Reliable and Real-time Communication in Industrial Wireless Mesh Networks

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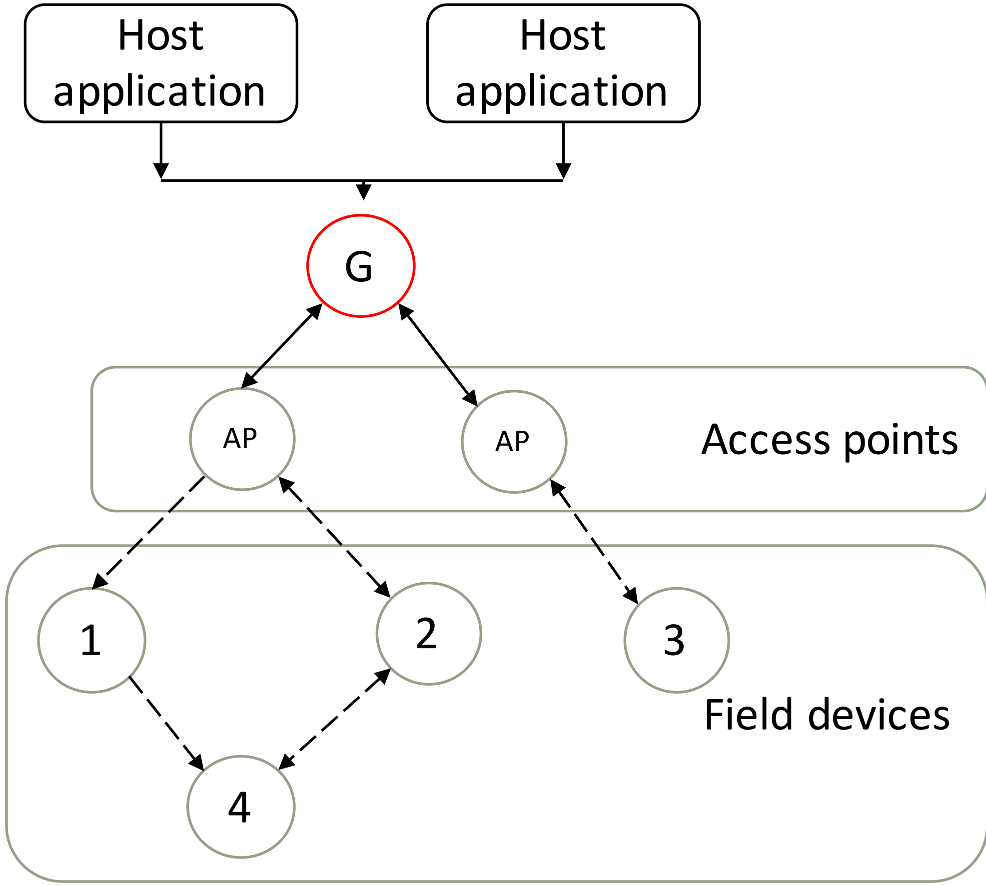
Motivation

- Industrial wireless networks are deployed in harsh conditions
- Devices may be mobile, wireless signal strengths may vary. So network topology will change
- Reliability, real-time performance are very important as missing/delayed data may degrade performance
- WirelessHART standard doesn't specify how to meet these goals

- The paper presents reliable counterparts of three routing graphs, algorithms for constructing them and scheduling them

