Reliable and Real-Time Communication in Industrial Wireless Mesh Networks

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Presentation Outline

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4. Routing Schemes
5. Routing Graphs
6. Constructing a Reliable Broadcast Graph
7. Constructing a Reliable Uplink Graph
8. Constructing a Reliable Downlink Graph
9. Problem for Reliable Downlink Graphs
10. The SRDR Algorithm
11. Communication Scheduling Constraints
12. Scheduling
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Background

- Industrial automation
- Wireless process control
- ISA, HART, and ZigBee
- Reliable communication
- Real-time communication
- Network management techniques

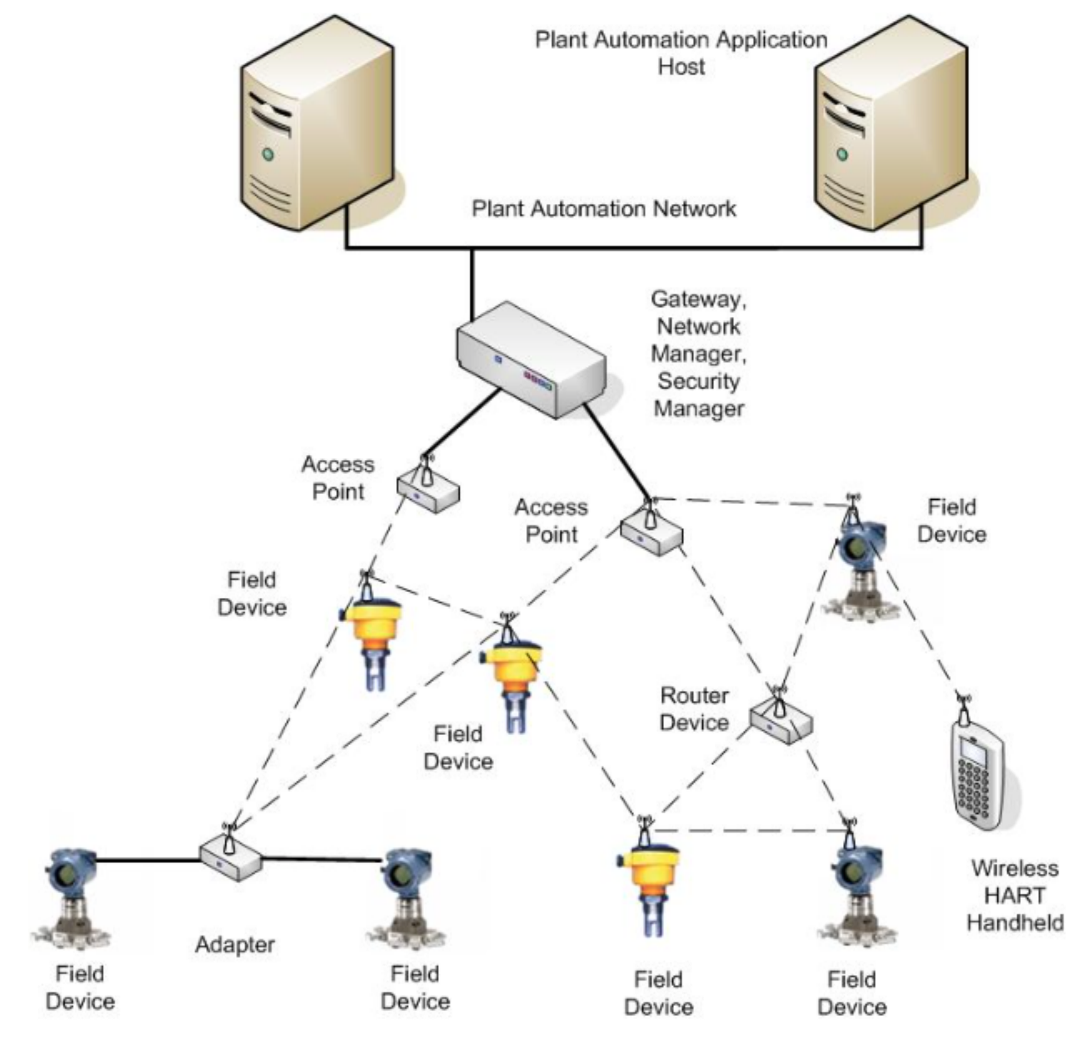
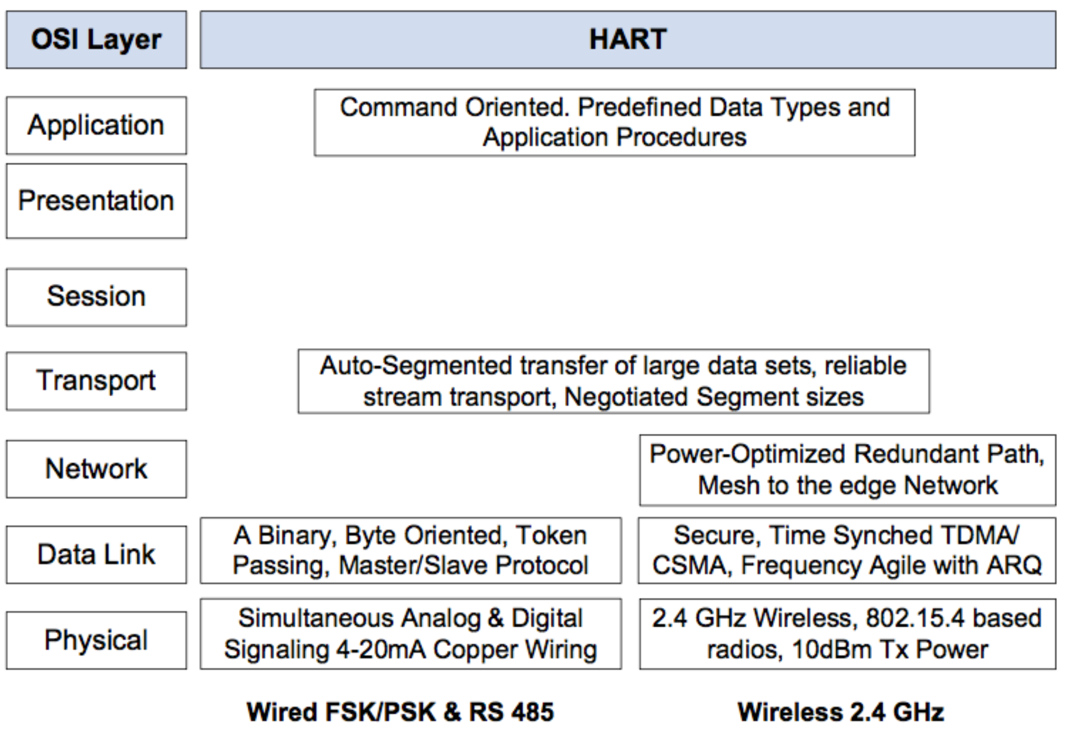


Fig. 2. A typical topology of a WirelessHART mesh network

The WirelessHART Network Architecture

- The architecture is centralized and focuses on the Network Manager
- The Network manager is in control of scheduling and configuring the routing in the network
- The Network manager receives process data from each of the WirelessHART nodes in the network
- Reliability is the key part of the architecture that needs to be guaranteed as well as efficiency



OSI Layer	**HART**	
Application	Command Oriented. Predefined Data Types and Application Procedures	
Presentation		
Session		
Transport	Auto-Segmented transfer of large data sets, reliable stream transport, Negotiated Segment sizes	
Network		Power-Optimized Redundant Path, Mesh to the edge Network
Data Link	A Binary, Byte Oriented, Token Passing, Master/Slave Protocol	Secure, Time Synched TDMA/ CSMA, Frequency Agile with ARQ
Physical	Simultaneous Analog & Digital Signaling 4-20mA Copper Wiring	2.4 GHz Wireless, 802.15.4 based radios, 10dBm Tx Power
	Wired FSK/PSK & RS 485	**Wireless 2.4 GHz**

Fig. 1. The architecture of HART communication protocol

Basic Node Types

- Network Manager: Configures the network, scheduling, and manages communication among WirelessHART devices
- Gateway: Connects host applications to field devices
- Access Point: Attached to the gateway and provides redundant paths between wireless network and the gateway
- Router: Deployed to improve coverage and connectivity
- Field Device: Collects data from a process plant
- Handheld: A portable wirelessHART computer

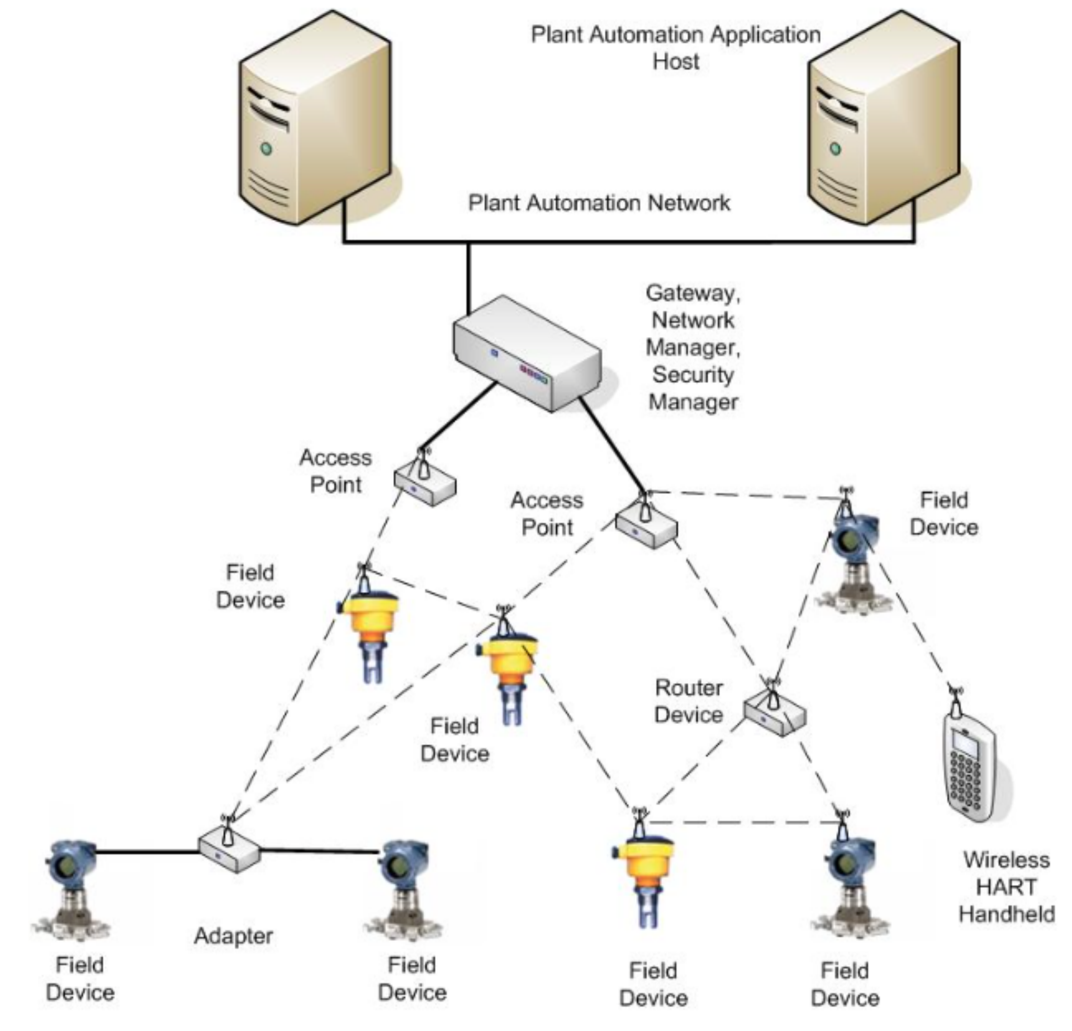


Fig. 2. A typical topology of a WirelessHART mesh network

Routing Schemes

- **Source routing:** all routing decisions made at the source node. This approach does not scale for large industrial networks and leads to large configuration overhead

- **Graph routing:** routing decisions made based on neighbors of the node that the message is currently visiting.

