Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

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Re: [Call for Final Proposals.]

Abstract: [This contribution presents a full proposal for the TG10.]

Purpose: [Final proposal to TG10.]

Hierarchical Mesh Tree Routing

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Outline

This proposal includes the following features:

- Hierarchical Mesh Tree formation, maintenance update
- HMT Routing
- High reliability
- Data aggregation

Typical Use cases

- Smart metering
- Environment monitoring
- Structure monitoring
- Parking monitoring

Motivation

- The current 802.15.4 builds a cluster tree topology
- Data frames can only be sent between device and coordinator
- Even when a routing protocol is applied from the upper layer, it is constrained at the MAC layer by the cluster tree topology
- The D2D function in 15.4m allows devices associated to the same coordinator to send packets to each other directly but does not provide routing capability to distant nodes

HMT formation(1)

- Each node is required to associate with a coordinator after performing an active or passive scan as described in Section 5.1.3.1 of IEEE Std 802.15.4-2011
- Each node has a depth representing the distance of that node to the root of the tree (a FFD providing a service or a gateway…) in number of hops
- The depth of a device is carried in an enhanced beacon (EB)
- The service(s)/gateway provided by the tree is advertised in the EB
- The construction of the tree starts with the broadcast of a EB advertising a service and with a depth 0 by the service provider or gateway which becomes the root of the tree

HMT formation (2)

- For a particular routing tree, a node holds a neighbor table filled based on the EBs and data frames received

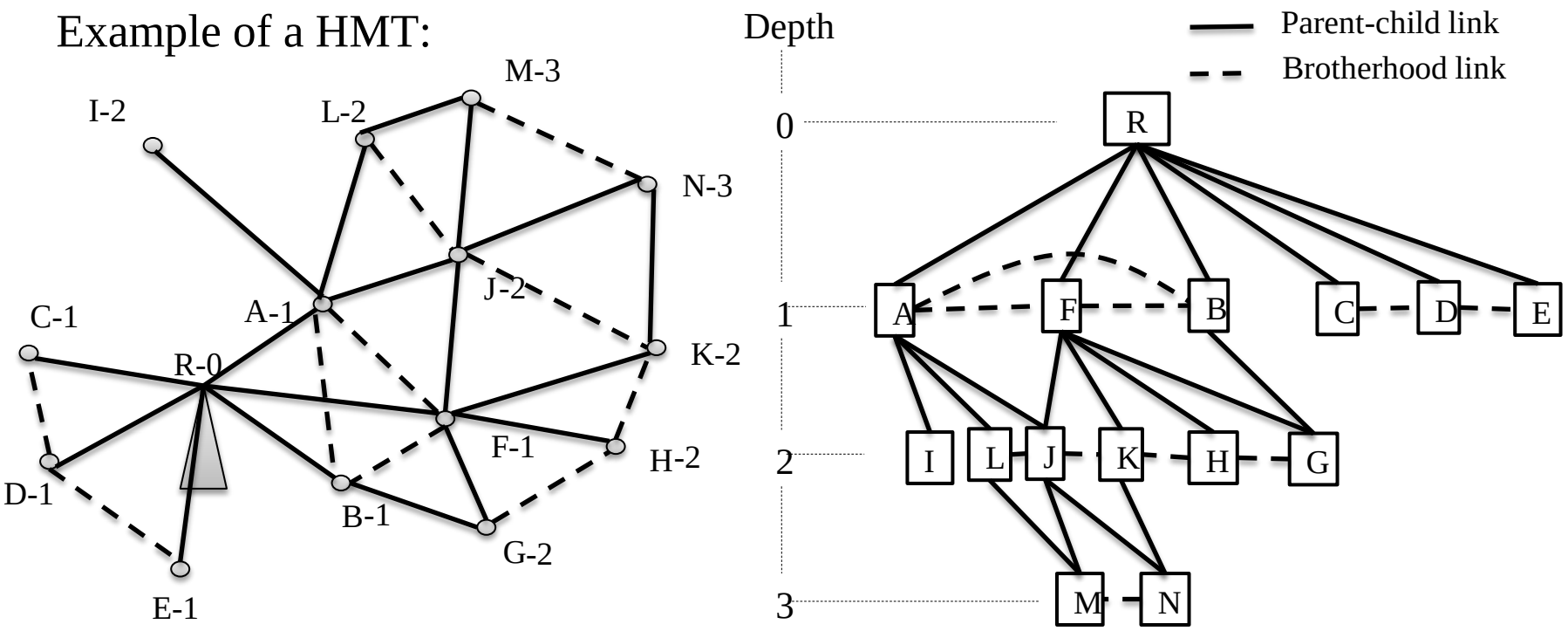
Neighbor ID	Neighbor Depth	Metric 1	…	Metric n	List of reachable destinations

- A neighbor is categorized according to its depth. If the depth of a node M is D_M and the depth of a neighbor N is D_N
  - If $D_M > D_N$ ➔ N is a parent
  - If $D_M = D_N$ ➔ N is a brother
  - If $D_M < D_N$ ➔ N is a child
- There may be a limit in the size of the neighbor table based on the resources of a node. In this case, only the best neighbors (metric-wise) are recorded.
- A device must have at least have one entry in its neighbor table with one parent
- A node starts filling up its neighbor table only after association to the PAN. It ensures that only nodes from the same PAN are recorded as neighbors