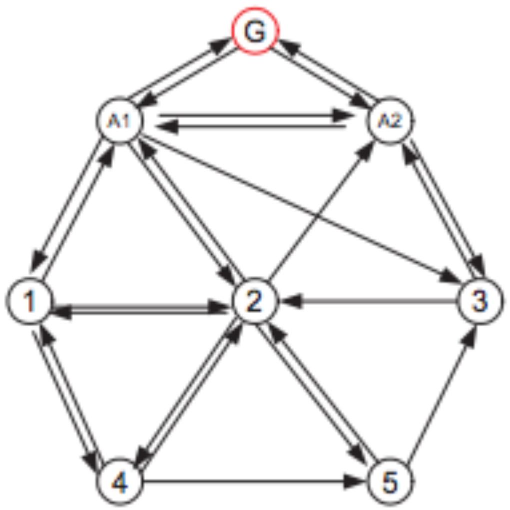
WirelessHART

- Industry standard protocol for wireless communication
- Extension of HART (Highway addressable remote transducer) protocol
- Centralized network management
- Mesh network
- Uses IEEE 802.15.4 in physical layer (which is also used in ZigBee, MiWi, etc)
- Elements in WirelessHART network
  - Wireless Field Devices: Data collection devices
  - Gateway: Connects host applications with field devices
  - Access Point: Connects field devices and Gateway

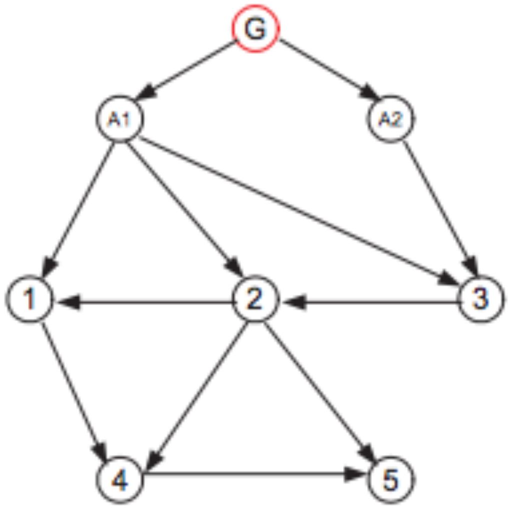


Broadcast graph

- Graph connecting gateway to all devices
- Used to broadcast common configuration, control messages to all nodes
- Broadcast graph is reliable if there are at least two parents for every device in graph



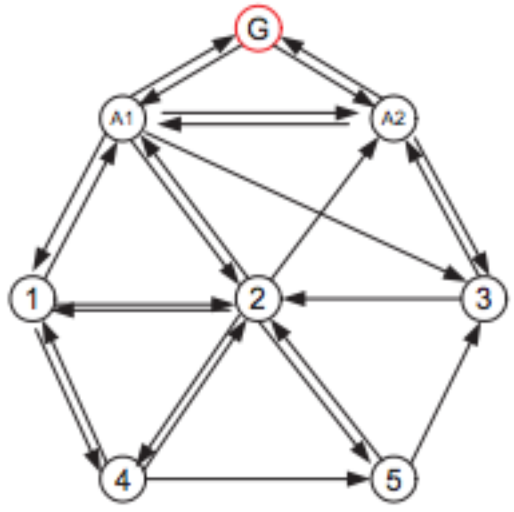
Original Network



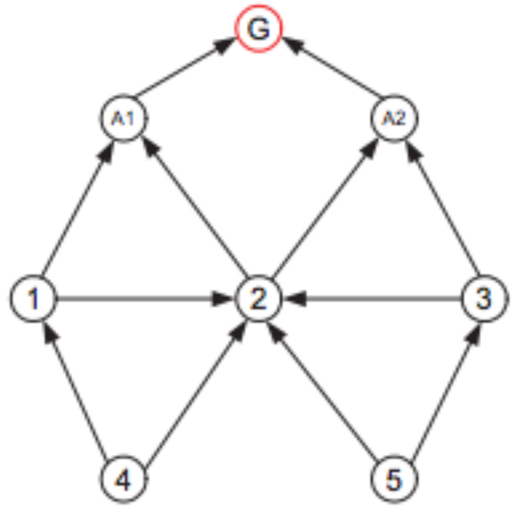
Broadcast graph

Uplink graph

- Graph connecting all devices to gateway
- Used to propagate devices' data periodically to gateway
- Uplink graph is reliable if every device has at least two in-edges