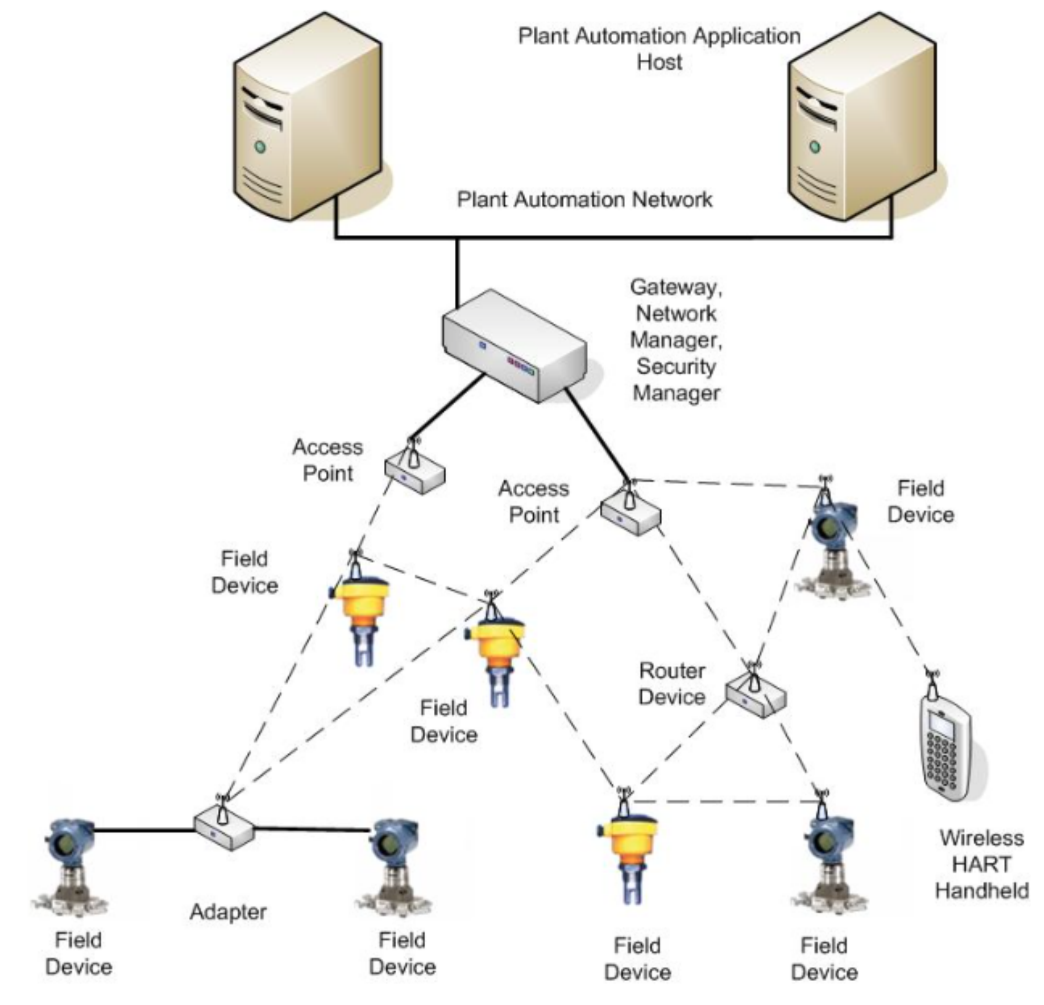
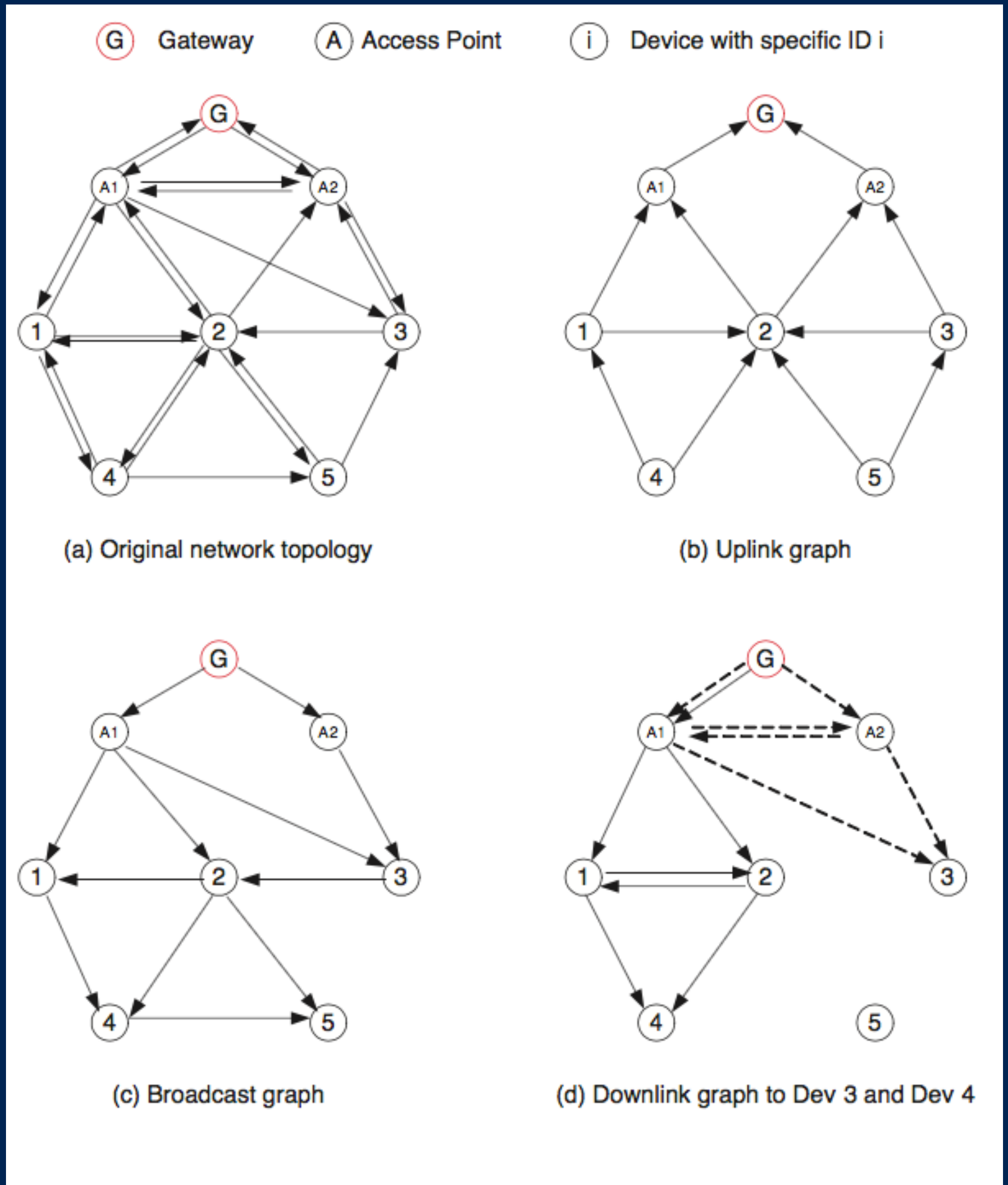


Fig. 2. A typical topology of a WirelessHART mesh network

Routing Graphs

- There are a total of 3 types of routing graphs relevant to the WirelessHart Architecture
- Broadcast routing graph
- Uplink routing graph
- Downlink routing graph



(a) Original network topology

(b) Uplink graph

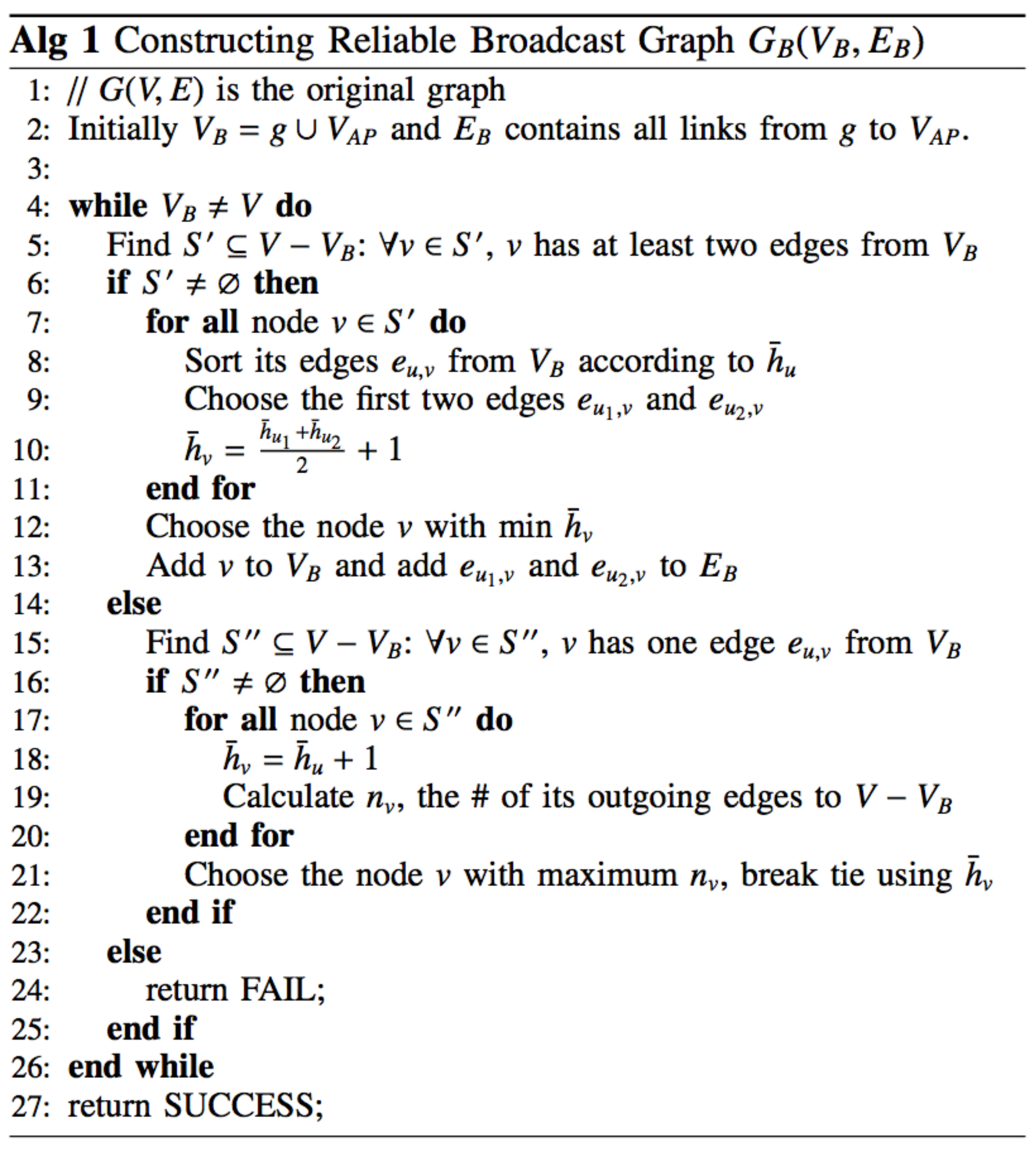
(c) Broadcast graph

(d) Downlink graph to Dev 3 and Dev 4

Fig. 4. Three types of routing graphs

Constructing a Reliable Broadcast Graph

- A node is reliable iff $\delta^{-}_{i} \geq 2$
- $S_B = \{ i \mid \delta^{-}_{i} \geq 2, i \in V \}$
- Maximize $\mid S_B \mid$ to get G_B
- Avg. hops from gateway is h_i
- Maintain V_B of explored nodes
- V_B contains $\{g\} \cup V_{AP}$
- Maintain E_B of explored edges
- Select one node v from V - V_B
- Find S' reliable nodes in V - V_B
- Choose v from S' with minimal average hops
- Add v to V_B
- If no reliable nodes search for S'' one incoming from V_B
- Worse case algorithm complexity $O(\mid V \mid^3)$

