

Low Power Wireless Mesh Network over the TDMA Link for Connecting Things

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Abstract— In this paper, a low power wireless mesh network over channel hopped TDMA links is introduced as an area network for connecting things. The links and virtual links over the IEEE 802.15.4e DSME MAC are established and unbalanced cluster-tree based network formation provides routed link paths for the things to have deterministic-latency and scalable wireless mesh connectivity.

Keywords – link path; wireless mesh network; IEEE 802.15.4e DSME MAC, virtual link; cluster-tree mesh routing

I. LOW POWER WIRELESS MESH NETWORK FOR IoT

To allow the things having deterministic-latency and scalable wireless mesh connectivity in the area network, a possible choice is to use a low powered TDMA link. The link over the IEEE 802.15.4e Deterministic and Synchronous Multi-Channel Extension (DSME) MAC provides the following features[1]:

- Multi-channel, multi-superframe, mesh extension to GTS for deterministic latency, flexibility, and scalability
- Two channel diversity modes (channel adaptation mode and channel hopping mode) for robustness and high reliability even in dynamic channel conditions

For capacity enhancement, DSME extends the existing standard in two important directions: extension of number of GTS time slots and the number of frequency channels used. The DSME adopts a versatile frame structure, supporting multi-superframe to overcome the seven slot limitation and single channel operation. The GTS service can be extended to cover multihop mesh networks with deterministic latency. For reliability, DSME equips with two channel diversity modes, channel adaptation and channel hopping, so that designers of mesh networks can choose either mode of operation to meet the network objectives.

The area network for connecting things requires optimal utilization of the channel-hopped TDMA links while maintaining a simple procedure and a light weight protocol. In this paper, a low power wireless mesh network (LPWMN) specification for devices that are operated on IEEE Std. 802.15.4-2011 PHY capable to support the channel-hopped TDMA links of the DSME MAC of IEEE Std. 802.15.4e-2012 is introduced.[2] The LPWMN performance, such as topology construction time, recovery time from link failure, average number of hops between PAC coordinator and device, and power consumption are evaluated.

II. LINK NETWORK FORMATION

The LPWMN consists of a gateway router, routers, and devices, which follow the IEEE Std. 802.15.4-2011 and have the DSME MAC sublayer of the IEEE Std. 802.15.4e-2012. The gateway router starts a network by configuring the attributes of the network and forming the network topology, and interconnects the LPWMN to an external network. The routers join a network and forward frames through the DSME MAC links. The devices are reduced-function device (RFD) or full-function device (FFD) of the IEEE Std. 802.15.4-2011 and perform applications.

The LPWMN operates in the star topology and the peer-to-peer topology, as shown in Figure 1. A device typically establishes a star topology to the routers and is either the initiation point or the termination point for network communications. The gateway router is the primary controller of the LPWMN. The gateway router and routers are capable to establish the peer-to-peer topology. All devices operating on a network have unique 64bit MAC addresses and 16bit network addresses. The network address is allocated by the cluster group.

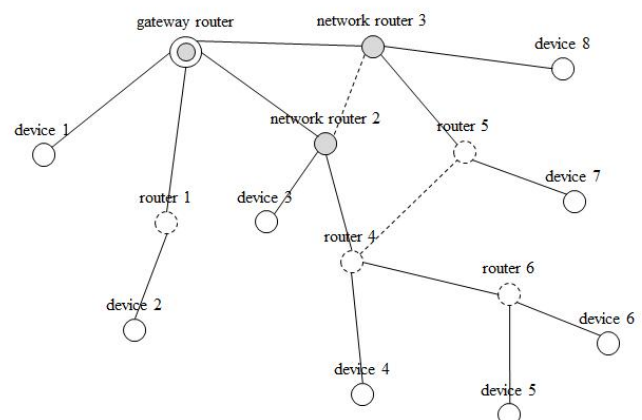


Figure 1-Link, virtual link, routed link-path

The LPWMN establishes a link between two devices neighbored and a virtual link between two devices multi-hopped apart, as shown in the Figure 1. The LPWMN provides a routed link-path that is constituted of links and virtual links from a source to a destination device.

The link connects the neighbored two devices: network router 2 and device 3 are neighbored and a link connects two devices. The virtual link is the multi-hop link connection through the routers which perform frame relaying instead of routed forwarding: network router 2 and device 6 are connected through router 4 and router 6 which relay the frames inward or outward. The routed link-path is provided by the LPWMN routing functions: for connecting between device 4 and device 8, the LPWMN can provide several routed link-paths which are the path 1 (device 4-router 4-network router 2-gateway router-network router 3-device 8), path 2 (device 4-router 4-network router 2-network router 3-device 8), and path 3 (device 4-router 4- router 5-network router 3-device 8).

