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Information technology — Specification of low power wireless mesh network over channel-hopped TDMA links

Technologies de l'information — Spécification des réseaux maillés sans fil à faible puissance par liens AMRT à saut de canaux

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Foreword

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The committee responsible for this document is ISO/IEC JTC 1, *Information technology*, SC 6, *Telecommunications and information exchange between systems*.

Introduction

This working draft defines the protocol for the low-power wireless mesh network over channel-hopped TDMA links (LPWMN). The objective of LPWMN is to define a wireless mesh network specification, which is relatively lightweight compared to the legacy WPAN network specifications and can maximize usefulness of the channel-hopped TDMA link which is followed by the deterministic and synchronous multichannel extension (DSME) MAC specified in IEEE 802.15.4e-2012 amendment.

In recent years, there is market demand for applying the low-energy short range communication of the WSN to the networks for mission-critical services or real-time services including remote monitoring and alarming of health devices or medicine equipment, sensing and actuation control of process automation, and voice service over the low-energy short range networks. To provide more reliable link and deterministic delay for the mission-critical services, enhancements of the IEEE 802.15.4-2006 MAC specification was started in March 2008 and the draft of the amendment is approved in February 2012. In the IEEE 802.15.4e-2012 amendment, three types of TDMA and two types of channel diversity function are added as optional MAC features.

These new MAC features introduce two attributes to be managed in the network layer, which includes time slots and radio channels. To employ the new enhanced MAC for the reliable and real-time services in the low-cost, low-power, short-range communication network, the network protocol needs to be designed for managing the network resources including time slots and radio channels. The LPWMN is a network specification over the DSME of IEEE 802.15.4e-2012 amendment. The LPWMN is applicable to industrial applications that require a loss sensitive large wireless network guaranteeing deterministic end-to-end delay with low-power resource-constrained communication nodes.

The International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) draw attention to the fact that it is claimed that compliance with this document may involve the use of a patent concerning the functional procedure and message structure of LPWMN given in Clauses 5, 6, 7, and 8, and a patent concerning the authentication and key establishment protocols given in Annex B.

ISO and IEC take no position concerning the evidence, validity, and scope of this patent right.

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Information technology — Specification of low power wireless mesh network over channel-hopped TDMA links

1 Scope

This International Standard defines the network specification for devices, which 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, to provide low-cost communication network that allows reliable, deterministic-latency, and scalable wireless mesh connectivity.

This International Standard provides the following:

— DSME MAC link control;

— unbalanced cluster-tree based network formation;

— directional multiple grades mesh connection;

— link-path routing and data forwarding;

— link and link-path maintenance.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEEE Std 802.15.4-2011, *IEEE Standard for Local and metropolitan area networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)*

IEEE Std 802.15.4e-2012, *IEEE Standard for Local and metropolitan area networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs), Amendment 1: MAC sublayer*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
coordinator
device in a low-rate wireless personal area network (LR WPAN) that provides synchronization services to other devices in the LR WPAN

3.2
device
any entity containing an implementation of the IEEE 802.15.4e-2012 DSME medium access control and physical interface to the wireless medium

Note 1 to entry: A device may be a reduced-function device or a full-function device.

3.3
frame
format of aggregated bits from a medium access control sublayer entity that are transmitted together in time

3.4
full-function device
FFD
device capable of operating as a coordinator

3.5
personal area network (PAN) coordinator
coordinator that is the principal controller of a PAN

Note 1 to entry: An IEEE 802.15.4 network has exactly one PAN coordinator.

3.6
reduced-function device
RFD
device that is not capable of operating as a coordinator

4 Abbreviations

The following acronyms are used in this document.

AKEP	Authentication and Key Establishment Protocols
CSMA-CA	Carrier Sense Multiple Access – Collision Avoidance
DLCE	DSME MAC Link Control sublayer Entity
DLIB	DSME MAC Link network Information Base
DLNE	DSME MAC Link Network sublayer Entity
DLPDU	DSME MAC Link network sublayer Protocol Data Unit
DLSDU	DSME MAC Link network sublayer Service Data Unit
DSME	Deterministic and Synchronous Multi-channel Extension
FFD	Full Function Device
GTS	Guaranteed Time Slot
ID	Identification
IDAP	ID-based Authentication Protocol
IEEE	Institute of Electrical and Electronics Engineers
LPWMN	Low-Power Wireless Mesh Network
LSAP	Light-weight Shared-key Authentication Protocol
MAC	Media Access Control
MCPS	MAC Common Part Sublayer
MIB	MAC Information Base
MLME	MAC Layer Management Entity
MSDU	MAC Service Data Unit
PAN	Personal Area Network