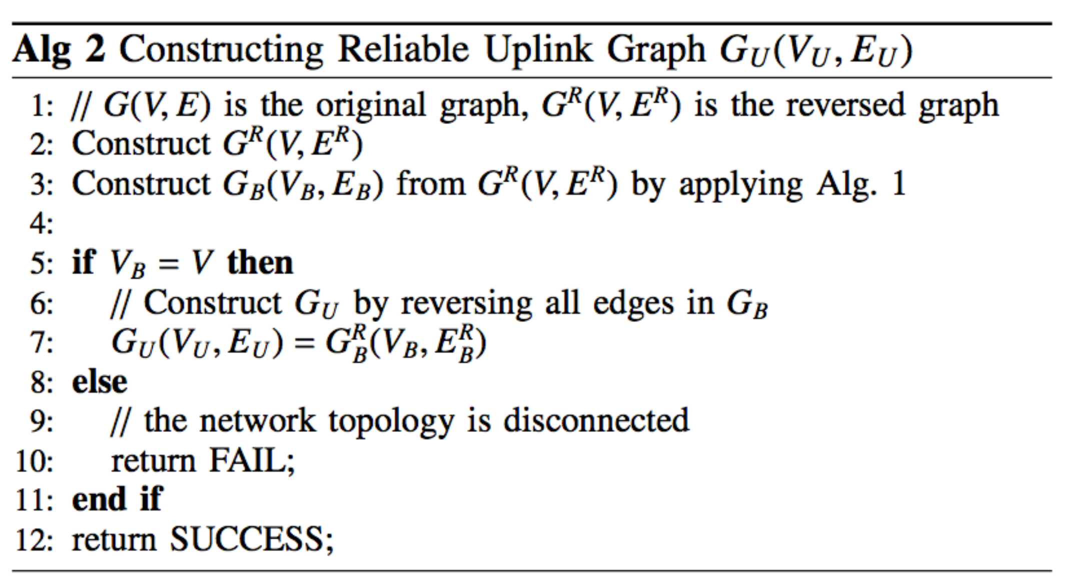


Alg 1 Constructing Reliable Broadcast Graph $G_B(V_B, E_B)$

```
// $G(V, E)$ is the original graph
Initially $V_B = g \cup V_{AP}$ and $E_B$ contains all links from $g$ to $V_{AP}$.

while $V_B \neq V$ do
    Find $S' \subseteq V - V_B$: $\forall v \in S'$, $v$ has at least two edges from $V_B$
    if $S' \neq \emptyset$ then
        for all node $v \in S'$ do
            Sort its edges $e_{u,v}$ from $V_B$ according to $\bar{h}_u$
            Choose the first two edges $e_{u_1,v}$ and $e_{u_2,v}$
            $\bar{h}_v = \frac{\bar{h}_{u_1} + \bar{h}_{u_2}}{2} + 1$
        end for
        Choose the node $v$ with min $\bar{h}_v$
        Add $v$ to $V_B$ and add $e_{u_1,v}$ and $e_{u_2,v}$ to $E_B$
    else
        Find $S'' \subseteq V - V_B$: $\forall v \in S''$, $v$ has one edge $e_{u,v}$ from $V_B$
        if $S'' \neq \emptyset$ then
            for all node $v \in S''$ do
                $\bar{h}_v = \bar{h}_u + 1$
                Calculate $n_v$, the # of its outgoing edges to $V - V_B$
            end for
            Choose the node $v$ with maximum $n_v$, break tie using $\bar{h}_v$
        end if
    else
        return FAIL;
    end if
end while
return SUCCESS;
```

Constructing a Reliable Uplink Graph

- The direction of information flow is reversed in the uplink scenario
- Devices send information to the gateway in the network graph
- All nodes are essentially broadcasting to the gateway
- All nodes should be apart of the uplink graph, otherwise an error has occurred
- Worse case algorithm complexity $O(|V|^3)$. This is bounded by the time needed to produce the broadcast graph

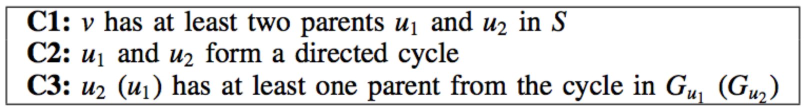


Alg 2 Constructing Reliable Uplink Graph $G_U(V_U, E_U)$

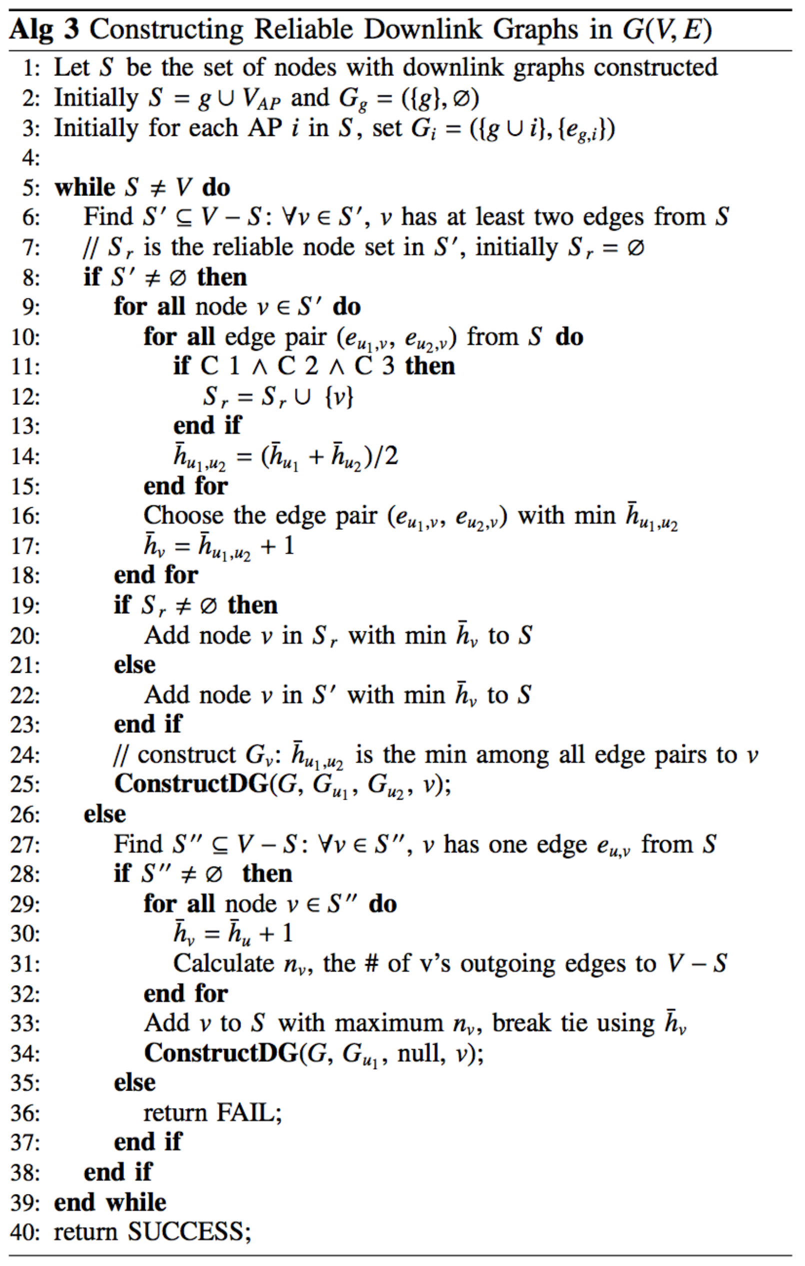
```
// $G(V, E)$ is the original graph, $G^R(V, E^R)$ is the reversed graph
Construct $G^R(V, E^R)$
Construct $G_B(V_B, E_B)$ from $G^R(V, E^R)$ by applying Alg. 1

if $V_B = V$ then
    // Construct $G_U$ by reversing all edges in $G_B$
    $G_U(V_U, E_U) = G_B^R(V_B, E_B^R)$
else
    // the network topology is disconnected
    return FAIL;
end if
return SUCCESS;
```

Constructing a Reliable Downlink Graph

- WirelessHART standard algorithm
- Only involves part of the nodes in the full network graph, *G(V, E)*
- Exactly one cycle in the downlink graph of length 2 between the two parents of the node for which the graph is being constructed
- Maximize # of nodes in the downlink graph
- Minimize the graph's average number of hops from the gateway
- Maintain *S*, set of nodes whose reliable downlink graphs have already been constructed



C1: v has at least two parents u_1 and u_2 in S
C2: u_1 and u_2 form a directed cycle
C3: u_2 (u_1) has at least one parent from the cycle in G_{u_1} (G_{u_2})



Alg 3 Constructing Reliable Downlink Graphs in $G(V, E)$

```
Let $S$ be the set of nodes with downlink graphs constructed
Initially $S = g \cup V_{AP}$ and $G_g = (\{g\}, \varnothing)$
Initially for each AP $i$ in $S$, set $G_i = (\{g \cup i\}, \{e_{g,i}\})$

while $S \neq V$ do
    Find $S' \subseteq V - S$: $\forall v \in S'$, $v$ has at least two edges from $S$
    // $S_r$ is the reliable node set in $S'$, initially $S_r = \varnothing$
    if $S' \neq \varnothing$ then
        for all node $v \in S'$ do
            for all edge pair $(e_{u_1,v}, e_{u_2,v})$ from $S$ do
                if C 1 $\wedge$ C 2 $\wedge$ C 3 then
                    $S_r = S_r \cup \{v\}$
                end if
                $\bar{h}_{u_1,u_2} = (\bar{h}_{u_1} + \bar{h}_{u_2})/2$
            end for
            Choose the edge pair $(e_{u_1,v}, e_{u_2,v})$ with min $\bar{h}_{u_1,u_2}$
            $\bar{h}_v = \bar{h}_{u_1,u_2} + 1$
        end for
        if $S_r \neq \varnothing$ then
            Add node $v$ in $S_r$ with min $\bar{h}_v$ to $S$
        else
            Add node $v$ in $S'$ with min $\bar{h}_v$ to $S$
        end if
        // construct $G_v$: $\bar{h}_{u_1,u_2}$ is the min among all edge pairs to $v$
        ConstructDG($G$, $G_{u_1}$, $G_{u_2}$, $v$);
    else
        Find $S'' \subseteq V - S$: $\forall v \in S''$, $v$ has one edge $e_{u,v}$ from $S$
        if $S'' \neq \varnothing$ then
            for all node $v \in S''$ do
                $\bar{h}_v = \bar{h}_u + 1$
                Calculate $n_v$, the # of v's outgoing edges to $V - S$
            end for
            Add $v$ to $S$ with maximum $n_v$, break tie using $\bar{h}_v$
            ConstructDG($G$, $G_{u_1}$, null, $v$);
        else
            return FAIL;
        end if
    end if
end while
return SUCCESS;
```