HMT formation (3)

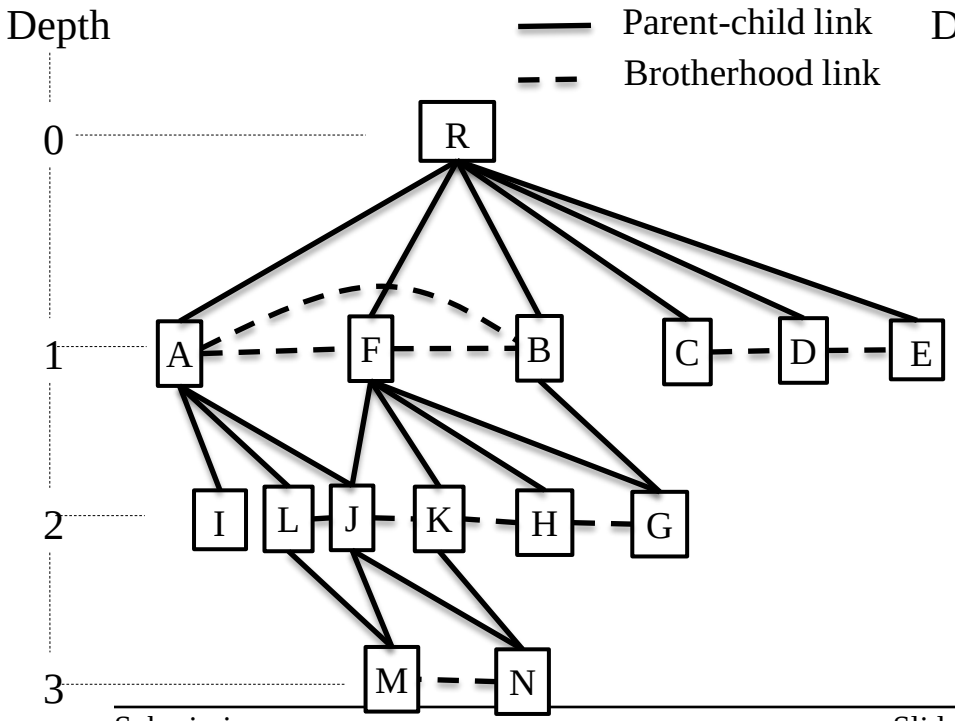
- After the HMT formation, a device can join a routing tree by performing an active or passive scan to listen to EBs and find the services/gateway available.
- A device (typically a FFD) may join different routing trees if it has enough resources.

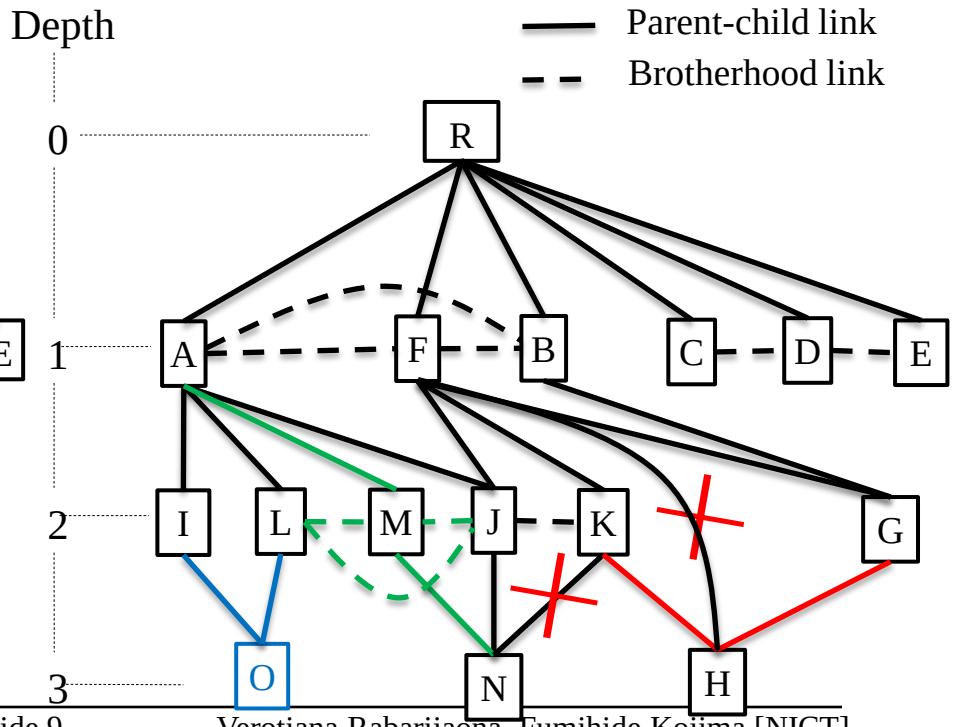
Example of a HMT:



HMT maintenance and update

- The neighbor table is maintained through periodic EB broadcasts
- A node's depth and the neighbor table is updated according to the changes in the network reflected by the presence/absence of EBs
- If a node is disassociated to its coordinator in the PAN, it either tries to re-associate or tries to associate with another parent in the neighbor table.