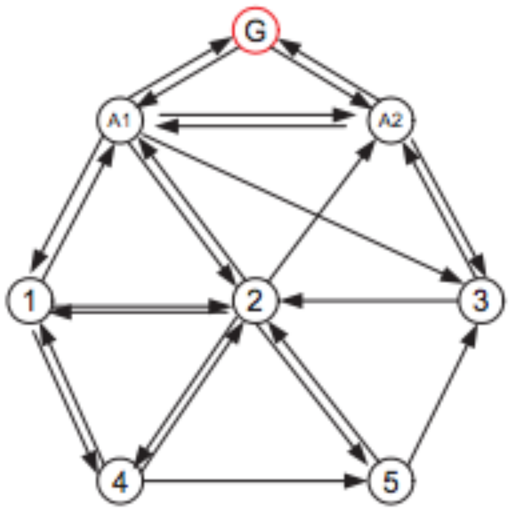
Original Network



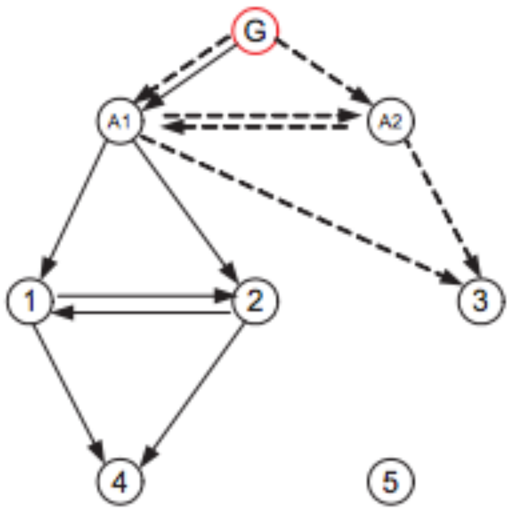
Broadcast graph

Downlink graphs

- One per device
- Used to send unicast messages from gateway to each device
- Downlink graph to a node is reliable if
  - There is one source and one sink
  - Every intermediate node at least two in-edges
  - There is only one cycle of length 2 and each node on cycle is parent of the node



Original Network



Downlink graphs for 3, 4

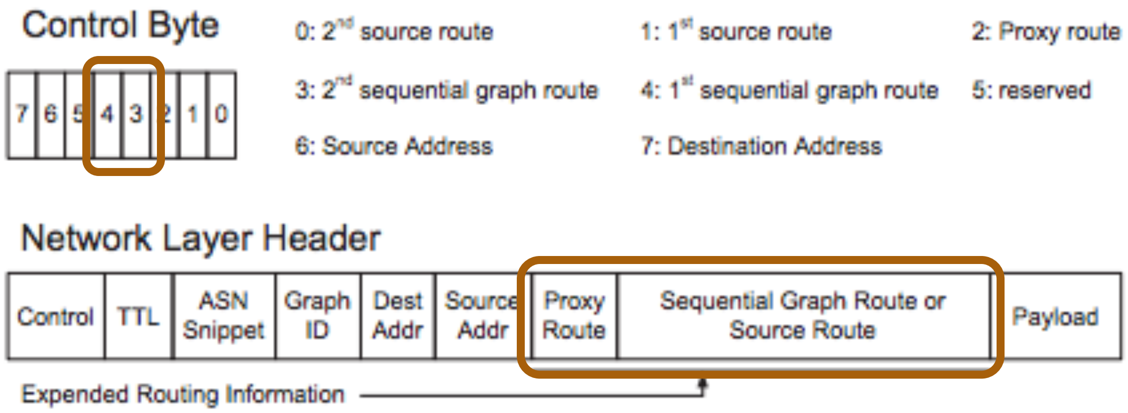
Construction of reliable broadcast graph

- Node is reliable if in-edge degree >=2
- Goals of reliable broadcast graph
  - Maximize number of reliable nodes
  - Minimize average no. of hops from gateway to each node
- Algorithm
  1. Add gateway, access points to set of explored nodes
  2. Select reliable nodes from remaining nodes
  3. For each of these nodes, sort in-edges in ascending order of average no. of hops to gateway
  4. Calculate no. of hops with first two edges
  5. Add node with minimum no. of hops to explored nodes
  6. If there are no reliable nodes at step 2, select node with maximum out-edges to explored nodes
  7. Goto 2
- Complexity $O(|V|^3)$
- Reliable uplink graph is constructed in same way after reversing all edges