Difficulty in Producing Completely Reliable Graphs

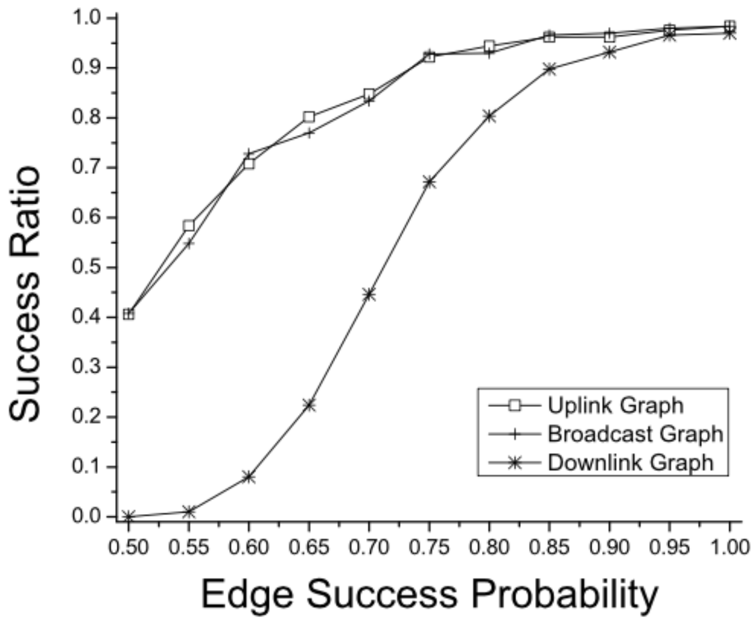


Fig. 5. Success ratio vs. Edge success probability

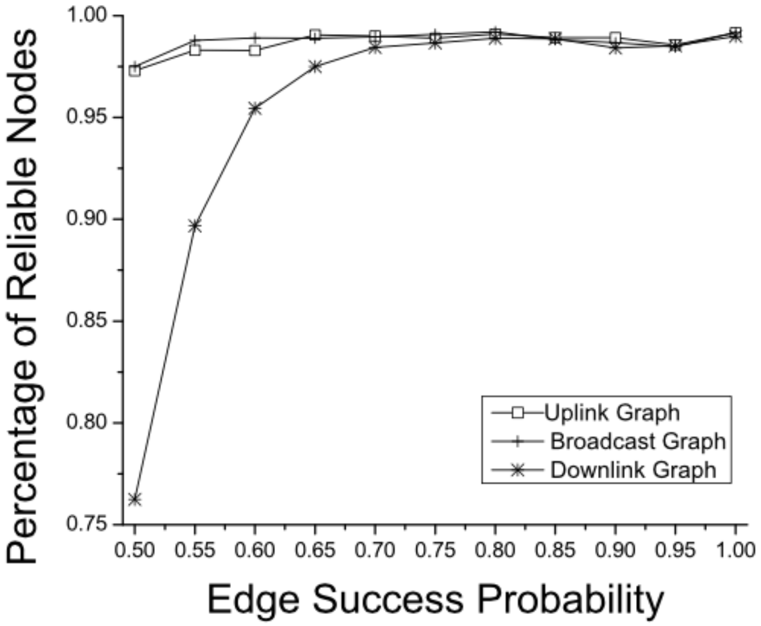


Fig. 6. Percentage of reliable nodes

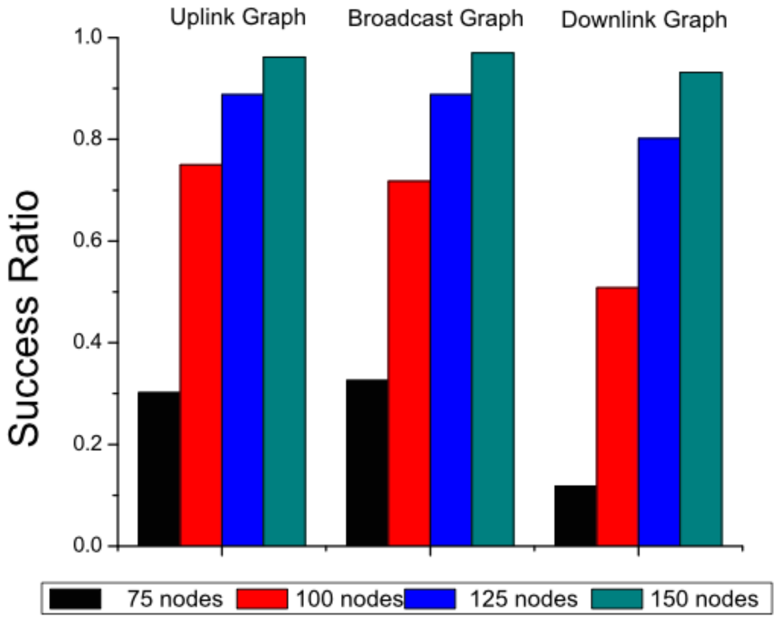


Fig. 7. Success ratio vs. Network density

Problem for Reliable Downlink Graphs

- The previous approach is not scalable because it introduces high configuration overhead
- Traversing a sequence of local known graphs seems more logical
- Sequential-Reliable-Downlink-Routing (SRDR)
- Each node maintains a small local graph to maintain reliable routing from its parents
- Downlink graph can be constructed by assembling intermediate local graphs based on a given order
- This allows existing device configurations to be reused

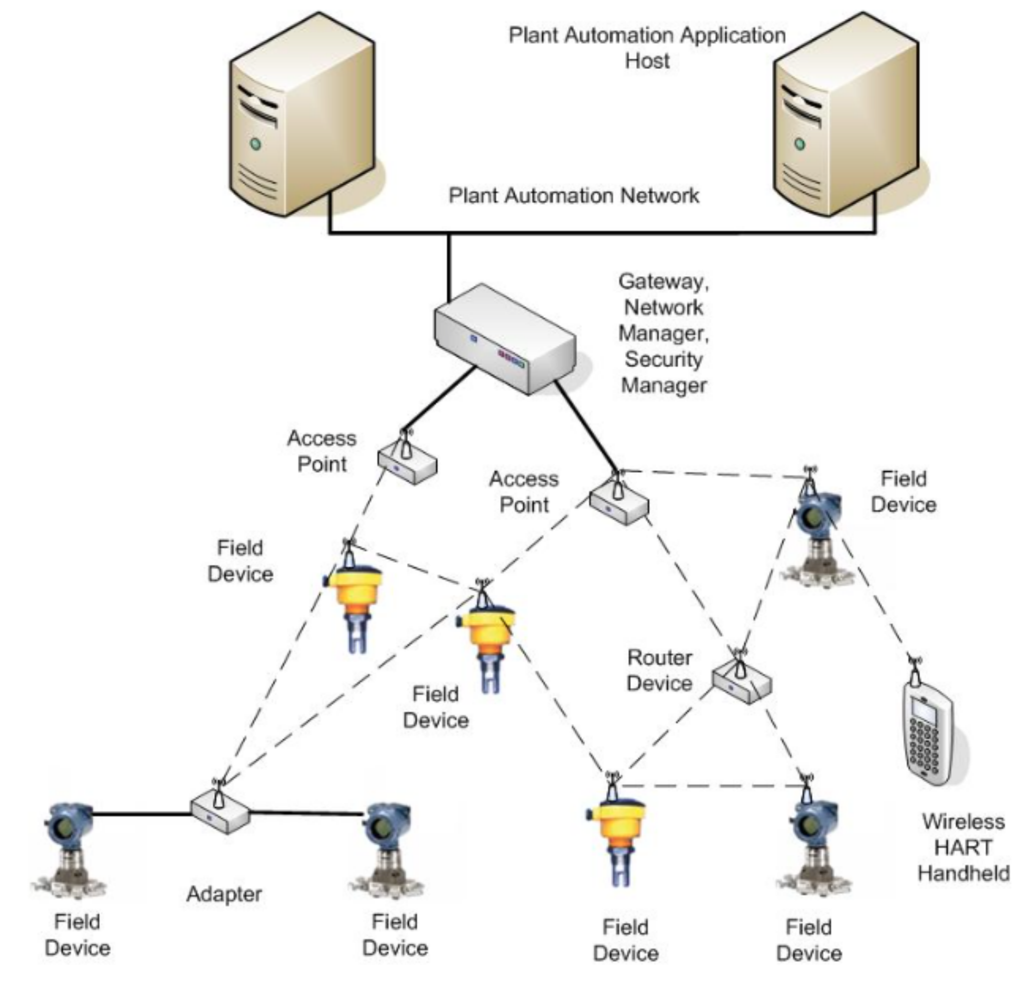
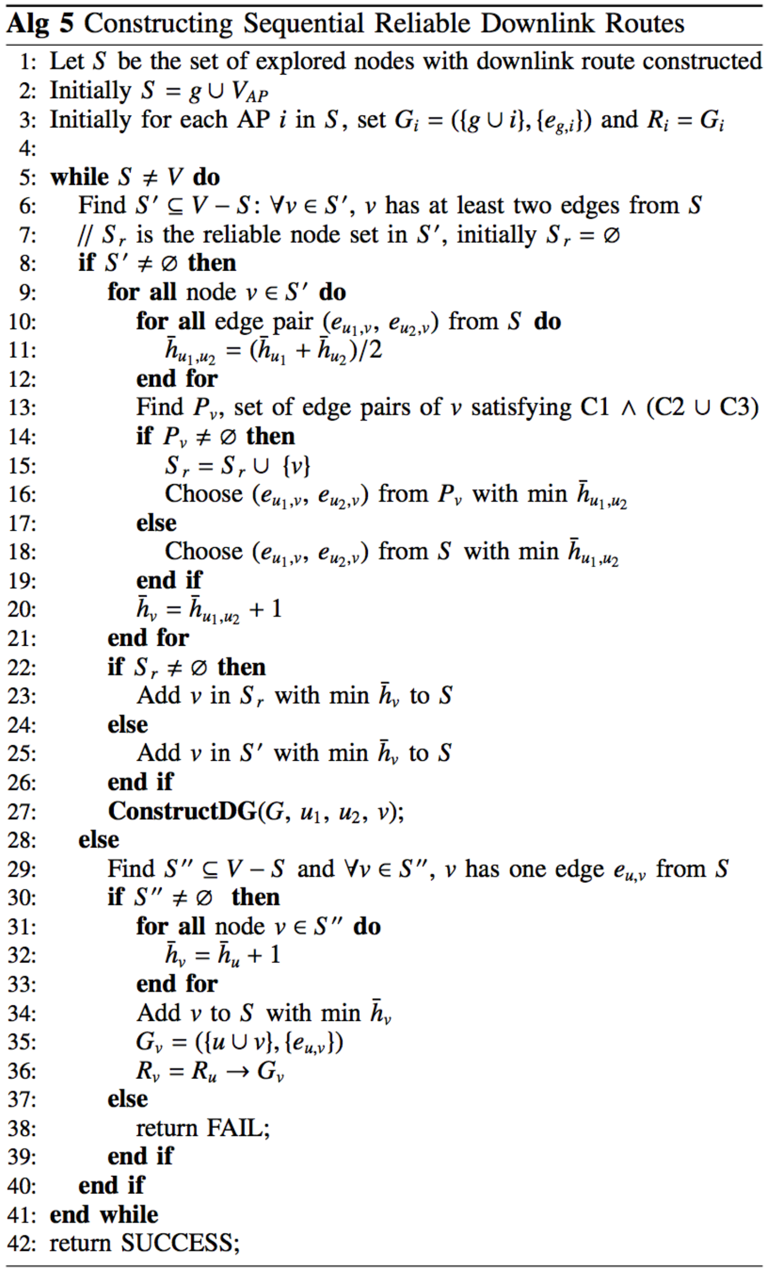


Fig. 2. A typical topology of a WirelessHART mesh network

The SRDR Algorithm

- Reserved bits 3-4 of the control byte in the network layer header indicate the presence of SRDR routing fields
- Source routing option field stores the ordered local graph list
- Routing module modified to support SRDR
- SRDR-opt allows nodes along the path to select shortcuts if available and replace graph ID information



Alg 5 Constructing Sequential Reliable Downlink Routes

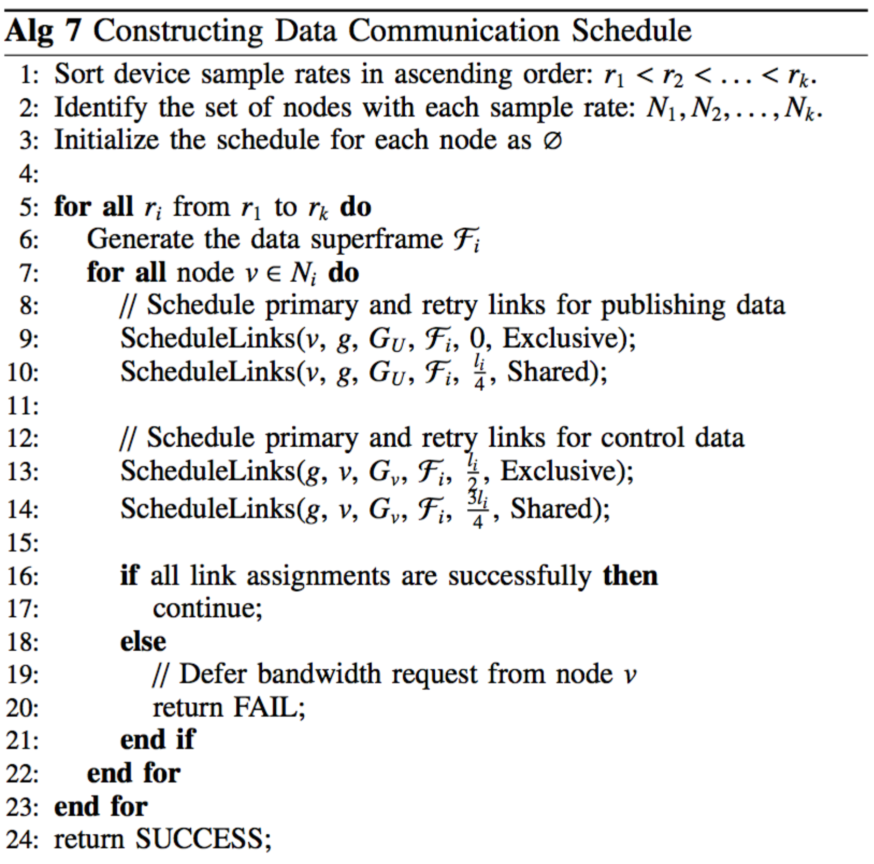
```
Let $S$ be the set of explored nodes with downlink route constructed
Initially $S = g \cup V_{AP}$
Initially for each AP $i$ in $S$, set $G_i = (\{g \cup i\}, \{e_{g,i}\})$ and $R_i = G_i$

while $S \neq V$ do
    Find $S' \subseteq V - S$: $\forall v \in S'$, $v$ has at least two edges from $S$
    // $S_r$ is the reliable node set in $S'$, initially $S_r = \varnothing$
    if $S' \neq \varnothing$ then
        for all node $v \in S'$ do
            for all edge pair $(e_{u_1,v}, e_{u_2,v})$ from $S$ do
                $\bar{h}_{u_1,u_2} = (\bar{h}_{u_1} + \bar{h}_{u_2})/2$
            end for
            Find $P_v$, set of edge pairs of $v$ satisfying C1 $\wedge$ (C2 $\cup$ C3)
            if $P_v \neq \varnothing$ then
                $S_r = S_r \cup \{v\}$
                Choose $(e_{u_1,v}, e_{u_2,v})$ from $P_v$ with min $\bar{h}_{u_1,u_2}$
            else
                Choose $(e_{u_1,v}, e_{u_2,v})$ from $S$ with min $\bar{h}_{u_1,u_2}$
            end if
            $\bar{h}_v = \bar{h}_{u_1,u_2} + 1$
        end for
        if $S_r \neq \varnothing$ then
            Add $v$ in $S_r$ with min $\bar{h}_v$ to $S$
        else
            Add $v$ in $S'$ with min $\bar{h}_v$ to $S$
        end if
        ConstructDG($G$, $u_1$, $u_2$, $v$);
    else
        Find $S'' \subseteq V - S$ and $\forall v \in S''$, $v$ has one edge $e_{u,v}$ from $S$
        if $S'' \neq \varnothing$ then
            for all node $v \in S''$ do
                $\bar{h}_v = \bar{h}_u + 1$
            end for
            Add $v$ to $S$ with min $\bar{h}_v$
            $G_v = (\{u \cup v\}, \{e_{u,v}\})$
            $R_v = R_u \rightarrow G_v$
        else
            return FAIL;
        end if
    end if
end while
return SUCCESS;
```