PHY	Physical Layer
PTK	Pairwise Temporal Key
QoS	Quality-of-Service
RF	Radio Frequency
RFD	Reduced Function Device
SAP	Service Access Point
TDMA	Time Division Multiple Access
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

5 General description

5.1 General

The LPWMN is a low cost communication network that allows reliable, deterministic-latency, and scalable wireless mesh connectivity with low-power and low-rate WPAN devices. The main objectives of an LPWMN are optimal utilization of the channel-hopped TDMA links, cluster-tree based mesh network formation, and multiple grade of path selection, while maintaining a simple procedure and a lightweight protocol.

Some of the capabilities provided by this standard are as follows:

— resource management of the DSME MAC links

— beacon-enabled multi-hop network formation

— unbalanced cluster-tree based address assignment

— directional multiple grades mesh connection

— address based mesh routing

— unicast data forwarding with deterministic-latency

— load balanced path maintaining

This standard defines the link network 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.

5.2 Components of the LPWMN

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 link network and forming the link network topology, and interconnects the LPWMN to an external network. The routers join a link 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 5.1. A device typically establishes a star topology to routers and is either the initiation point or the termination point for link network communications. The gateway router is the primary controller of the LPWMN. The gateway router and routers are capable to establish a peer-to-peer topology. All devices operating on a link network have unique 64bit MAC addresses and 16bit link network addresses. The link network address is allocated by the cluster group.

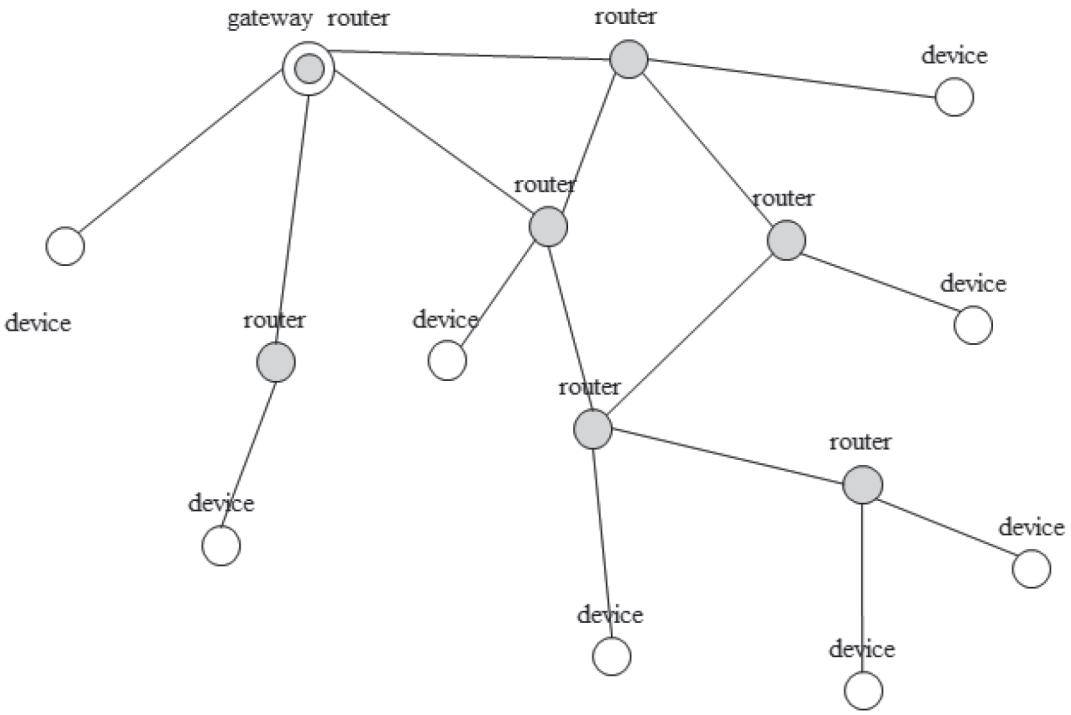

Figure 5.1 — An LPWMN topology

5.3 Architecture of the LPWMN

The reference architecture of the LPWMN is defined in terms of layers, as illustrated in Figure 5.2. The LPWMN provides link control layer interfaces to the next higher layer and link network layer interfaces to the next higher or to the application layer. The LPWMN operates over the IEEE Std 802.15.4e-2012 DSME MAC Sublayer and the IEEE Std 802.15.4-2011 PHY. The LPWMN offers services to the next higher layer.

