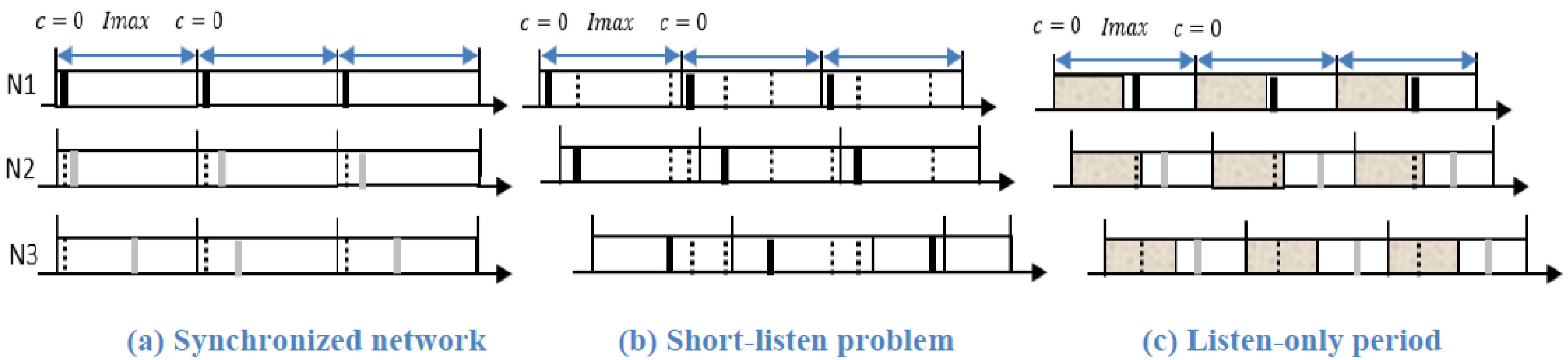


Figure 2 Short-listen problem and listen-only period with k = 1. Black boxes are transmissions, dotted lines are receptions and grey boxes are suppressed transmissions.

- **Short-listen comes from non-synchronized intervals among neighbors.**
- **N2 and N3 in (b) suffer from short-listen problem.**
- **(c) shows listen-only impact.**

Figure 4: Transmissions vs Nodes

These graphs assume nodes are synchronized.

Figure 4: Trickle's transmissions per interval scales logarithmically with density. The base of the logarithm is a function of the packet loss rate (the percentages)