The LPWMN is a link network that connects two devices by switching the time slots. The DSME MAC sublayer provides the contention access period (CAP) and guaranteed timeslots (GTS) in a beacon interval for communicating, as illustrated in Figure 2. A CAP link is active periodically and is used for the bidirectional data transmission. A GTS link in the LPWMN is established by assigning the offset of channel hopping sequence and the DSME timeslots between two devices.

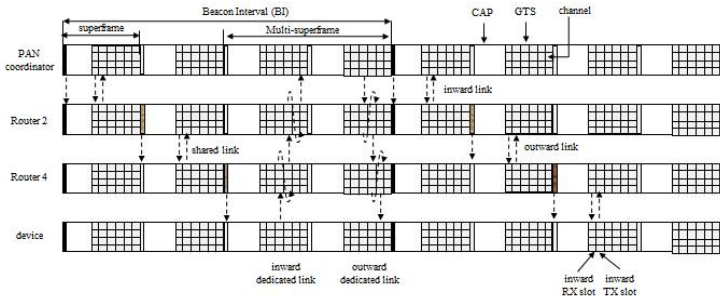


Figure 2-CAP link, shared link, and dedicated link

The LPWMN GTS link can be established not only between two directly connected devices, but also between two devices which can be connected with multi-hop routed links. To form a link-path from a source device to a destination device, each device on the path requests to allocate DSME timeslots.

The LPWMN GTS link can be used as shared link or dedicated link. The default shared link is established during joining a network. An inward rx timeslot and an inward tx timeslot of a link to the inner router are assigned as the default shared link and the default path to the gateway router is established.

If the next higher layer of the LPWMN needs a dedicated link, it is required to setup a link connection before sending data. To establish a dedicated link connection, link network layer routing is performed through the routers on the routed link-path from a source device to a destination device. To establish a bidirectional dedicated link, it needs to establish an inward dedicated link and an outward dedicated link separately. The link setup procedure from the source device and the link setup procedure from the destination device are required.

The dedicated link transmits a frame received only at the source device of the link. The shared link may transmit a

frame received at the routers on the link-path to the destination device of the link.

III. ROUTED LINK PATH FOR CONNECTING THINGS

When the next higher layer of the LPWMN requests to transmit data, according to the required quality of transmission, it selects a type of data transmission, which specifies the type of link for communications and the recovery procedure, and flow control. The LPWMN provides six types of data transmission.

- Type 1: The data frames shall be exchanged during the contention access period, CAP link. The data frames shall not be acknowledged, and shall be transmitted without flow control and error recovery.
- Type 2: The data frames shall be exchanged during the contention access period, CAP link. The data frames shall be acknowledged, but shall be transmitted without flow control and error recovery.
- Type 3: The data frames shall be exchanged in the shared guaranteed time slots, shared link, which are allocated for connecting two neighbour devices. The data frames shall not be acknowledged, and shall be transmitted without flow control and error recovery.
- Type 4: The data frames shall be exchanged in the shared guaranteed time slots, shared link. The data frames shall be acknowledged, but shall be transmitted without any flow control and error recovery.
- Type 5: The data frames shall be exchanged on the dedicated path which is established by allocating the dedicated guaranteed time slots on each hop link between two devices, dedicated link, prior to exchange. The data frames shall not be acknowledged, and shall be transmitted without flow control and error recovery.
- Type 6: The data frames shall be exchanged on the dedicated path. The data frames shall be acknowledged, and shall be transmitted with flow control between two end devices.

To support the fast formation of a network and to provide address based tree routing, the distributed address allocation scheme with an unbalanced cluster-tree structure is designed as shown in Figure 3.

The 16-bit addressing space is divided two parts for identifying a cluster and a device in the cluster. The gateway router manages the cluster identifier space and assigns a cluster ID when the root router of the cluster joins a network. The root router of the cluster assigns an address to a device by using the distributed address allocation scheme with the maximum depth of the cluster (L), the maximum number of devices connected to a router (D), and the maximum number of routers among devices connected to a router (R) values.

The locator identifier of the root router of a cluster is 0 and the locator identifier of a device connected to a router h -hopped from the root router of a cluster shall be assigned as follows. If the device is a router, the locator identifier is calculated as follows: *device identifier of a*

parent router + 1 + (sequential order of a router at cluster depth $h - 1$) * size of address block at cluster depth h . If the device is an end device, the identifier is calculated as follows: device identifier of a parent router + 1 + maximum number of a router at cluster depth h * size of address block at cluster depth h + sequential order of an end device at cluster depth h . The sequential order of a device at each cluster depth is assigned from 1. The size of address block at cluster depth h , $B(h)$, is calculated as follows: If $R = 1$, $B(h) = 1 + D * (L - h - 1)$. If $R \neq 1$, $B(h) = (1 + D - R - D * R^{L-h-1}) / (1 - R)$.