The LPWMN consists of two sublayers: DSME MAC Link Control sublayer (DLC) and DSME MAC Link Network sublayer (DLN). The LPWMN DLC sublayer entity (DLCE) provides services to the next higher layer via the DSME MAC Link Control sublayer Service Access Point (DLC-SAP). The LPWMN DLN sublayer entity (DLNE) provides services to the next higher layer via the DSME MAC Link Network sublayer Service Access Point (DLN-SAP).

The DLC sublayer provides link connection control, link management services, data transmission on a link, and relaying frames with supporting of the DSME MAC sublayer via the MCPS-SAP and the MLME-SAP.

The DLN sublayer consists of link network formation block, addressing block, routing block, and link network management block, and data processing block which provides receiving function and forwarding function for the frames received from the MAC layer or for the data received from the next higher layer.

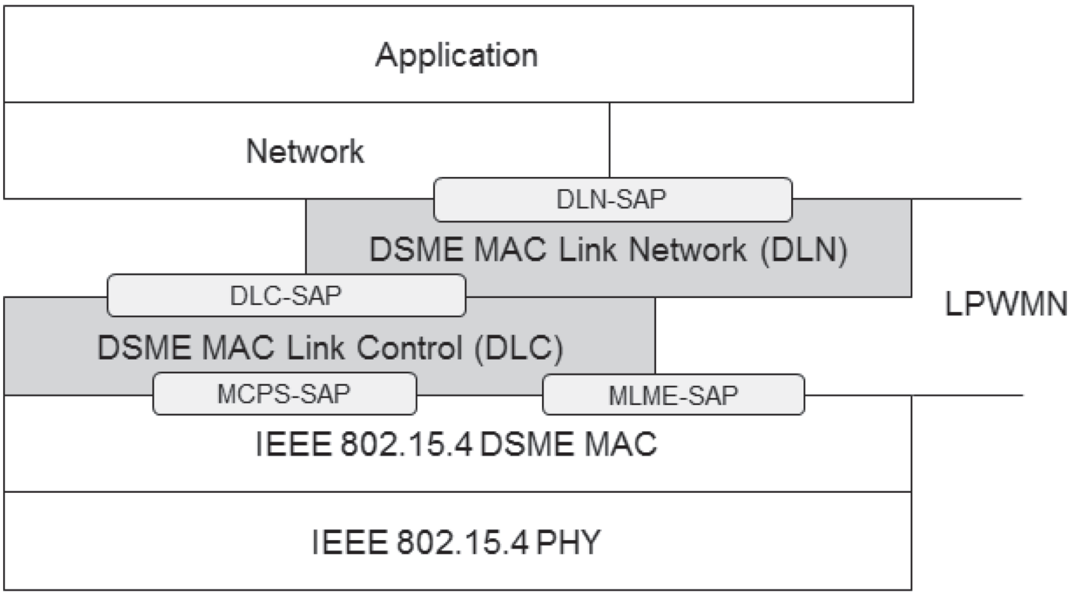

Figure 5.2 — Reference architecture of the LPWMN

5.4 Functional overview

5.4.1 Link network formation

The LPWMN establishes a link between two neighbour devices and a virtual link between two devices multi-hopped apart, as shown in the Figure 5.3. The LPWMN provides a routed link-path, link network, which is constituted of links and virtual links from a source to a destination device.

The link connects the two neighbour devices: link network router 2 and device 3 are neighbour 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 DLN sublayer's routing functions: for connecting between device 4 and device 8, the LPWMN provides several routed link-paths which are the path 1 (device 4 - router 4 - link network router 2 - gateway router - link network router 3 - device 8), path 2 (device 4 - router 4 - link network router 2 - link network router 3 - device 8), and path 3 (device 4 - router 4 - router 5 - link network router 3 - device 8).