Downlink graph

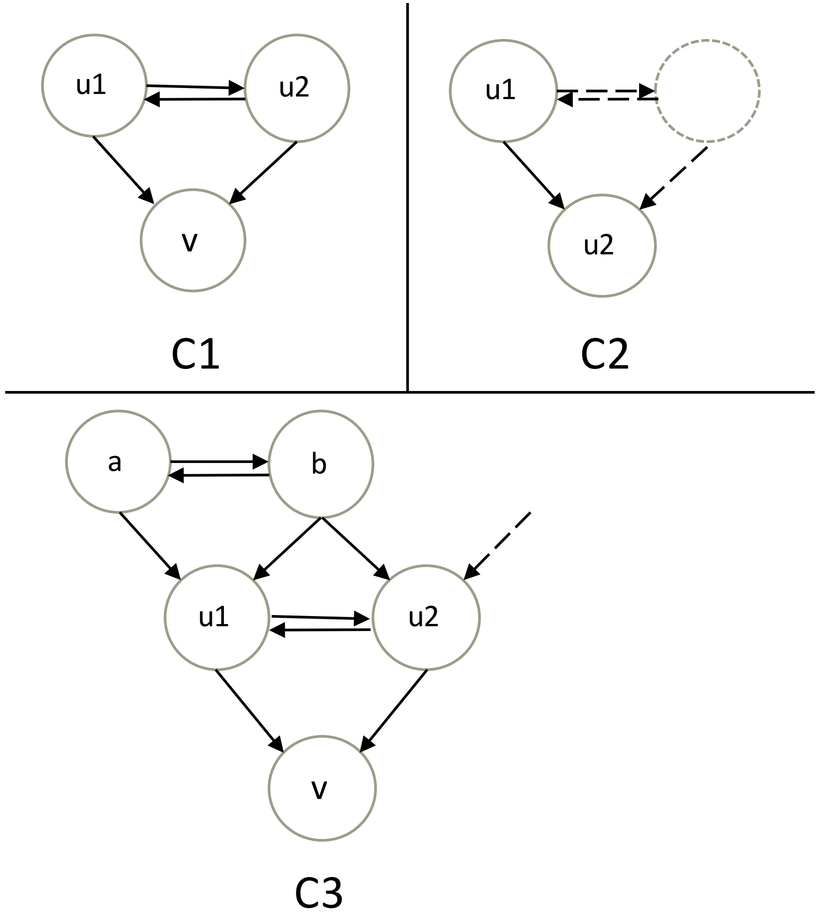
- In WirelessHART standard, there is one reliable downlink graph from gateway to every node
- This results in high configuration overhead as each downlink graph has to go from gateway through all intermediate nodes to the destination node

- In Scalable reliable downlink routing (SRDR), each node contains a small local graph
- Reliable downlink graph for each node can be obtained by assembling intermediate nodes' local graphs
- To support SRDR, WirelessHART is extended