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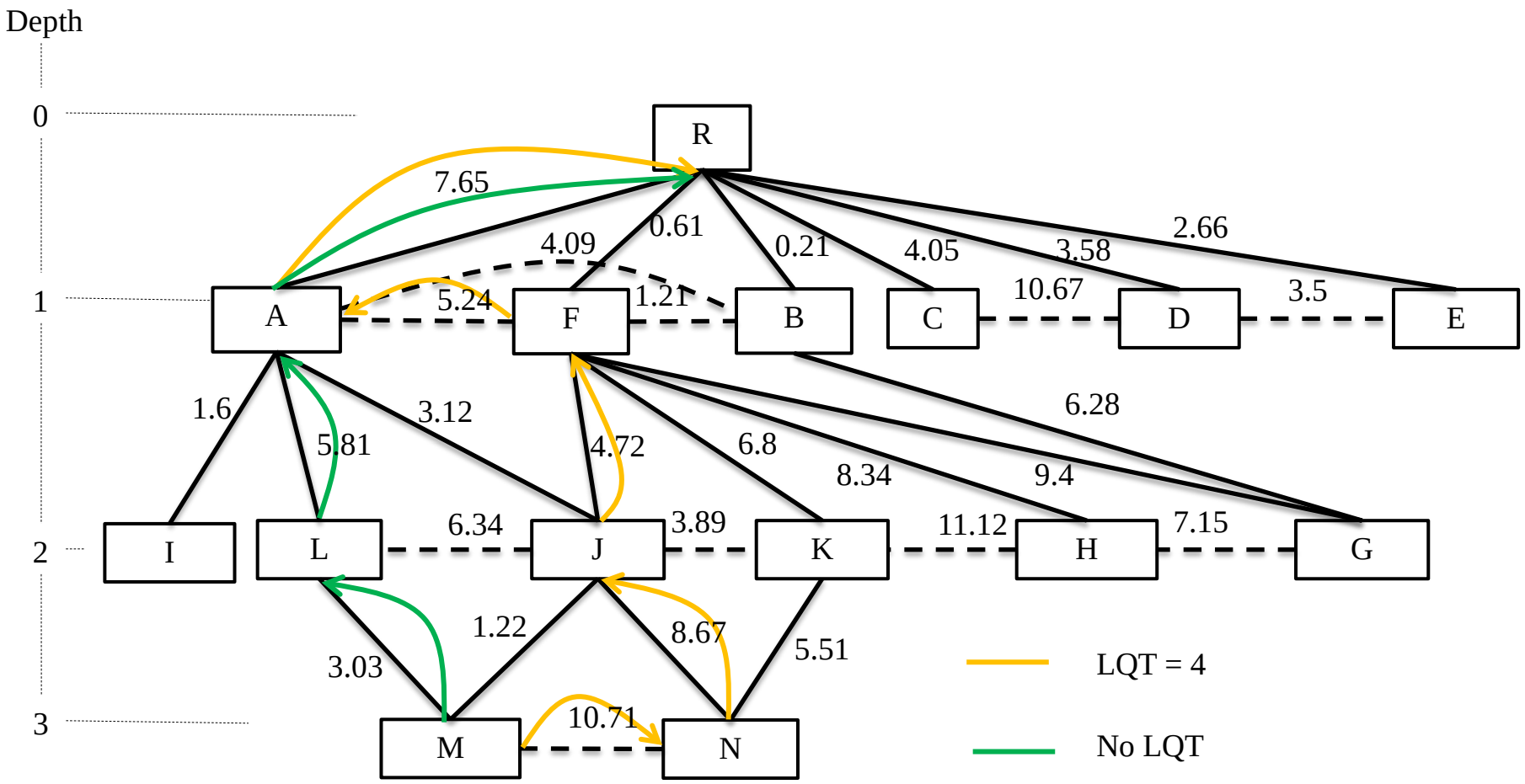
HMT Routing - MP2P (1)

- Based on a link quality metric (BER, success rate, latency, SINR …).
- The metric(s) to be used is determined by the root of the tree and spread through EBs
- Reactive routing through parents and/or brothers with priority given to the parents through a Link Quality Threshold (LQT) w.r.t the chosen metric:
  - If the metric offered by the best parent does not satisfy the LQT, the packet is routed through the best brother.
  - If the metric offered by the best brother does not satisfy the LQT, the packet is routed through the device with the best metric between the best parent and the best brother.
- The LQT may be set globally by the root, or locally and dynamically by a device to adapt to the local channel conditions
- A node holds the list of TAs and RAs of a packet with a given (SN, SA, DA) tuple. In order to avoid loops, a node shall select a next hop that is not in that list. The list shall be erased after a TBD time

HMT Routing - MP2P (2)

- Example of M→R routing



HMT Routing - P2MP(1)

- When a device receives/overhears(if allowed) a packet to forward upstream (i.e. to the root), it includes the address of the source of the packet in the "**List of reachable destinations**" of the neighbor from which it received the packet (i.e. previous hop.) This list can be classified into 16-bit addresses and 64-bit addresses.