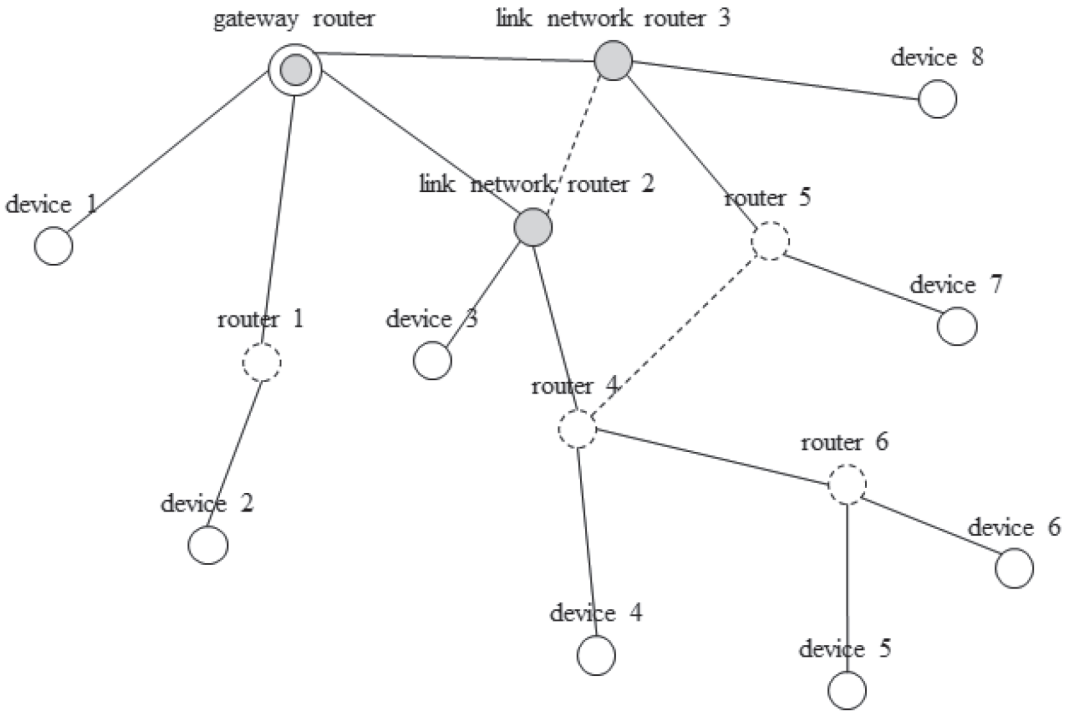

Figure 5.3 — Link, virtual link, routed link-path in the LPWMN

The link network formation of the LPWMN is performed in two stages: link connection and link network routing. In the link connection phase, the DLC sublayer entity of the LPWMN scans the neighbour devices, selects the links to the neighbour devices, establishes connections, and maintains the links. In the link network routing phase, according to the request of the next higher layer of the LPWMN, a set of virtual link is established and/or a set of routed path is established.

5.4.2 Link connection

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 5.4.

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. To allocate the DSME timeslots between devices, the LPWMN issues MLME-DSME-GTS.request primitive with attribute values on the link which are the direction of DSME-GTSs, the number of slots to be allocated, preferred slots, and current information on the slot availability in one hop neighbourhood of the requesting device.

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. The LPWMN provides a primitive for establishing a routed link connection. To form a link-path from a source device to a destination device, each device on the path requests to allocate DSME timeslots. As a result of the success of the routed link connection, the link connection identifier will be provided to the next higher layer of the source device.

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.

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, the recovery procedure, and flow control. The LPWMN provides six types of data transmission.