Communication Schedule Constraints

- The maximum number of concurrent active channels is 16
- Each device can only be scheduled to TX/RX once in a slot
- Multiple devices can compete to transmit to the same device simultaneously (in shared timeslot)
- On a multi-hop path, early hops must be scheduled first
- The practical sample rates are defined from 250 ms to 32 s
- Timeslot duration is 10 ms

Scheduling

- Use the concept of a super frame to group a sequence of consecutive timeslots
- Data superframes: Used to support data transmissions
- Management superframes: Used to support exchanging network management messages
- The # of data superframes is determined by the number of different sampling rates in the network
- Global matrix for timeslots and channels
- Timeslots in the matrix can be unused, exclusive, shared, or reserved
- Schedules are distributed to devices in the network
- Management schedule construction follows the same approach



Alg 7 Constructing Data Communication Schedule

```
Sort device sample rates in ascending order: $r_1 < r_2 < \ldots < r_k$.
Identify the set of nodes with each sample rate: $N_1, N_2, \ldots, N_k$.
Initialize the schedule for each node as $\emptyset$

for all $r_i$ from $r_1$ to $r_k$ do
    Generate the data superframe $\mathcal{F}_i$
    for all node $v \in N_i$ do
        // Schedule primary and retry links for publishing data
        ScheduleLinks($v$, $g$, $G_U$, $\mathcal{F}_i$, 0, Exclusive);
        ScheduleLinks($v$, $g$, $G_U$, $\mathcal{F}_i$, $\frac{l_i}{4}$, Shared);

        // Schedule primary and retry links for control data
        ScheduleLinks($g$, $v$, $G_v$, $\mathcal{F}_i$, $\frac{l_i}{2}$, Exclusive);
        ScheduleLinks($g$, $v$, $G_v$, $\mathcal{F}_i$, $\frac{3l_i}{4}$, Shared);

        if all link assignments are successfully then
            continue;
        else
            // Defer bandwidth request from node $v$
            return FAIL;
        end if
    end for
end for
return SUCCESS;
```

Experiment Assumptions

- Open field, line-of-sight experimental scenarios
- The simulation area is fixed at 450 m x 450 m
- Default device communication distance is 100 m
- No edge between a pair of nodes if they are not in each other’s communication range