Neighbor ID	Neighbor Depth	Metric 1	…	Metric n	List of reachable destinations

- This neighbor table allows memory saving compared to a regular routing table

  Ex: R's table, assuming 16-bit addresses, 1-byte depth, 4-byte metric

Destination	Next hop	Metric
A	A	7.65
M	A	7.65
N	A	7.65
I	A	7.65
L	A	7.65
J	A	7.65
F	F	0.61
J	F	0.61
K	F	0.61
H	F	0.61
G	F	0.61

88 bytes

Neighbor ID	Depth	Metric	List of reachable destinations				
A	1	7.65	M	N	I	L	J
F	1	0.61	J	K	H	G	

Filled based on received EBs

Filled with the SA of received data frames

32 bytes

HMT Routing - P2MP(2)

- If a device does not have a data packet to transmit for a prolonged period of time, it sends a **MP frame with a Destination Announcement IE (Dest-A IE)** upstream

- When a device needs to forward a packet downstream, it looks up into its neighbor table and finds the neighbor with the best link quality metric through which the destination is reachable, with priority given to the child neighbors through a LQT

- If the devices of the network (besides the root) do not have enough memory to maintain the list of reachable destinations (non-storing mode), source routing is used. Each intermediate device on the way upstream appends its own address to the Dest-A IE. The list of intermediate hops is included in a packet to be sent downstream. Each intermediate device removes its address from the list before forwarding the packet.

HMT Routing - P2MP(2)

- Example of R → J routing

R

Neighbor ID	Depth	LQ	List of reachable destinations				
A	1	7.65	M	N	I	L	J
F	1	0.61	J	K	H	G	
...	...	...	...	...	...	...	...

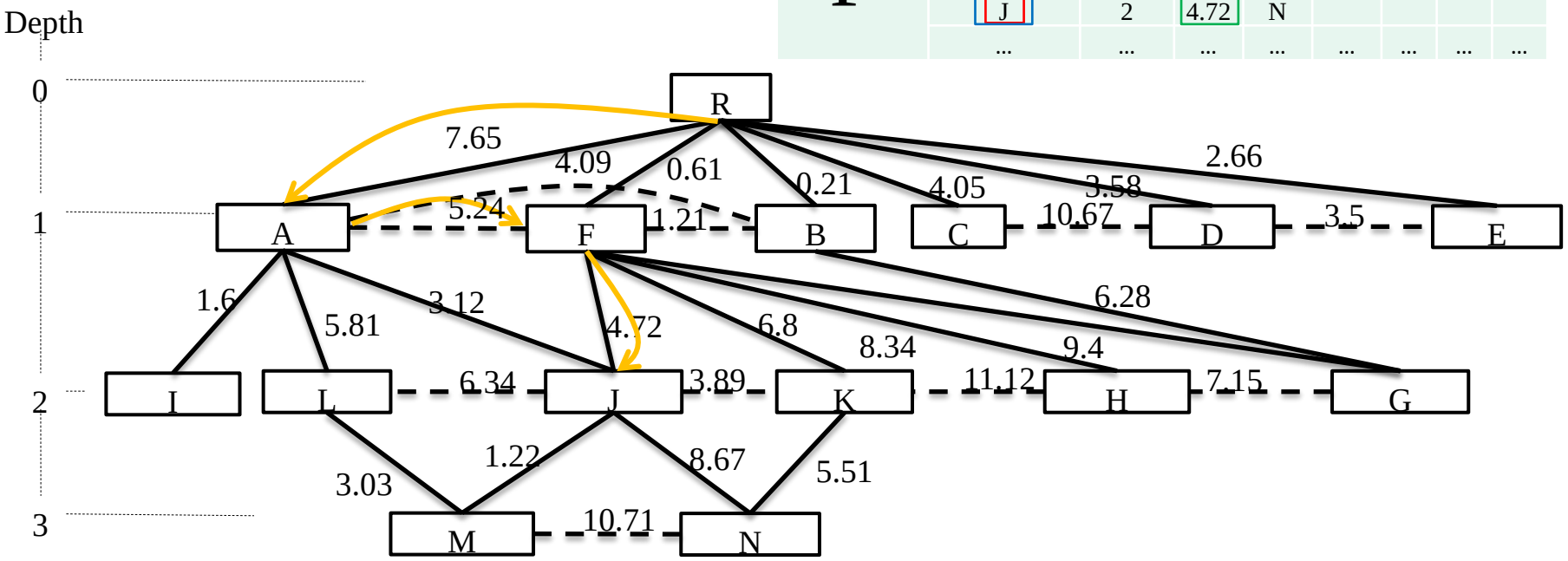
A

Neighbor ID	Depth	LQ	List of reachable destinations				
R	0	7.65					
F	1	5.24	J	K	H	G	
J	2	3.12	N				
...	...	...	...	...	...	...	...

F

Neighbor ID	Depth	LQ	List of reachable destinations				
R	0	0.61					
A	1	5.24	L	M	J		
J	2	4.72	N				
...	...	...	...	...	...	...	...