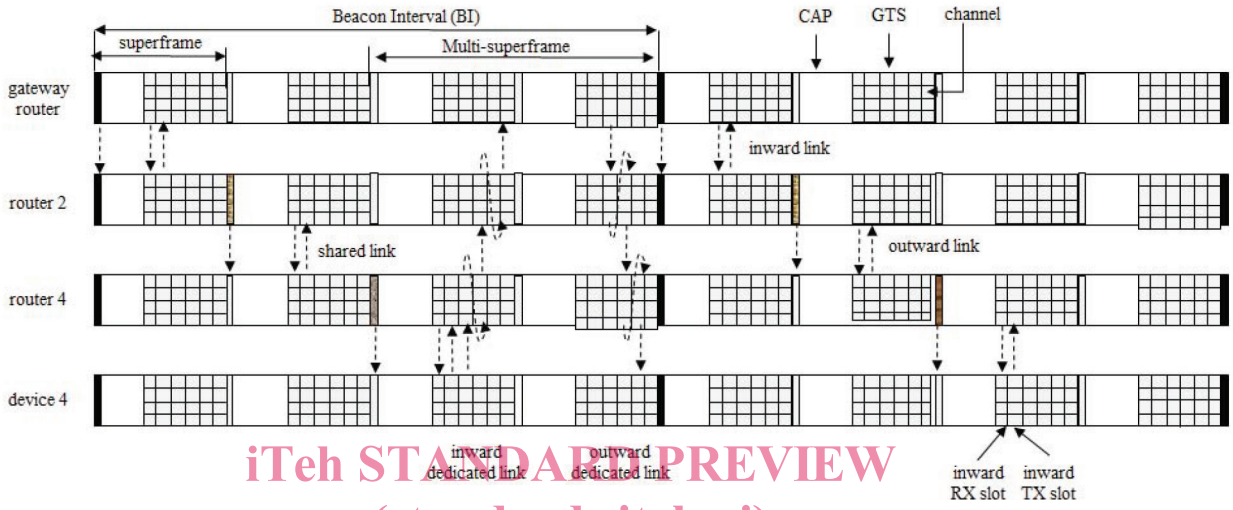

Figure 5.4 — CAP link, shared link, dedicated link of the LPWMN

5.4.3 Unbalanced cluster-tree addressing

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 5.5.

The 16-bit addressing space is divided two parts for identifying a cluster (cluster ID) and a device in the cluster (locator ID). The gateway router manages the cluster identifier space and assigns a cluster identifier when the root router of a cluster joins a link network. The root router of a cluster assigns an identifier 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 $R \neq 1, B(h) = (1+D-R-D*R^{L-h-1})/(1-R)$.

In case of running out of address on the cluster tree or enlarging the network topology dynamically, a router could request assignment of a cluster to the gateway router as a root router of the cluster. The gateway router maintains the connectivity matrix among the clusters. The router provides the cluster-tree routing table based on the cluster connectivity matrix.