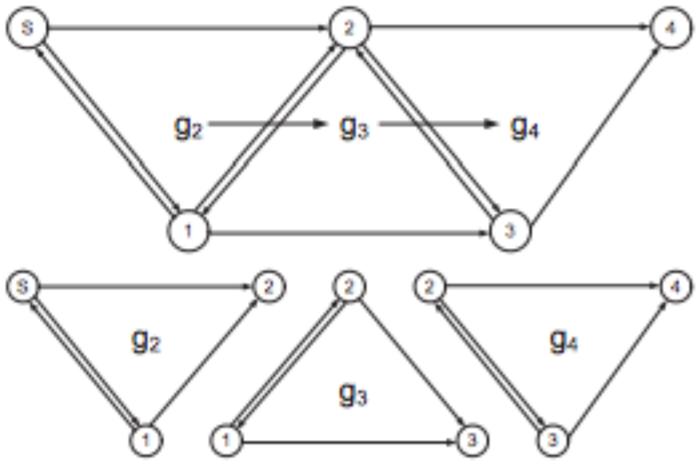
Constructing reliable downlink routes

- Routes for gateway, access points are already known, and so are added to “nodes with known routes” list
- Constraints when constructing routes for node v
  - C1: v has at least two parents u_1, u_2, and they form a cycle
  - C2: u_1 is u_2’s parent in u_2’s local downlink graph
  - C3: u_2 has at least one parent from the cycle in G_{u1}
- For each node, calculate average hops for every edge pair and select edge pairs satisfying C1 and (C2 or C3) with minimum average hops.
- If C1 ^ C2 is satisfied, downlink route of v is R(v) = R(u2) -> g(v)
- If C1 ^ C3 is satisfied, downlink route of v is R(v) = R(u1) -> g(v)
- If constraints are not satisfied, a node with two parents from known list with minimum average latency is selected



SRDR - Optimized

- In basic SRDR, routing is strictly according to ordered graph list
- But when each node can keep graph information to multiple destinations, closest node can be chosen for routing
- When packet arrives at a node, instead of using earliest graph ID, ordered graph list is searched backward and first graph ID that is stored in its routing table is selected
- If this routing is successful, at the next node, all graph IDs up to current ID are removed



Device/link failure recovery

- WirelessHART has network maintenance commands which can be used to notify Network Manager of communication statistics, signal strengths, path/routing failure
- Recovery includes finding nodes which are still reliable after network topology change and constructing network graphs again
- Broadcast graph and Uplink graph can be easily constructed starting from the set of reliable nodes
- Construction of downlink graph is more difficult

Communication schedule, channel management

- Devices specify bandwidth requirements, Network Manager allocates timeslots
- WirelessHART constraints
  - 16 maximum concurrent active channels
  - Each device can only be scheduled to transmit/receive in one time slot
  - Simultaneous transmissions are allowed in shared timeslot
  - On multi-hop path, early hops must be scheduled first
  - Practical sample rates are 2^n sec ($-2 <= n <= 9$)

Constructing communication schedule

- Timeslots are allocated in Fastest Sample Rate First policy (FSRF)
- Algorithm:
- For all nodes from fastest sample rates to slowest
  - Schedule primary and retry links for publishing data
  - Schedule primary and retry links for control data
  - If link assignment is not successful, defer bandwidth request for that node
- Primary links are exclusive but retry links are shared
- Link for publishing/control data from a node A to node B is scheduled by allocating intermediate links on path from A to B one by one in depth-first manner
- When there are 2 successors to a node, allocating time-slots for both successors is wasteful as only one is used. So, transmission rate to each of the successors is reduced to half of sample rate and data is sent on both. It is ensured that communication pattern is same as that of original sample rate.

Performance

- Communication overhead is low (less than 2 links per node)
- Reachable nodes count between that of Broadcast tree and Max-reliable Broadcast graph in case of link failures
- Recovery overhead to regain connectivity and reliability are worse than RDG(standard)
- Configuration overhead for downlink graphs is much better than RDG(standard) and is comparable to single shortest path

- By dividing traffic on successors,
  - Scheduling success (no. of successfully scheduled nodes) is vastly improved
  - For lower sampling rates, network utilization is much better