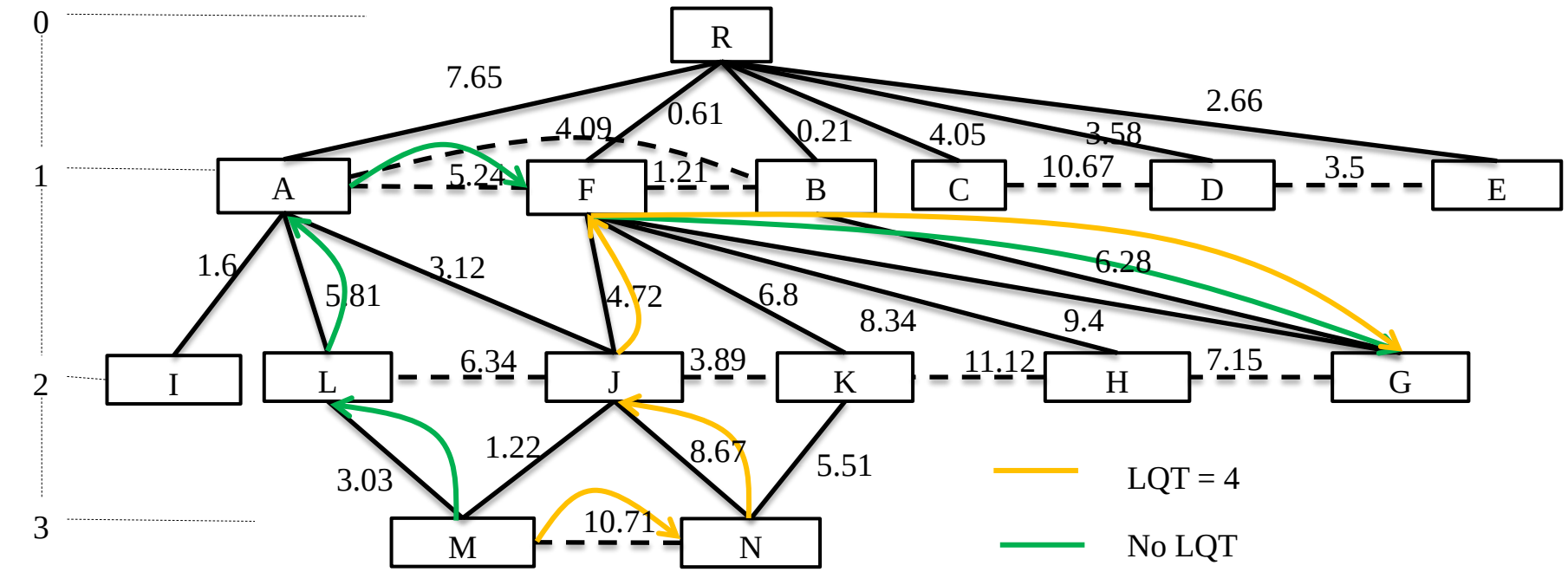
Destination
Best link quality
Selected next hop



HMT Routing – P2P

- When a device D1 has a packet to transmit to another device D2, it looks into its neighbor table if there is a route to D2.
  - If there is a route, the packet is forwarded to the neighbor through which D2 is reachable
  - If there is no route, the packet is forwarded upstream