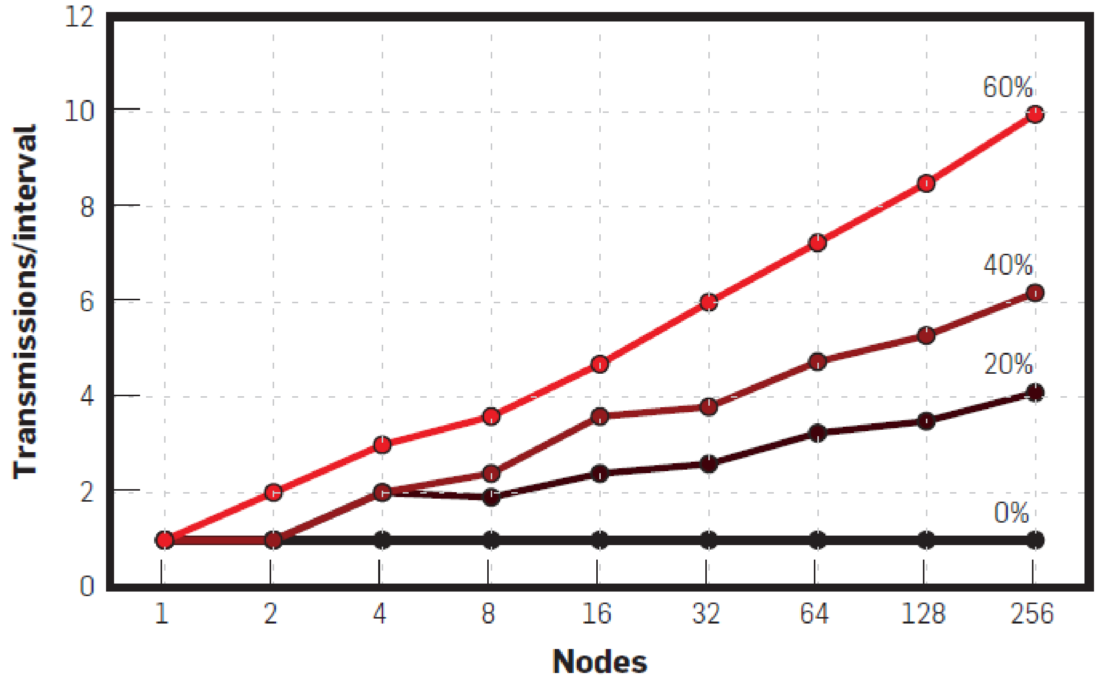
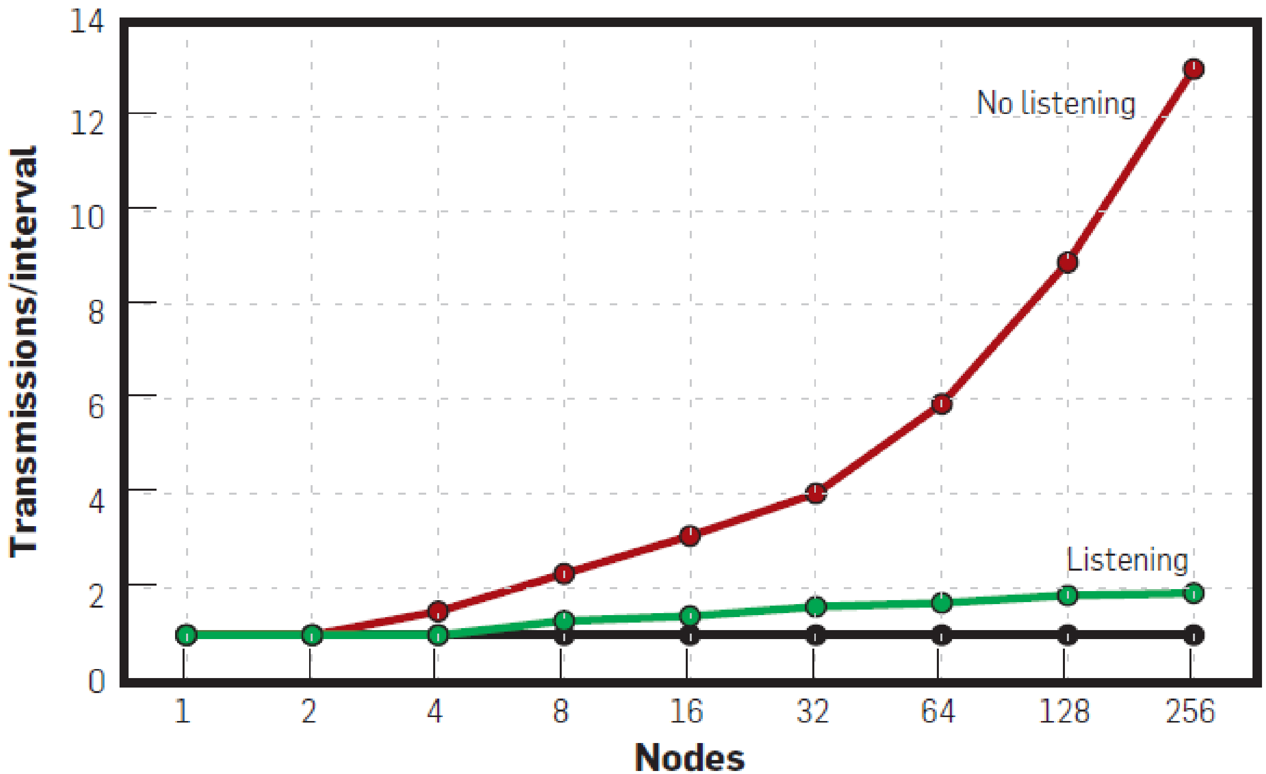


Figure 5: Listen-only Effect

Figure 5: Without a listen-only period, Trickle's transmissions scale with a square root of the density when intervals are not synchronized. With a listen-only period of duration $\frac{\tau}{2}$, the transmissions per interval asymptotically approach 2*k*. The black line shows how Trickle scales when intervals are synchronized. These results are from lossless networks.



Maté Case Study

- Maté :: a lightweight, bytecode interpreter for WSNs.
- Maté uses Trickle as a propagation service to periodically broadcast version summaries.
  - 30-byte code fits into one frame.
  - Consistency mechanism – broadcast missing routines 1,3 and 7 seconds after hearing there is an inconsistency.
- Trickle resources are small (70 bytes RAM, 11 bytes counters, 1.8K executable).

TOSSIM Simulation Details

- TOSSIM, a TinyOS simulator, models wireless connectivity at the bit level and wireless loss.
- **Node density** modeled via spacing between nodes (5 to 20 ft. in 5 ft. increments).