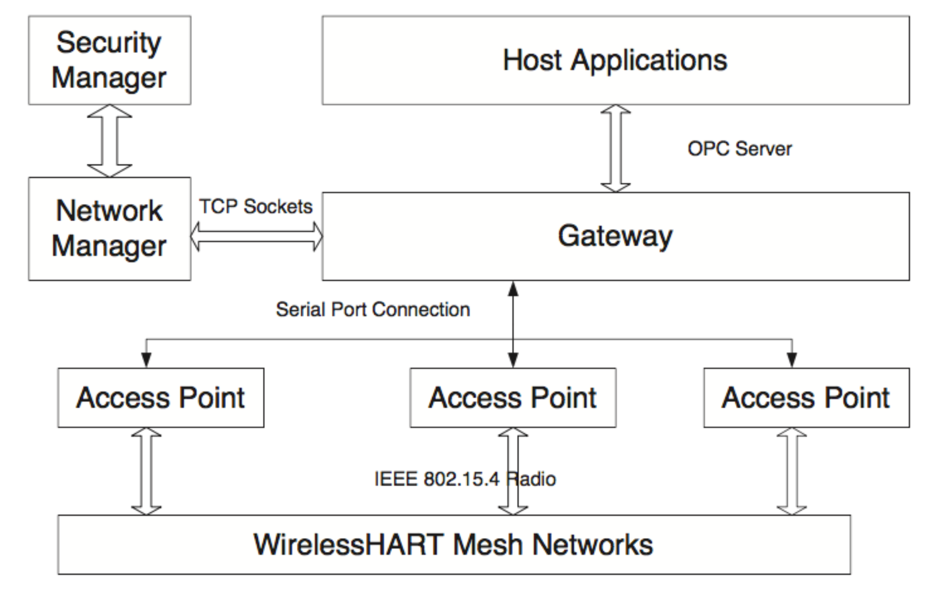


Fig. 12. Architecture of the complete WirelessHART communication system

Configuration Overhead

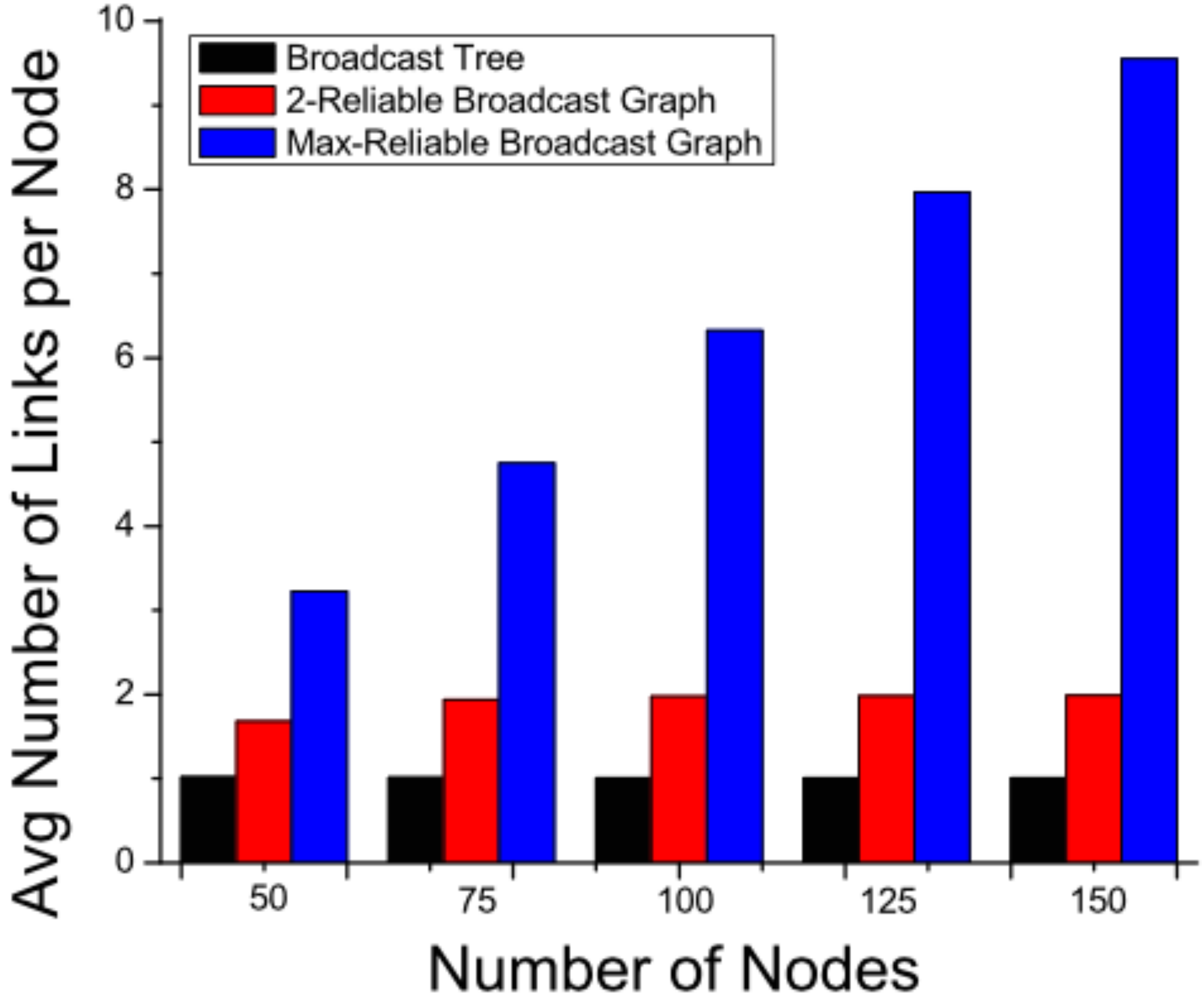


Fig. 18. Configuration overhead in broadcast graphs

Reachability

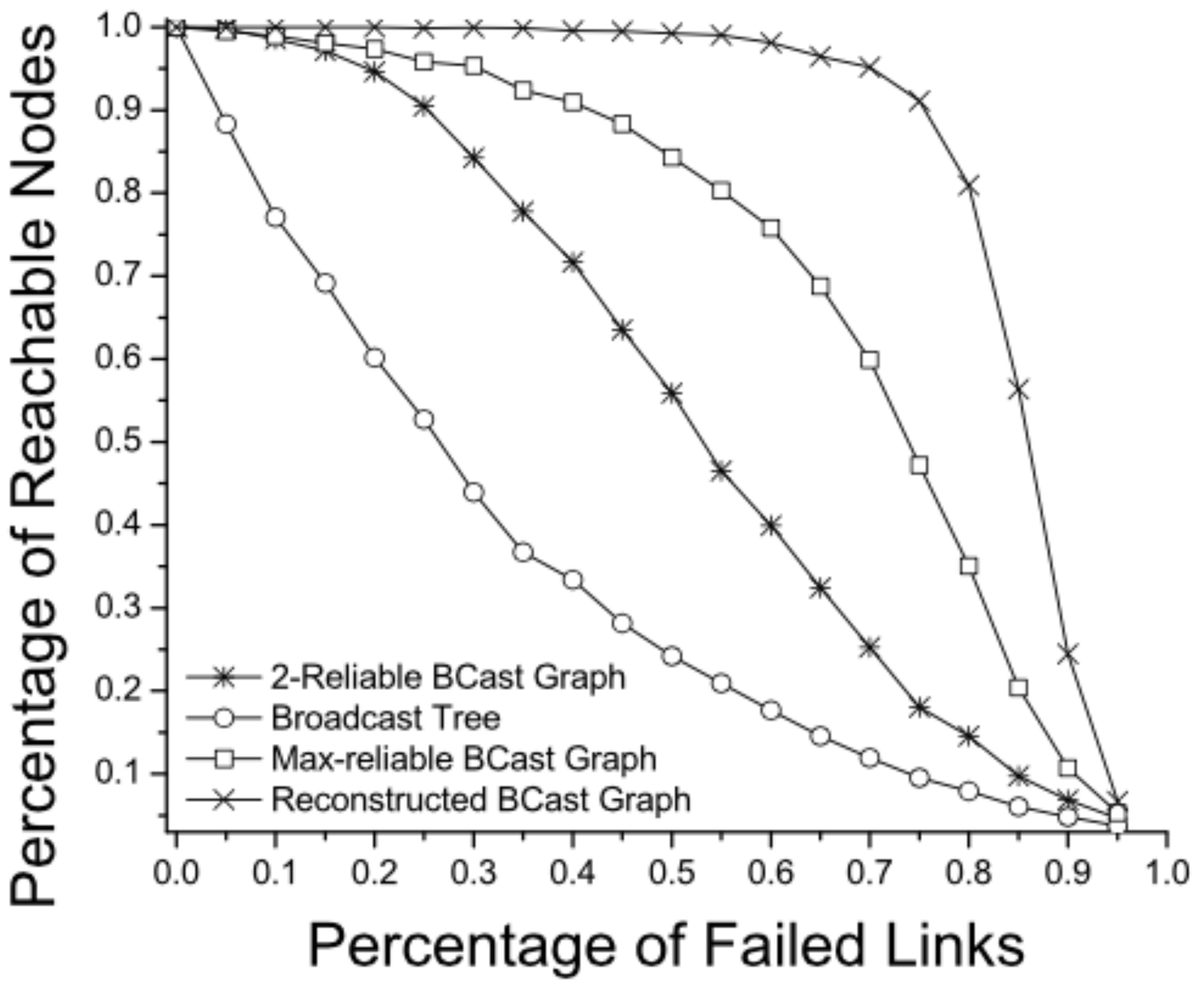


Fig. 19. Reachability in broadcast graphs

Recovery Overhead for Connectivity

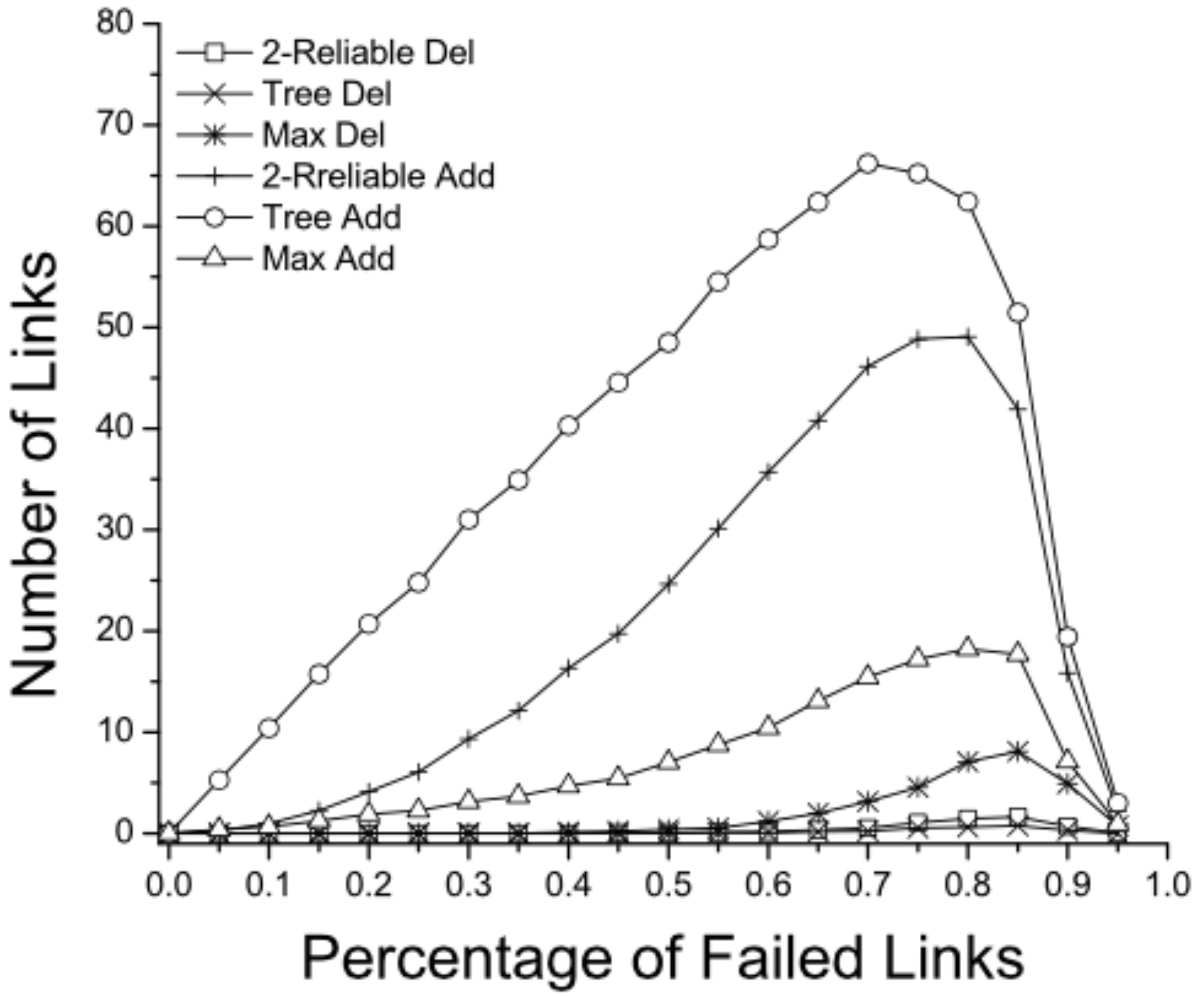


Fig. 20. Recovery overhead to regain connectivity

Recovery Overhead for Reliability Properties

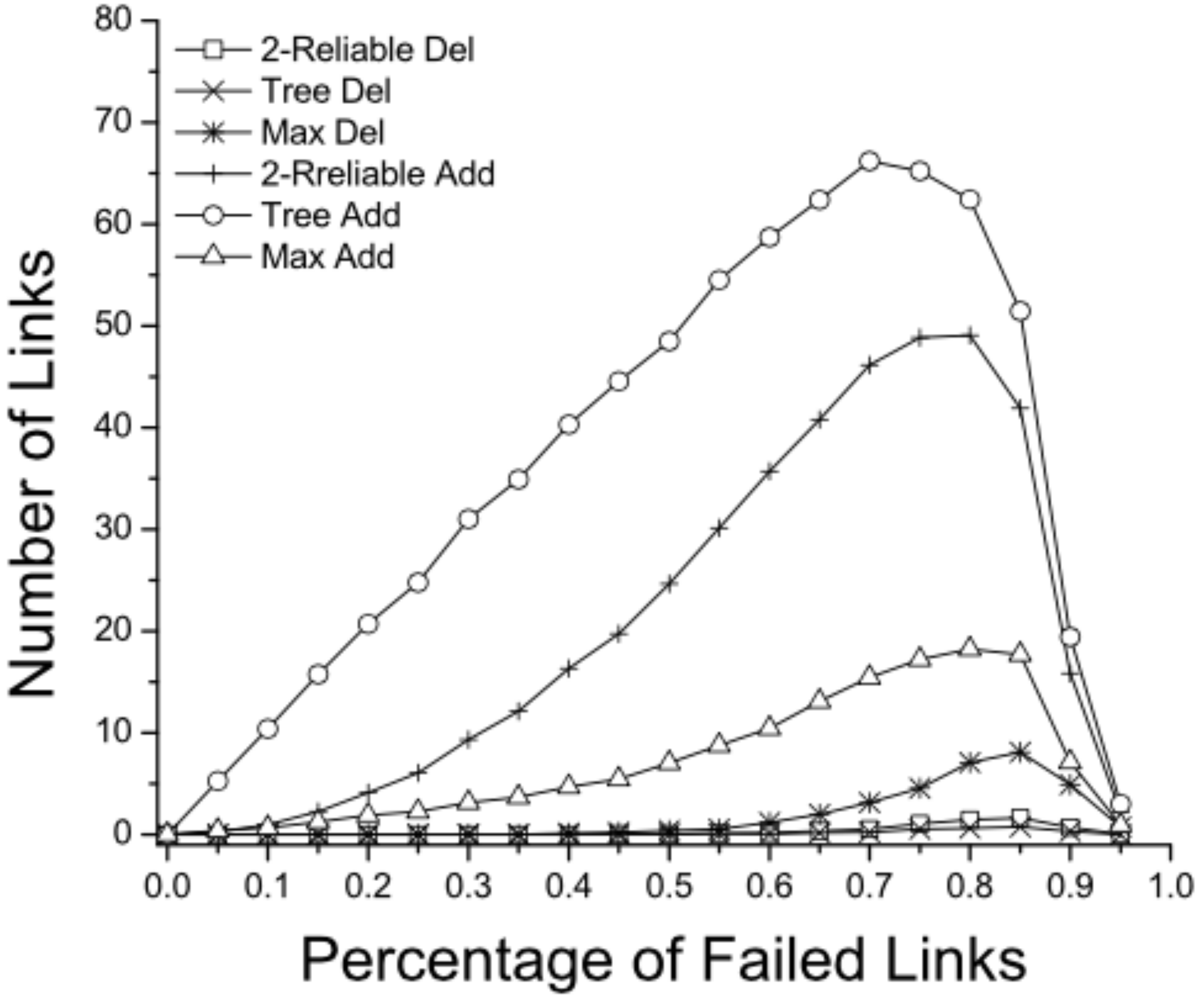


Fig. 20. Recovery overhead to regain connectivity

Reachability in Downlink Graph

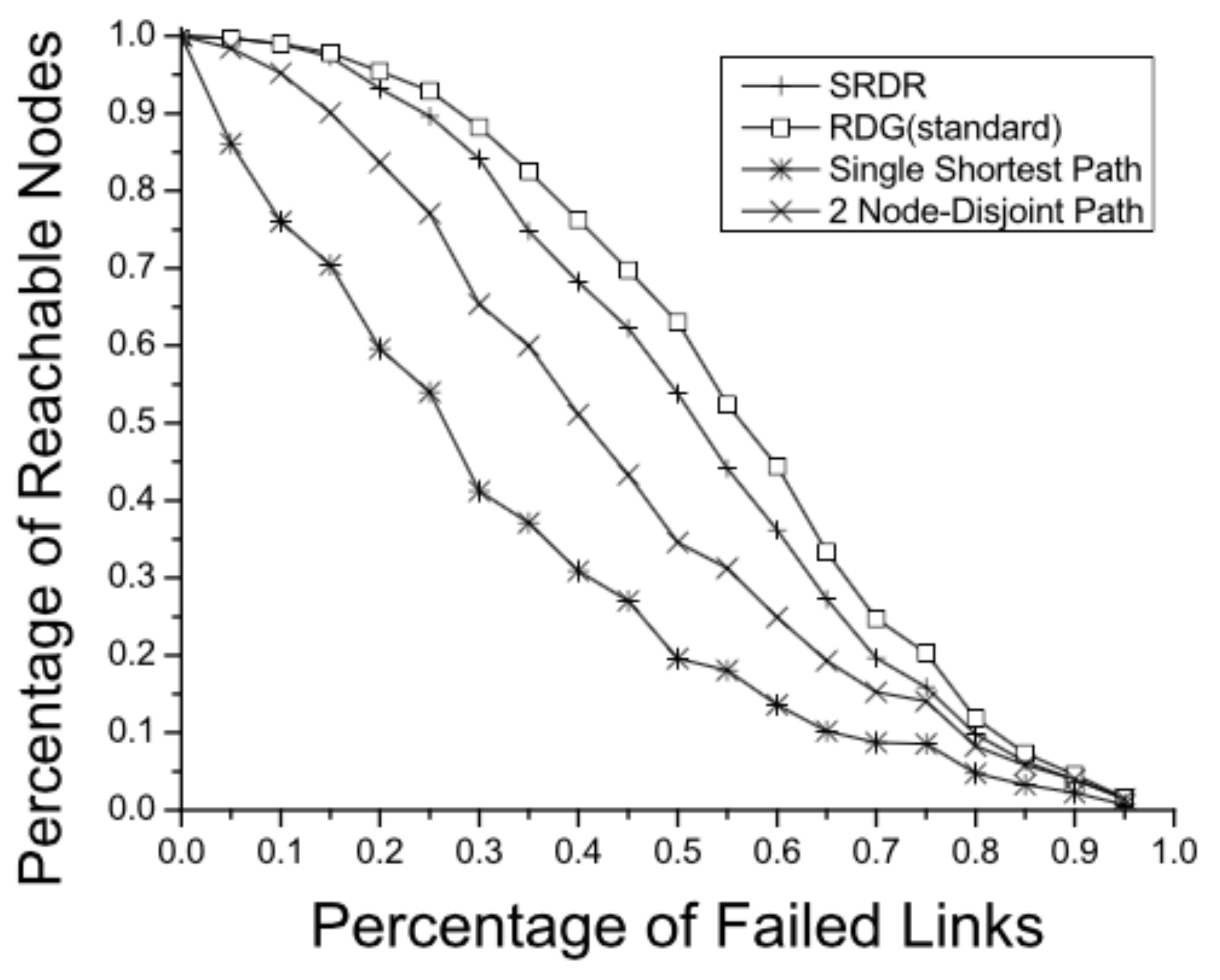