Example of M →G routing

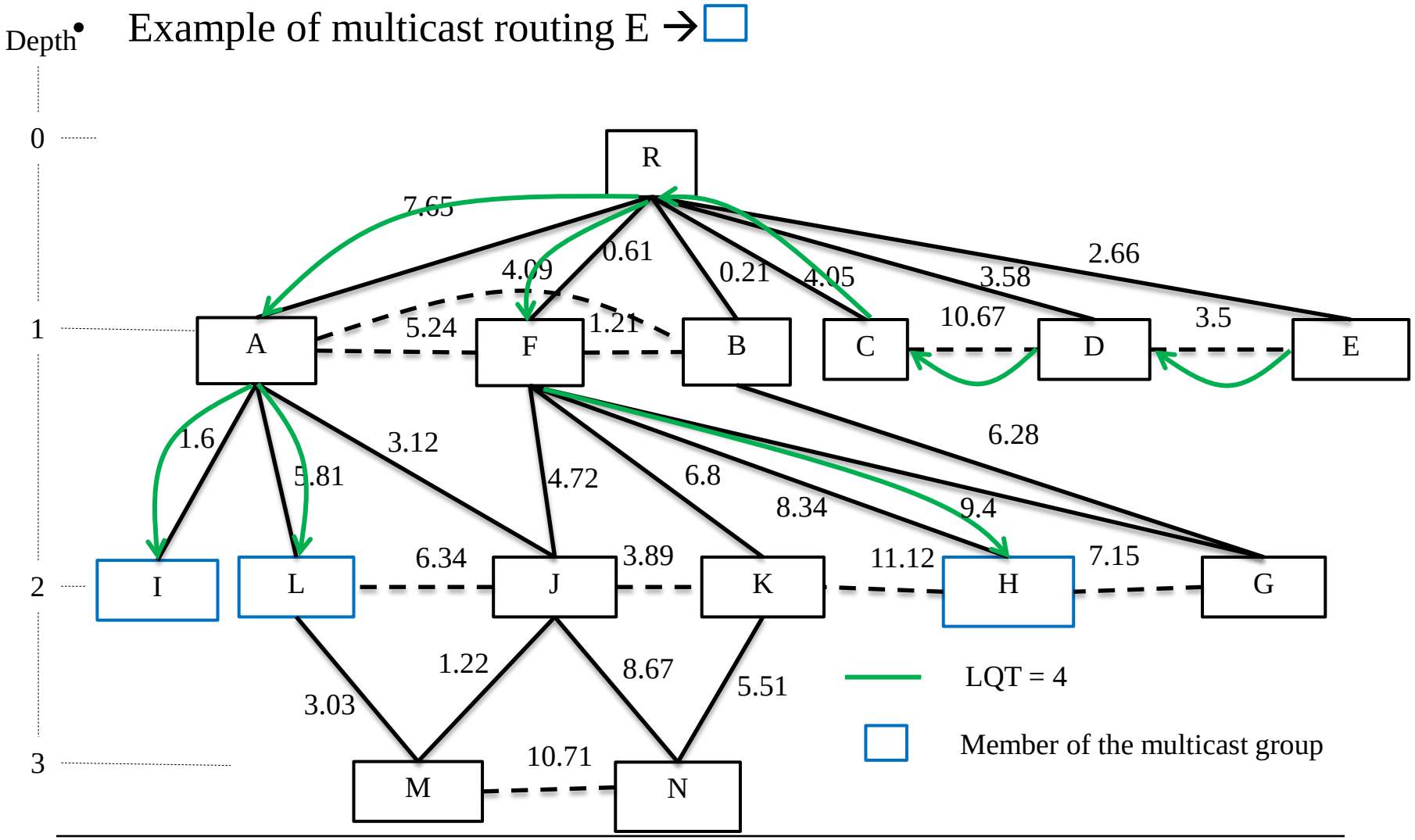


HMT Routing – Multicast(1)

- If a node is subscribed to a multicast group, it informs the network with the **Dest-A IE** including a **Multicast subscription** field, containing the multicast address.
- When a device receives a Dest-A IE with a **Multicast subscription** field, the multicast address is added to the **list of reachable destinations**
- A device uses the same algorithm as for P2P routing with the multicast address as the destination address and as the next hop address, i.e. a device forwards a multicast packet only if the multicast address is reachable through one of its neighbors. This avoids flooding the network.
- A device forwards a packet only once, except if the packet requires an ACK and ACK was not received from each intended next hop

HMT Routing – Multicast(2)

- Example of multicast routing E →



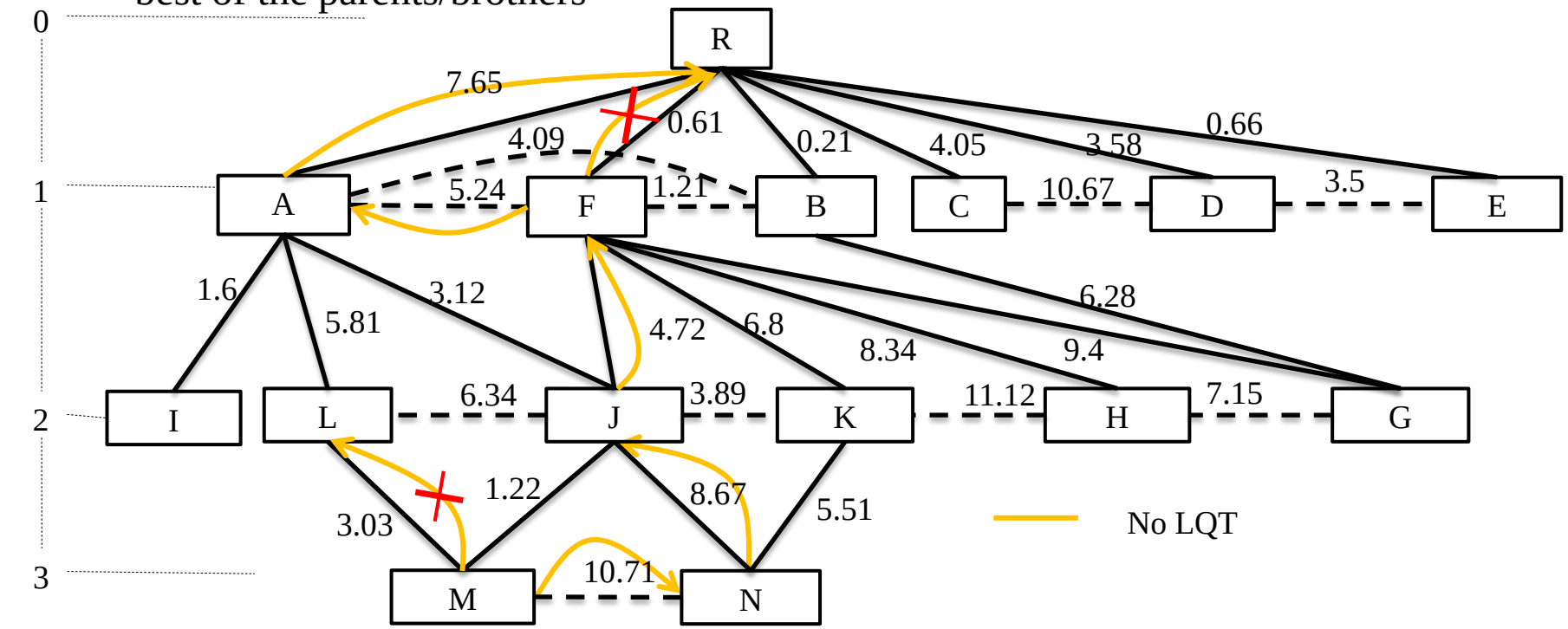
HMT Routing - Broadcast

a. If the root of the tree is the source of a broadcast data frame, a device shall forward the packet only if it has children neighbors.

b. If a device other than the root of the tree is the source of a broadcast data frame, the frame shall be sent to the root first and broadcast downstream as in a.