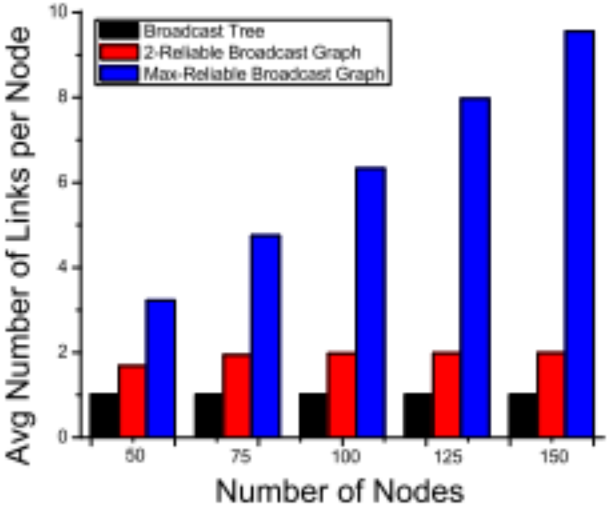


Fig. 18. Configuration overhead in broadcast graphs

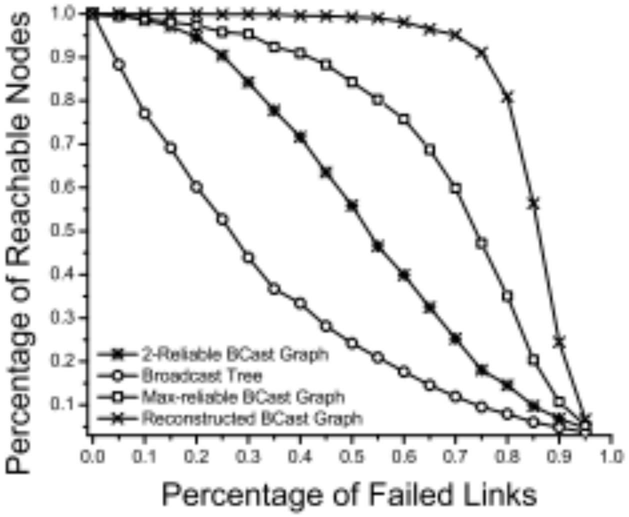


Fig. 19. Reachability in broadcast graphs

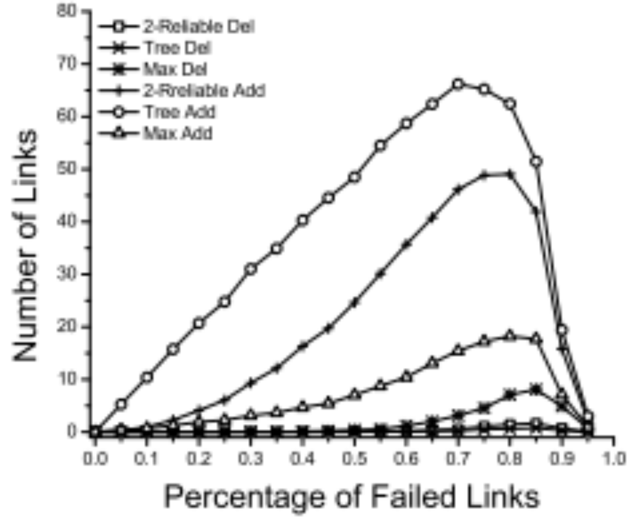


Fig. 20. Recovery overhead to regain connectivity

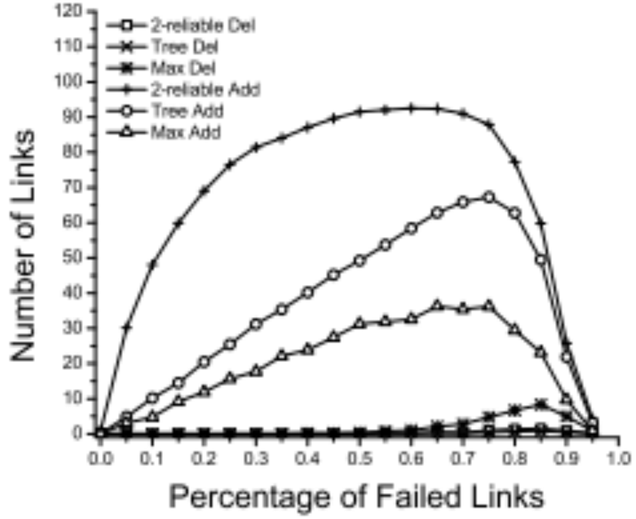


Fig. 21. Recovery overhead to regain reliability

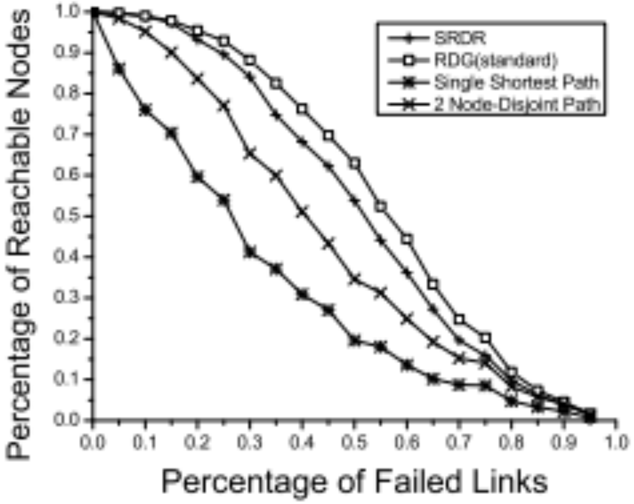


Fig. 22. Reachability in downlink graph

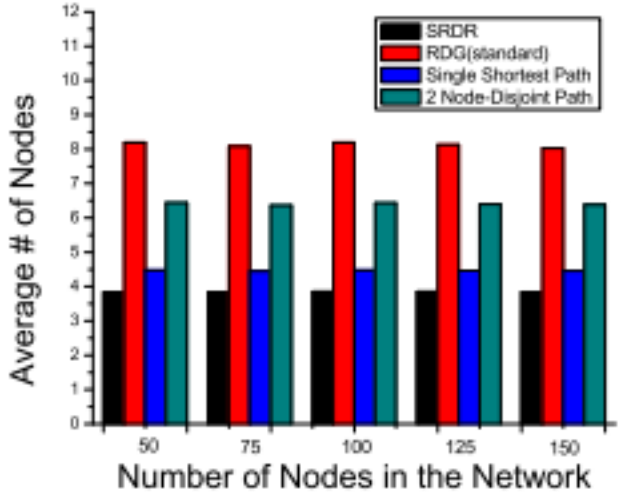


Fig. 23. Average # of nodes per downlink graph