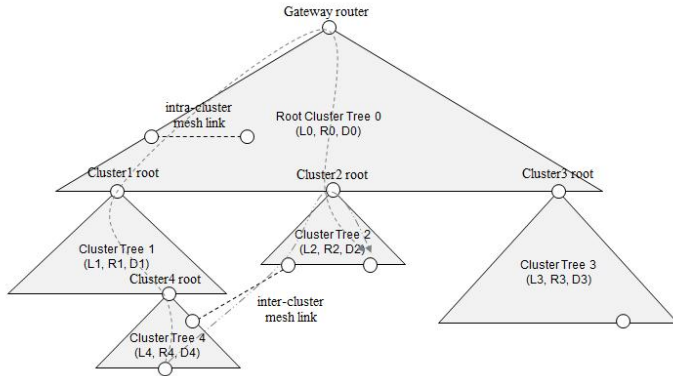


Figure 3- Unbalanced cluster-tree based mesh routing

The DSME MAC offers TDMA slots with two types of channel diversity function. The routing function concerns with not the only matter of connectivity, but considering a series of the time slot and channel number pairs which are allocated on the radio links in a path. The channels occupied by nodes within 2-hops range have to be excluded for avoiding the collision by hidden nodes. To utilize the TDMA MAC optimally, the network protocol has to offer the light-weight network protocol for reserving the time slots on a link from one end to the other end. The routing protocol has to support the fair load balancing among devices contended to reserve the time slots and channels.

The selection of a route relies on the cluster table maintained by the gateway router and the route table maintained by the router. The cluster table maintains the root router information of a cluster and the router information of an inter-cluster mesh link. The cluster connectivity matrix provides relations among the root routers of the clusters and inter-cluster mesh links. The route table maintains the reachable destinations through the current established links, which are one-hop CAP link or shared link to the neighbor device, multi-hop shared link-path, and dedicated link-path that the router is the source.

When a device joins a link network, the cluster connectivity matrix is provided from the gateway router or the root router. When a device joins a link network or needs to update the entire routing table, the router shall request the full cluster table to the gateway router. When a device completes to establish or release a link and updates the routing table, the router shall request the gateway router to update the cluster connectivity matrix.

An optimal link for a path is chosen and recorded on the cluster-tree table and the mesh connectivity matrix. Selection of a route is performed based on the cluster identifier of reachable devices. The device of which the cluster level or cluster-tree level is closer to the destination is selected for forwarding a frame, as shown in Figure 3.

A data packet is forwarded to the next hop on a reserved GTS link or a shared link, which is specified by a certain time slot and a hopping channel.

IV. EVALUATION OF CLUSTER-TREE LINK NETWORK

The routing performance of LPWMN that is operated on IEEE Std. 802.15.4-2011 PHY capable to support the channel-hopped TDMA links of the DSME MAC of IEEE Std. 802.15.4e-2012 is evaluated. The performance evaluation metrics are topology construction time, recovery time from link failure, average number of hops between PAC coordinator and device, transmission delay of end-to-end device, and power consumption of the unicast, multicast, and broadcast communication in the link network.

We use square grid as radio range for each node, as shown in Figure 4. The figure shows possible routed paths: (a) PAN coordinator to m end devices, (b) the farthest end-to-end devices, (c) multicast from an end device to m end devices, (d) multi devices to an end device. When the nodes in the area larger than 5×3 go down for 11×11 , the neighbors have to change route drastically. For the larger topology, disabled area may be larger like 6×6 for 33×33 and 20×20 for 100×100 .

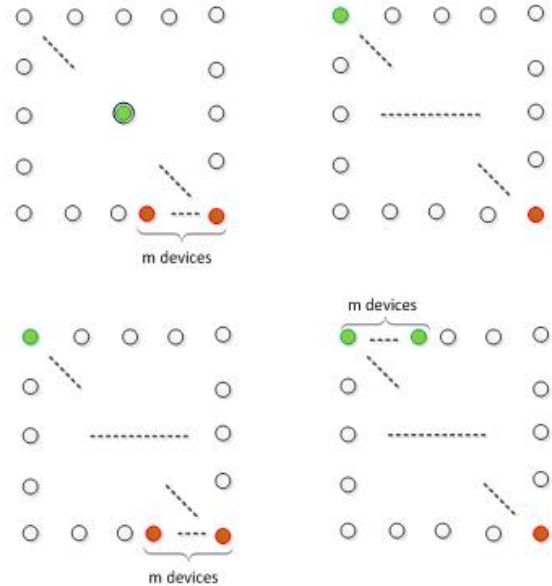


Figure 4- Scenarios for evaluation of routing performance

For evaluating routing performance, the LPAMN emulator is designed with the PHY and MAC chosen as follows:

PHY specification

- PAN coordinator – device : 100Kbps
- . 868MHz, O-QPSK, 25ksymbol/s
- . BaseSlotDuration (2.4ms, 30bytes)

- device – device : 250Kbps
- . 2.4G, O-QPSK, 62.5ksymbol/s
- . BaseSlotDuration (0.96ms, 30bytes)

MAC specification

- superframe
 - . slot length = $2^{SO} * \text{BaseSlotDuration}$
 - . superframe duration = slot length x 16
 - . beacon interval = $2^{BO} * \text{BaseSlotDuration} \times 16$
- nonbeacon-enabled PAN
 - . 100Kbps : slot length = 19.2ms
- IEEE 802.15.4 beacon enabled PAN
 - . data rate is 250Kbps : BO = 7 (BI = 1.966 sec), SO = 3 (SD = 122.88ms)
 - . slot length is 7.68ms, length of CAP = $8 \times 7.68 = 56.54$ ms, length of CFP = $7 \times 7.68 = 53.76$ ms
- IEEE 802.15.4e DSME PAN
 - . data rate is 250Kbps : BO = 7, SO = 3, MO = 5 (number of superframe in a multi-superframe = 2^{5-3})
 - . number of CFP slots is 112

The topology construction time for 11x11, 33x33, and 100x100 unit grids are calculated as Table 1. It takes 13.762 sec for joining a node located at the shortest edge of 11x11, and takes 220.192 sec for joining a node located at the longest edge of 100x100.

Table 1-Construction time

Location of Device	11x11	33x33	100x100
Shortest edge	13.762	35.388	121.892
Longest edge	21.626	66.844	220.192

To evaluate routing recovery time, we assume two cases, full cluster table and routing update and partial routing table update. It takes 29.49 sec for partial route update of 11x11, and takes 37.24 sec for partial route update of 100x100.

Table 2-Recovery time

Recovery Type	11x11	33x33	100x100
Initializing	13.762	35.388	121.892
Route Update	29.49	37.24	37.24

The number of hops and transmission delay between PAC coordinator and device are calculated as Table 3. It takes 5.88 sec for transmitting a frame from the farthest device to PAN coordinator of 11x11.

The power consumption of the unicast, multicast, and broadcast communication in the link network are calculated as Table 4, when the packets are generated as follows:

- PAN coordinator : 1 packet/300min
- device : 1 packet/min

When PAN coordinator broadcasts a frame to devices, PAN coordinator consumes 1.058mAh/day for 11x11, 1.321 mAh/day

for 33x33, and 3.747mAh/day for 100x100. The PAN coordinator of 11x11 can work for 5 years and 65 days long.

Table 3-Number of hops and transmission delay

Comm. Type	Performance	11x11	33x33	100x100
Dev → PAN coord	Number of Hops (avg, max)	2.28, 5	8.5, 16	25.5, 50
	Transmission Delay (min, avg, max)	1.96, 5.88, 17.64	1.96, 33.32, 60.76	1.96, 96.04, 194.04
PAN coord → Dev	Number of Hops (avg, max)	2.28, 5	8.5, 16	25.5, 50
	Transmission Delay (min, avg, max)	1.96, 5.88, 17.64	1.96, 33.32, 60.76	1.96, 96.04, 194.04
PAN coord → Dev multicast	Number of Hops (avg, max)	3.8, 5	14, 16	45.5, 50
	Transmission Delay (min, avg, max)	9.8, 13.72, 17.64	45.08, 52.92, 60.76	158.76, 178.36, 194.04

Table 4-Power consumption

Comm. Type	Device Type	11x11	33x33	100x100
PAN coord → Dev broadcast	PAN Coordinator	1.058mAh/day (5y 65day)	1.321mAh/day (4y 54day)	3.747mAh/day (1y 168day)
	Device	0.4103mAh/day (13y 129day)	0.4103mAh/day (13y 129day)	0.4103mAh/day (13y 129day)
PAN coord → Dev multicast	PAN Coordinator	1.0267mAh/day (5y 122day)	1.0281mAh/day (5y 120day)	1.0308mAh/day (5y 115day)
	Device	0.4103mAh/day (13y 129day)	0.4103mAh/day (13y 129day)	0.4103mAh/day (13y 129day)
Dev → Dev unicast	Source Device	0.488mAh/day (11y 83day)	0.488mAh/day (11y 83day)	0.488mAh/day (11y 83day)
	PAN Coordinator	1.135mAh/day (4y 302day)	1.135mAh/day (4y 302day)	1.135mAh/day (4y 302day)

V. CONCLUSIONS

The LPWMN can be applied for the area network to provide deterministic-latency and scalable wireless mesh connectivity. The topology construction, routing recovery time, and transmission delay are dictated by the length of beacon interval, but the LPWMN allows minimum transmission overheads and low processing time for route selection and route update.

ACKNOWLEDGEMENT

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