High reliability option

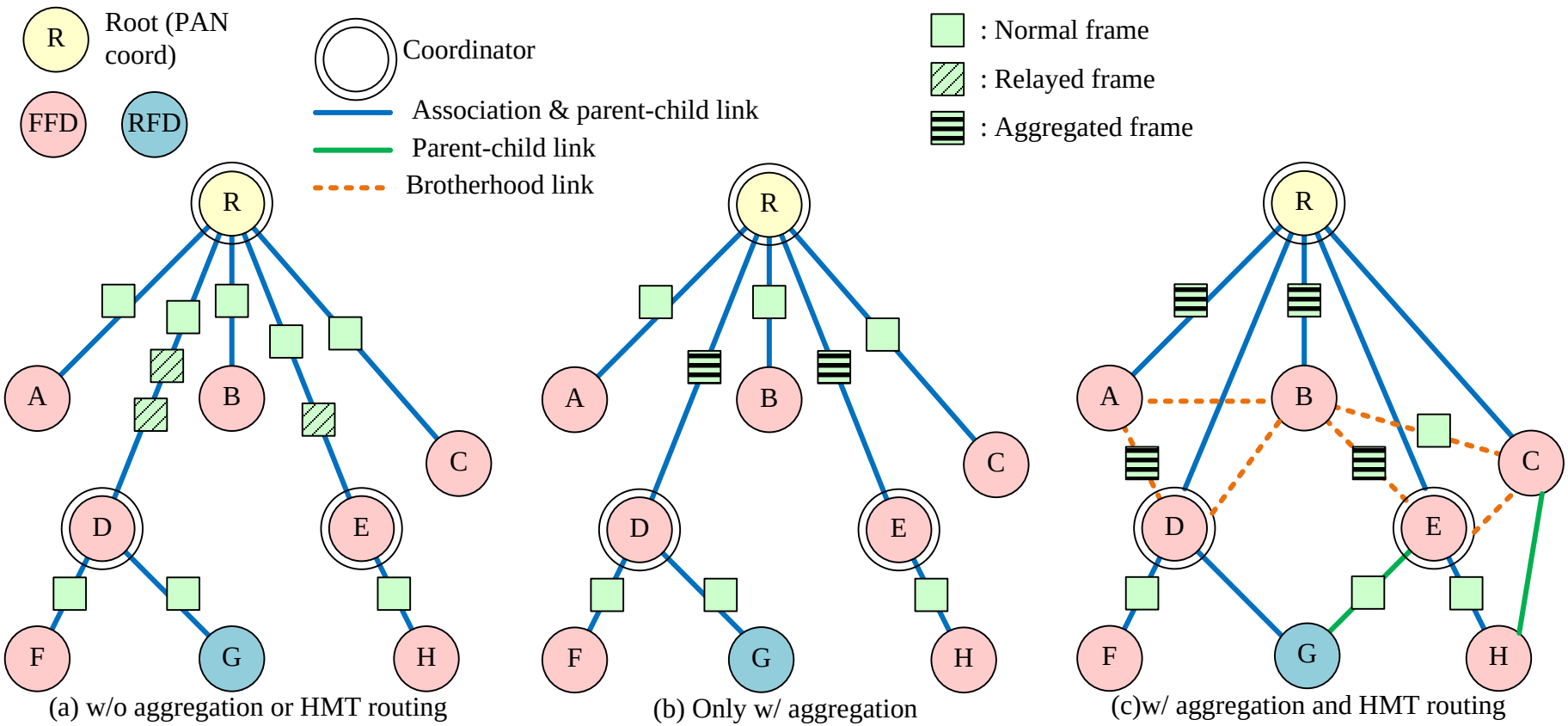
- If the high reliability (HR) option is on, the AR field must be set to 1. If an acknowledgment is not received after a packet transmission, the packet is forwarded through another neighbor
- In particular, the HR option can be used when no LQT is set, i.e. the next hop must be a parent but if the transmission fails, the packet is rerouted through the best of the parents/brothers



Data aggregation (1)

- A node aggregates the packets collected from its neighbors with its own pending packet (if present) before forwarding them.
- Reduce collisions
- Reduce the bottleneck effect as we get closer to the root of the tree
- The number of aggregated packets is limited by the maximum size of a frame
- Packets can be aggregated only if they have the same destination

Data aggregation (2)



(a) w/o aggregation or HMT routing

(b) Only w/ aggregation

(c)w/ aggregation and HMT routing

HMT Construction IE

Used in EBs or command frames

Bit: 0 - 6	7 - 14	15	Octets: Variable
Length	Element ID	Type = 0 (Header)	IE content