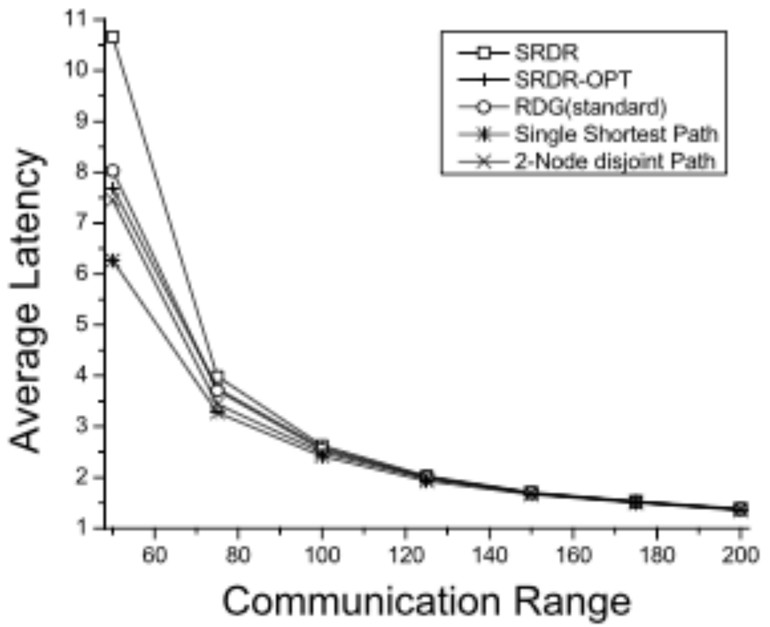


Fig. 11. Average latency vs. Communication range

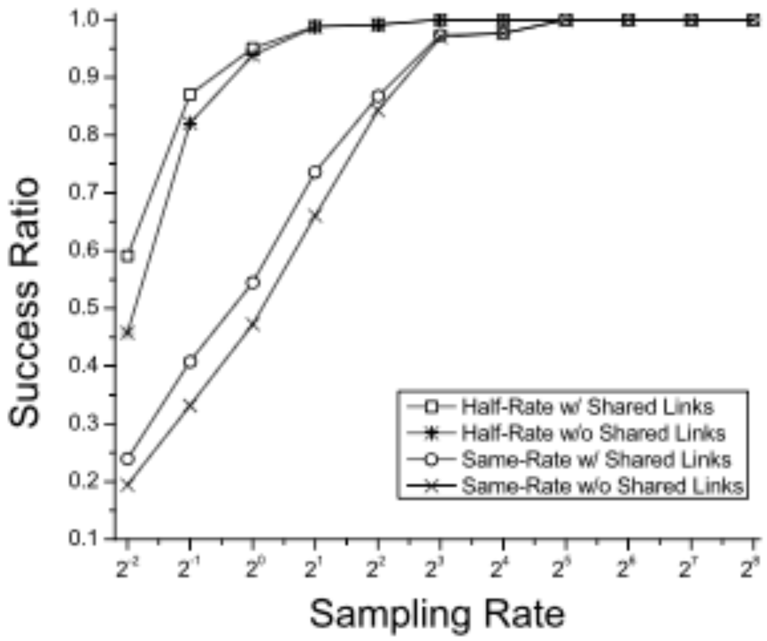


Fig. 12. Success ratio vs. Sample rate

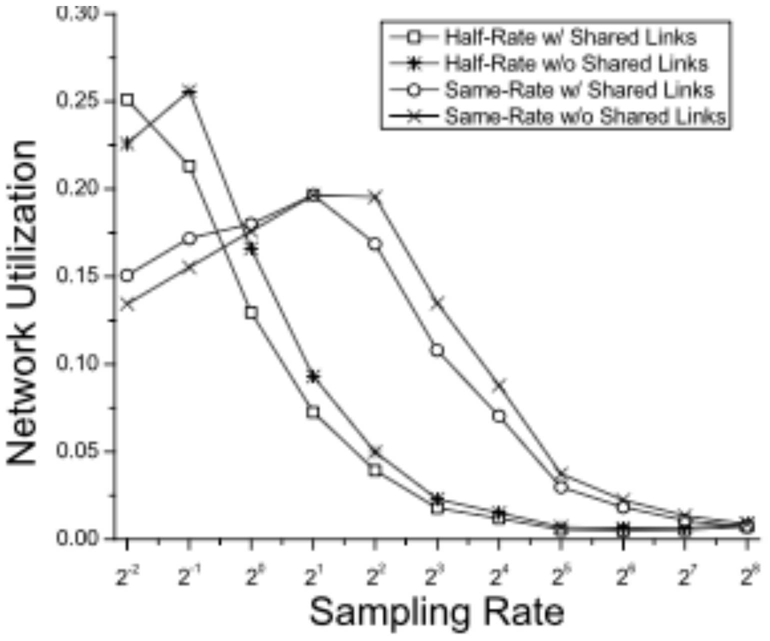


Fig. 13. Network utilization vs. Sample rate

Critical analysis

- When SRDR – OPT is used, during routing, a node may forward data to another node skipping some nodes in the ordered graph list. But the other node may not be ready for receiving at that time slot. This problem is not discussed in the paper.
- Since traffic is divided between two successors of a node, if any of them goes down, shouldn't the communication schedule should be recalculated?

References

- Han, Zhu, Chen, Mok, Nixon, "Reliable and Real-time Communication in Industrial Wireless Mesh Networks" (RTAS 2011)
- Han, Zhu, Chen, Mok, Nixon, "Reliable and Real-time Communication in Industrial Wireless Mesh Networks", Technical Report (http://apps.cs.utexas.edu/tech_reports/reports/tr/TR-1994.pdf)
- http://en.hartcomm.org/