Fig. 22. Reachability in downlink graph

Average Number of Nodes Per Downlink Graph

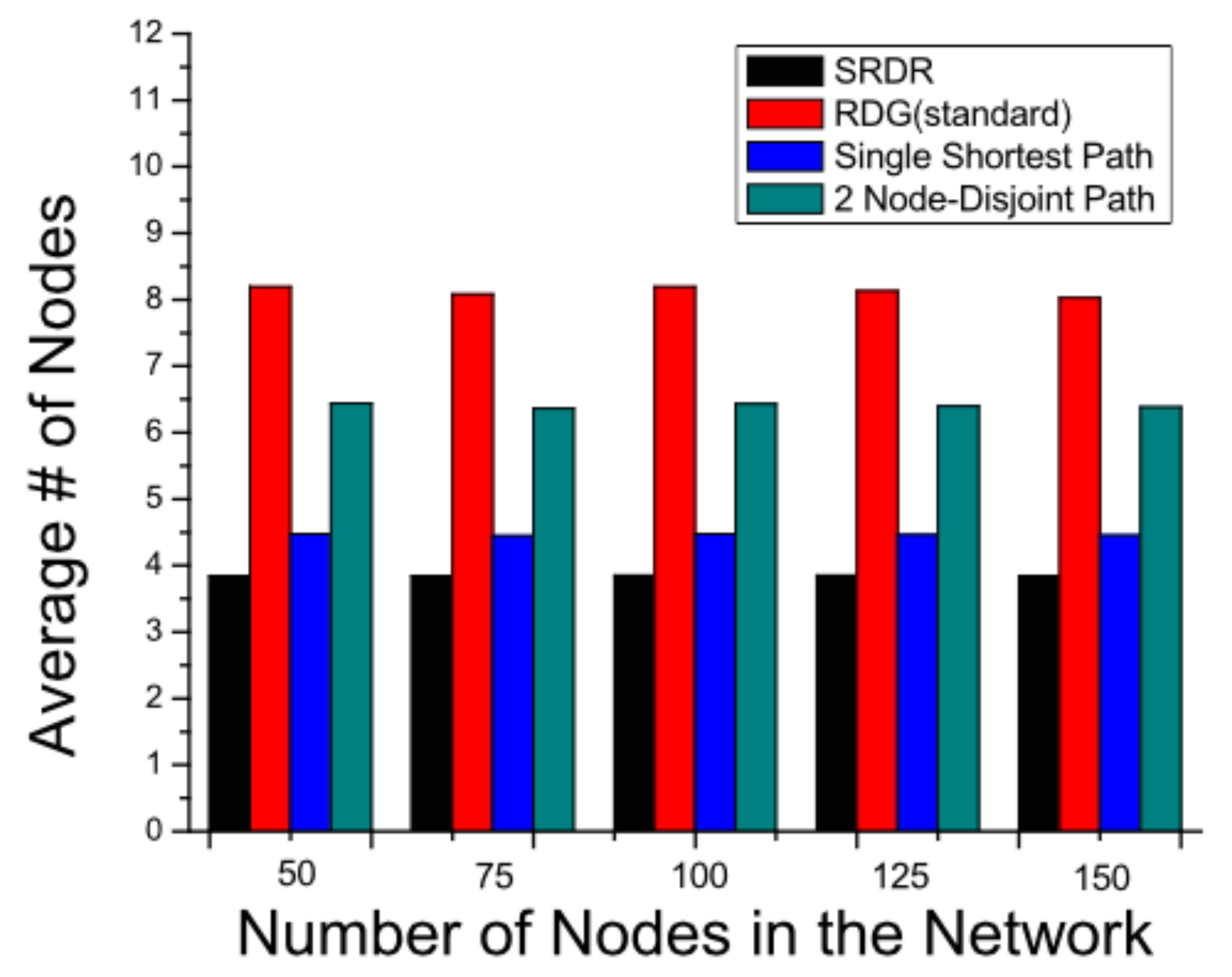


Fig. 23. Average # of nodes per downlink graph

Average Number of Edges Per Downlink Graph

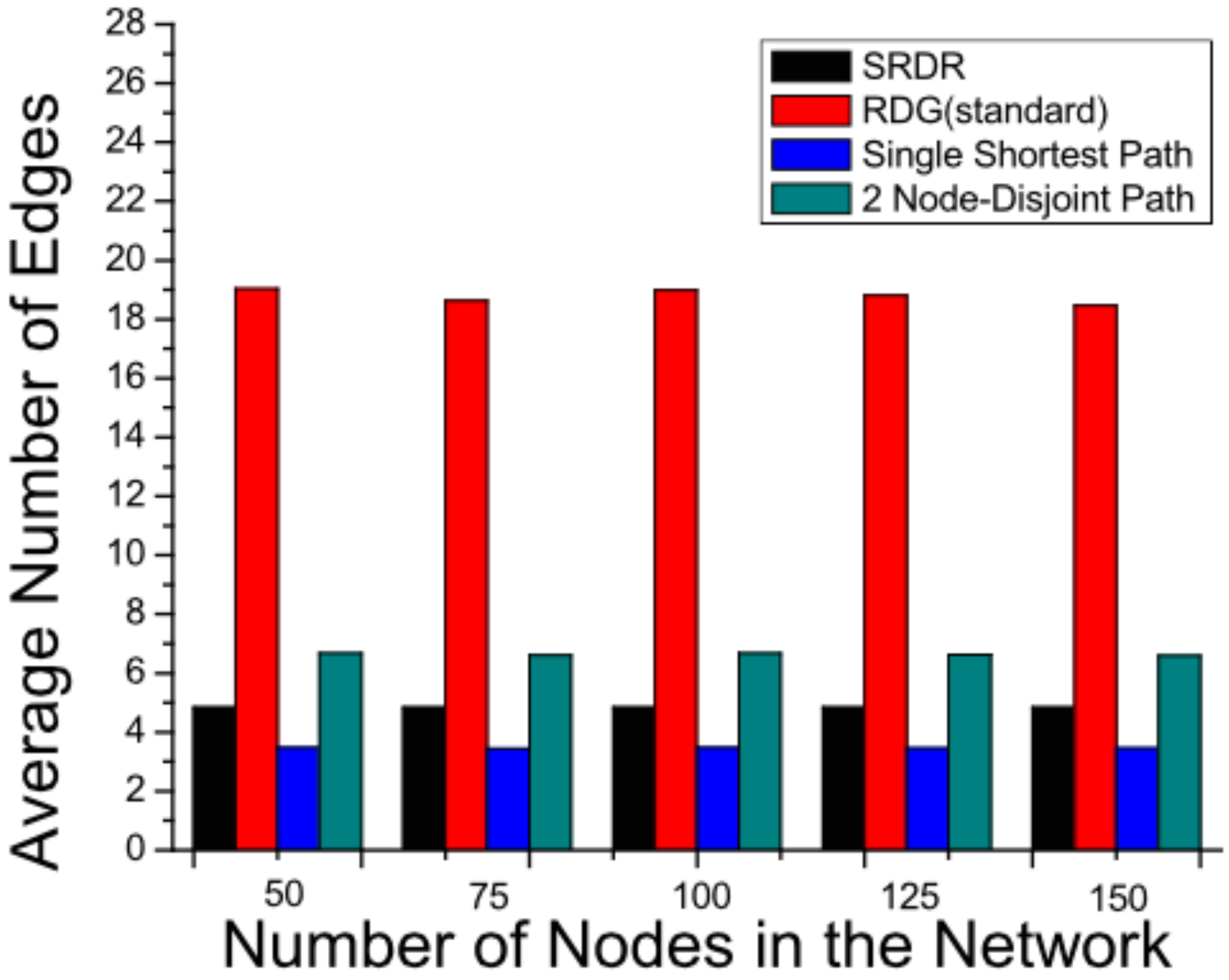


Fig. 24. Average # of edges per downlink graph

Average Downlink Latency vs. Network Size

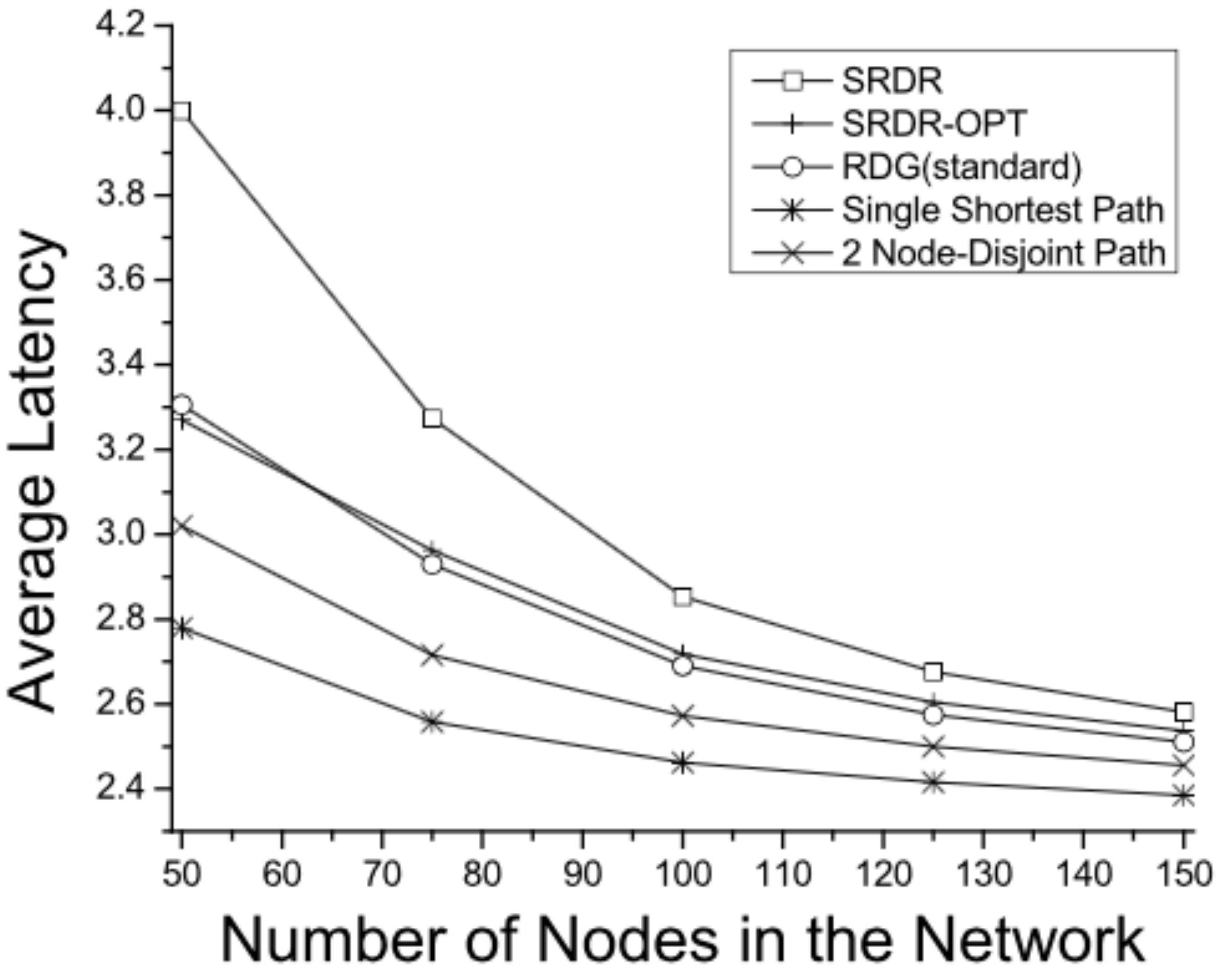


Fig. 25. Average latency vs. Network size

Average Downlink Latency vs. Communication Range

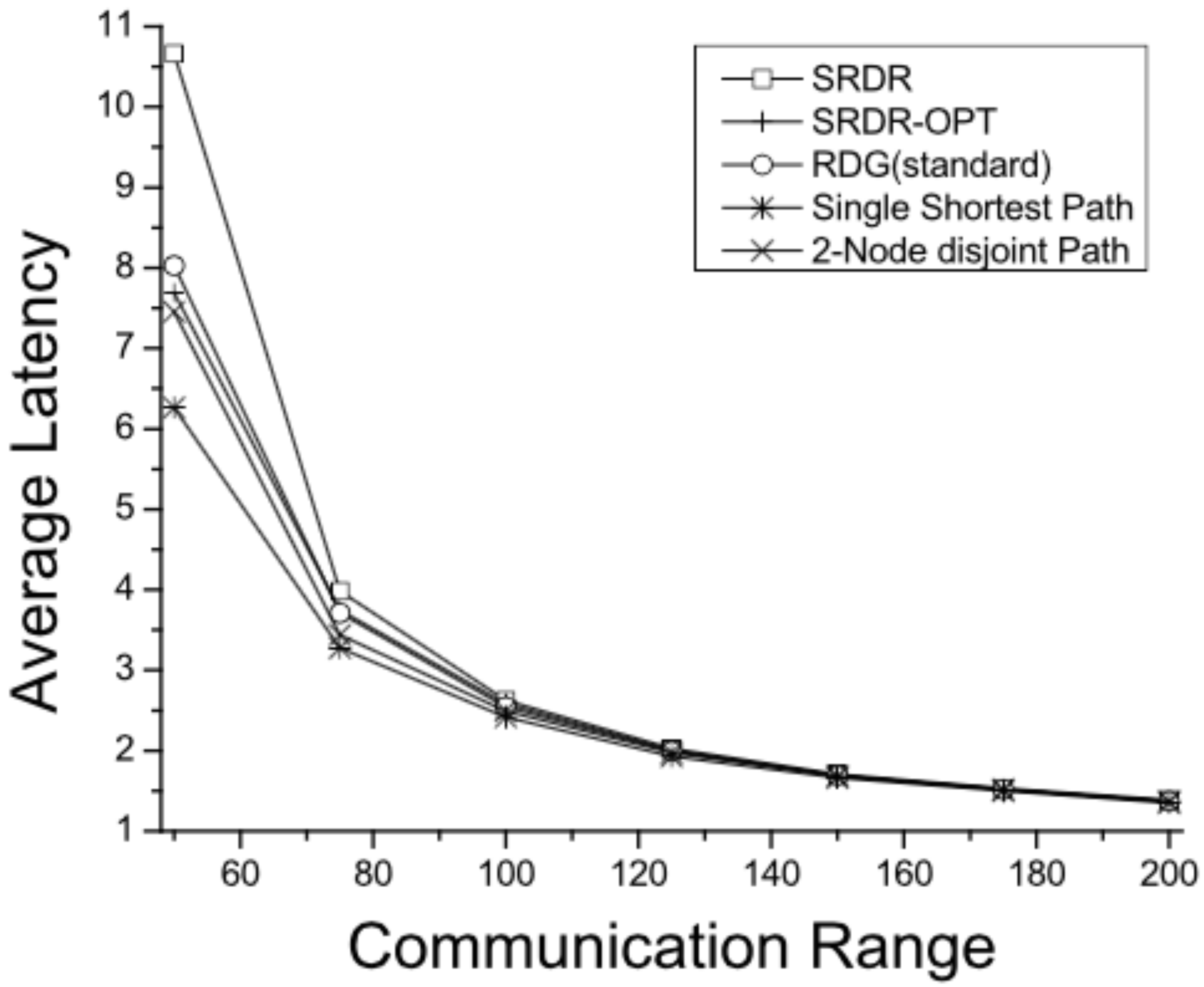


Fig. 26. Average latency vs. Communication range

Scheduling Success Ratio vs. Sampling Rate

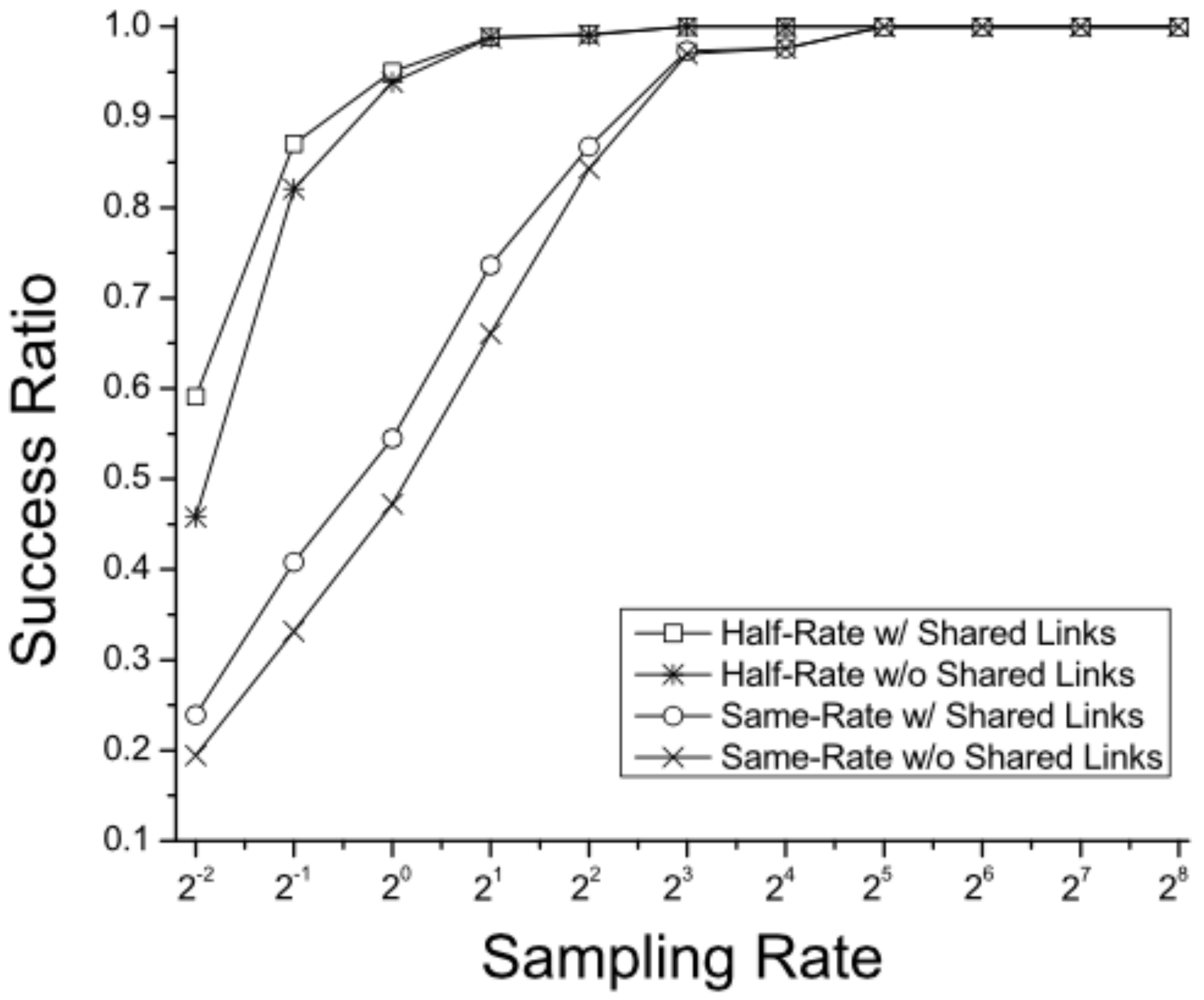