Octets: 1	0/2/8	0/1	Bits: 0	1	2-5	6-7	Octets: variable	…	Octets: 0-variable
Service/ Gateway ID[1]	Tree Root ID	Depth	High reliability	Data aggregation 0: not allowed 1: allowed	Number N of metrics	Reserved	Link Quality Metric 1[2]	…	Link Quality Metric N

X Number of services/ gateway provided/ subscribed/ connected to

Bits: 0-3	4-7	0/Variable	0/Variable
Link quality metric ID	Priority	Threshold	Value

[1] In a *Enhanced Beacon Request*, if the device knows the service or gateway it is trying to connect to, only the *Service/Gateway ID* is present. Otherwise the IE content is empty

[2] The link quality metrics and the related parameters are up to the implementer and are set in the PIB

L2R Routing IE

Used in data frames

Bit: 0 - 6	7 - 14	15	Octets: Variable
Length	Element ID	Type = 0 (Header)	IE content

Octets: 2	2/8	4	0/Variable	Bits: 0	1-2	3-7
Service/ Gateway ID	Tree Root ID	Depth	Addressing fields	Data aggregation 0: must not be buffered and aggregated, must be forwarded immediately 1: may be buffered and aggregated	Flow 00: Up 01: Down 10: broadcast up[1] 11: broadcast down	Reserved

Octets: 2/8 [2]	2/8
Final Destination address (D)	Original Source address (D)

[1] Used for a broadcast data frame originated by a device other that the root of the tree. The data frame is forwarded to the root first then broadcast. The flow is switched to 11 (broadcast down) when the data frame reaches the root

[2]The addressing mode shall be the same as those used in the MHR

Data aggregation IE

Used in data frames

Bit: 0-6	7-14	15	Octets : variable
Length	Element ID	Type = 0 (Header)	IE content

Bits: 0-3	6-7	Octets: 1	…	1
Number N of aggregated packets	Reserved	Size of the aggregated packet 1 in octets	…	Size of the aggregated packet N in octets

Destination Announcement IE

Used in a MP frame sent to the root of the tree.

Bit: 0-10	11-14	15	Octets : variable
Length	Element ID	Type = 0 (Header)	IE content

Octets: Variable	0/2/8	…	0/2/8
Multicast subscription	Intermediate hop address 1[1]	…	Intermediate hop address N

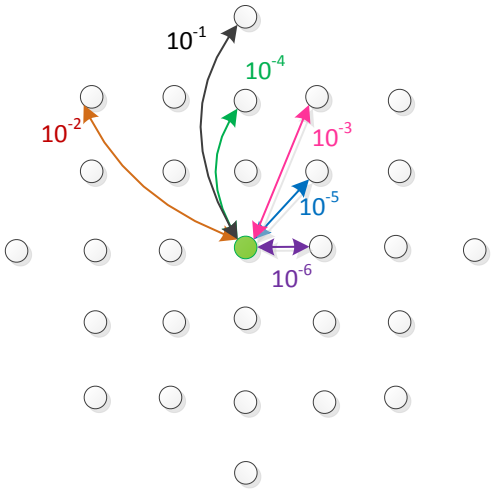
Bits: 0-5	6-7	Octets: 0/2/8	…	0/2/8
Number M of multicast group[2]	Addressing mode	Multicast address 1	…	Multicast address M

[1] Intermediate hop addresses are used for source routing in a non storing mode network, otherwise, they are not appended at each hop.

[2] If the node does not belong to any multicast group M = 0

Simulation results (1)

- Link quality metric: SINR
- Link failure rate and SINR mapping



LFR	SINR
10^{-6}	23
10^{-5}	19
10^{-4}	12
10^{-3}	10
10^{-2}	6
10^{-1}	5

Preliminary Simulation results (2)

Scenario: 11 x 11 devices

Performance criteria	No SINR threshold	SINR threshold = 9	SINR threshold = 18
Initialization time (s)	26.319235		
US E2E successful transmission ratio (%)	97.298	99.456	99.815
DS E2E successful transmission ratio (%)	98.687	99.625	99.89
Number of hops			
Min Max US Average DS Average	1 5 2.047 2.356	1 9 4.429 4.452	1 12 5.494 5.33
E2E transmission delay (s)			
Min Max US Average DS Average	0.0163 0.0976 0.0391 0.0444	0.0163 0.125 0.0849 0.0884	0.0163 0.241 0.105 0.1041

No

Preliminary Simulation results (3)

Scenario: 33 x 33 devices

Performance criteria	No SINR threshold	SINR threshold = 9	SINR threshold = 18
Initialization time (s)	51.24705		
US E2E successful transmission ratio (%)	83.296	87.135	98.945
DS E2E successful transmission ratio (%)	83.8403	86.901	90.756
Number of hops			
Min Max US Average DS Average	1 11 5.147 5.331	1 7 9.352 9.503	1 25 14.322 13.401
E2E transmission delay (s)			
Min Max US Average DS Average	0.0163 1.168 0.0989 0.1025	0.0163 1.331 0.18 0.1815	0.0163 1.415 0.274 0.257

Thank you

Q/A