  I_{min} = 1 second;

  $I_{min} \times 2^{I_{max}}$ = 1 minute;

- 400 sensor nodes "regularly spaced" in a 20 x 20 grid (note - graph shows distances between a 19 x 19).

Figure 7: Time to Consistency

- Crossing the network takes from 6 to 40 hops.
- Time to complete propagation varied from 16 sec (dense network) to 70 sec (sparce network).
- Minimum per hop delay is *Imin/2* with 1 sec broadcast time → best case delay is 1.5 sec/hop.
- Claim: graphs show nodes cooperate efficiently.

Figure 7: Time to consistency in 20 × 20 TOSSIM grids (seconds). The hop count values in each legend are the expected number of transmissions necessary to get from corner to corner, considering loss.

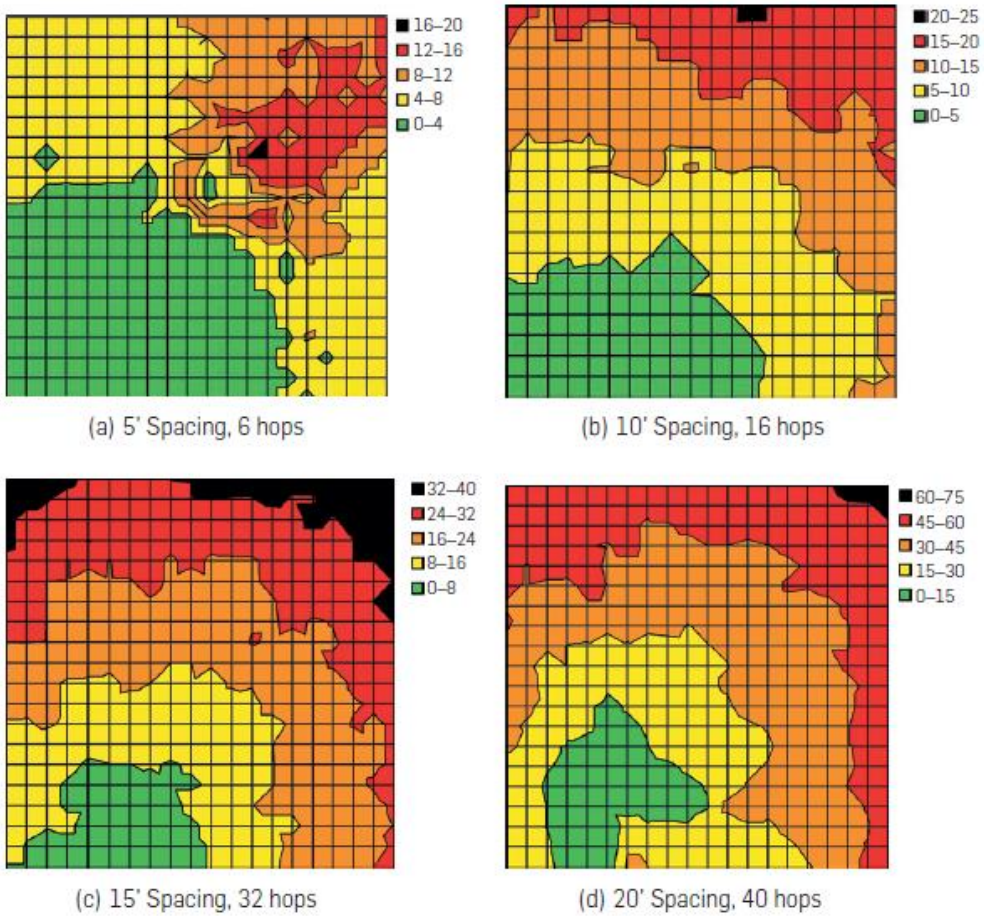
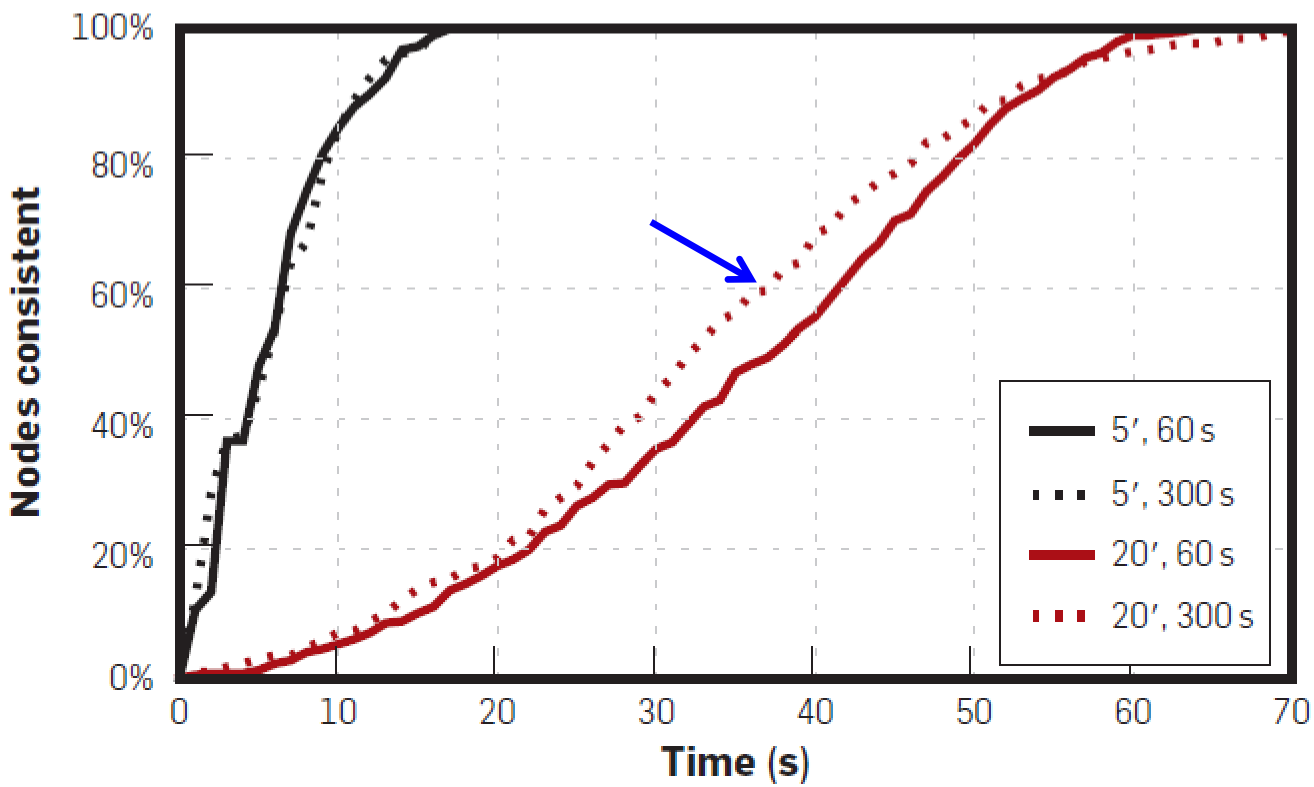