Fig. 27. Success ratio vs. Sample rate

Network Utilization vs. Sampling Rate

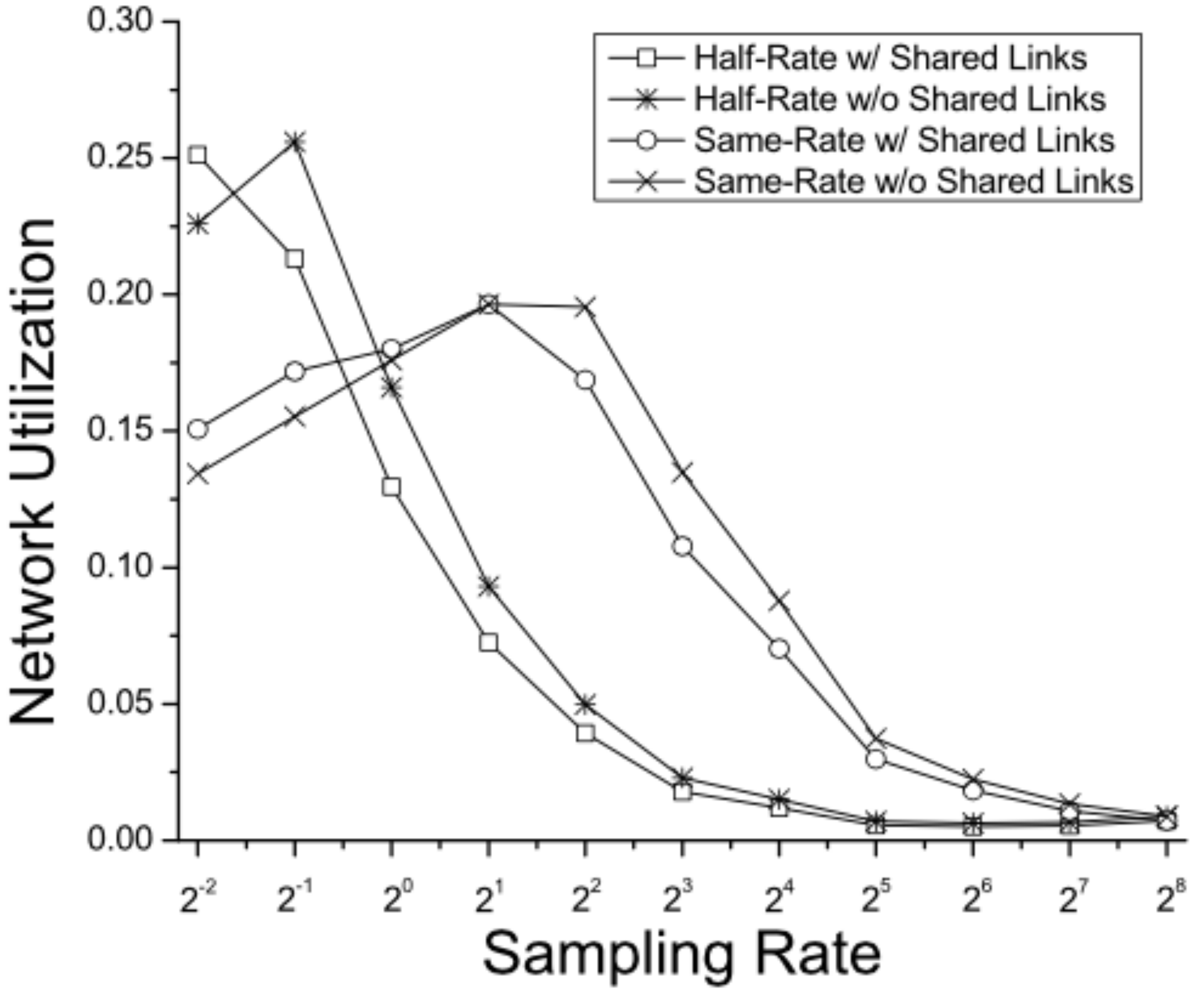


Fig. 28. Network utilization vs. Sample rate

Critique

- A well-organized paper describing WirelessHART networks
- Experimentation is done in real-world simulated settings that may not necessarily describe everything that occurs in the industrial setting

Questions ?

Sources Cited

1. Song Han; Xiuming Zhu; Mok, A.K.; Deji Chen; Nixon, M., “Reliable and Real-Time Communication in Industrial Wireless Mesh Networks,” in *Real-Time and Embedded Technology and Applications Symposium (RTAS), 2011 17th IEEE*, vol., no., pp.3-12, 11-14 April 2011. doi: 10.1109/RTAS.2011.9