Figure 8: Consistency Rate

Figure 8: Rate nodes reach consistency for different τ_hs in TOSSIM. A larger τ_h does not slow reaching consistency.



Uses and Improvements

- Trickle used in many dissemination protocols today (e.g., Deluge, MNP, Drip and Tenet).
- More efficient collection protocols also using Trickle for consistency (e.g., TinyOS, 6LoWPAN IPv6 routing tables and ICMP neighbor lists).
- Drawback – Trickle maintenance costs grow O(n) with number of data items.

Trickle Discussion

- WSNs do not know interconnection topology apriori. This topology is not static (even when nodes are NOT mobile).
- Redundancy both helps and hurts!
- Trickle's design comes from two areas:
  - Controlled, density-aware flooding algorithms from wireless and multicast networks
  - Epidemic and gossip algorithms for maintaining data consistency in distributed systems.

Trickle Discussion

- Trickle adapts to local network density like controlled flooding, but continually maintains consistency in a manner similar to epidemic algorithms.
- Trickle uses broadcast nature of wireless channel to conserve energy.
- Trickle's exponential times work in reverse of standard backoff. Namely, it defaults to largest time window and decreases only for inconsistency.

Trickle Discussion (cont)

- Trickle leads to energy-efficient, density-aware dissemination by avoiding collisions and suppressing unnecessary retransmissions.
- Trickle suppresses implicitly through nearby nodes that hear a broadcast.

Conclusions

- Two authors also authored original Trickle RFC (author list is impressive).
- Paper puts Trickle into a WSN routing context and does not just define Trickle.
- Trickle algorithm explanation is not concise.
- Discussed well the tension in performance associated with run time choices.
- Paper shows basic performance trends and Maté case study.

References

[Djamaa 2015] Djamaa, B. and Richardson, M. *The Trickle Algorithm: Issues and Solutions.* Cranfield Univesity Reseach Report. January 2015.