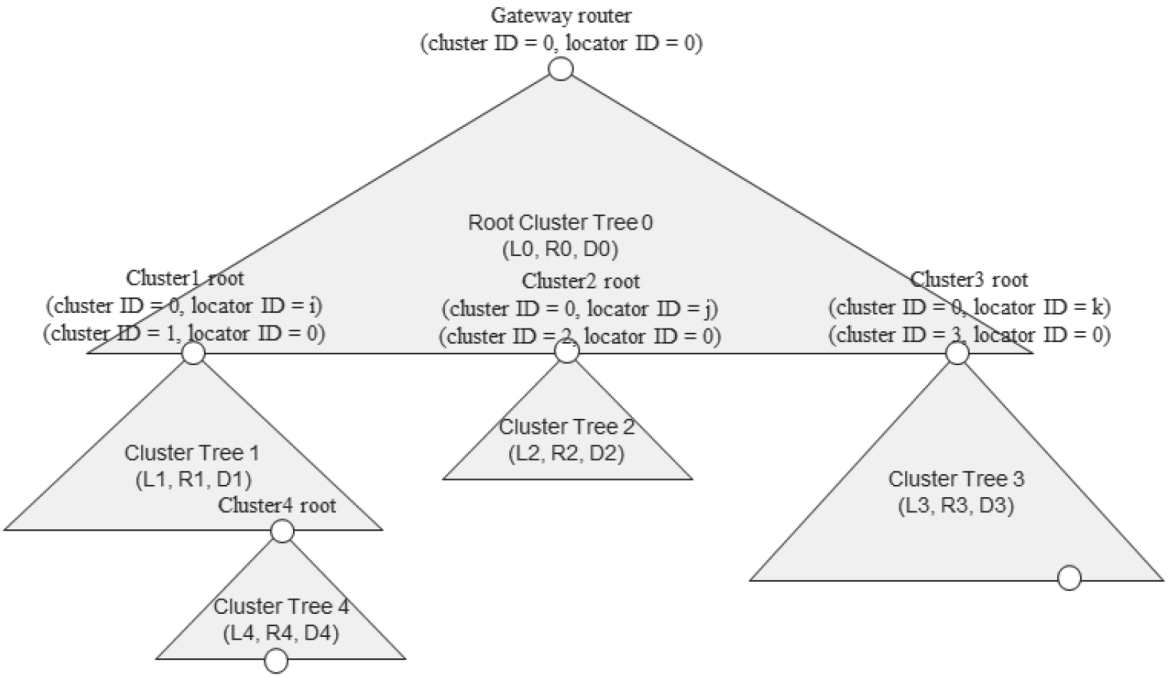

Figure 5.5 — Address assignment based on asymmetrical tree structure

5.4.4 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. To utilize the TDMA MAC optimally, the link 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 channels occupied by nodes within 2-hops range have to be excluded for avoiding the collision by hidden nodes. Based upon the neighbour device information, possible links to the inner router are searched by selecting time slot and channel number pairs.

When a device joins a link network, the cluster connectivity matrix is provided from the gateway router or the root router. The cluster connectivity matrix provides relations among the root routers of the clusters and inter-cluster mesh links. 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 5.6. 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.

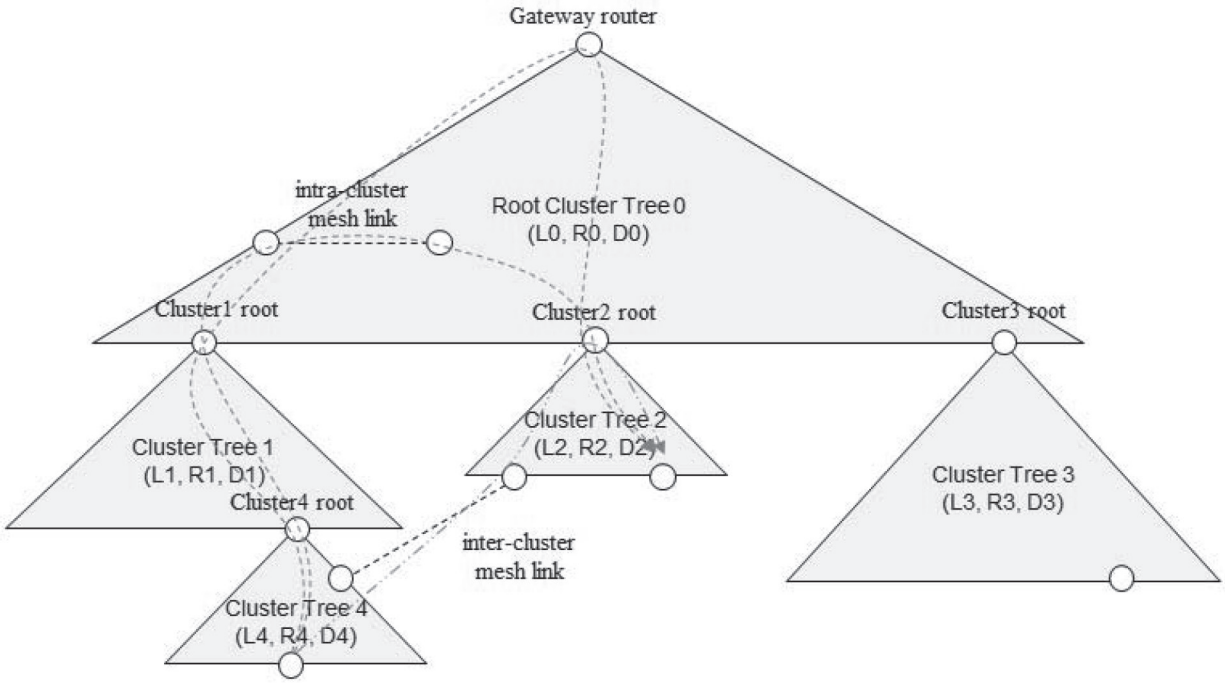

Figure 5.6 — Cluster-tree address based mesh routing

6 Functional description

6.1 Starting the LPWMN

6.1.1 Starting a link network

The gateway router which is not currently joined to a link network shall attempt to establish a new LPWMN. When the next higher layer of the device issues the DLN-START-NETWORK.request primitive, the procedure to establish a new LPWMN is initiated. If the device is not the gateway router or is joined to a link network, the DLNE shall terminate the procedure and notify the next higher layer of the illegal request by issuing the DLN-START-NETWORK.confirm primitive with the Status parameter set to INVALID_ REQUEST.

The DLNE shall reset the MAC sublayer by issuing the MLME-RESET.request primitive with the SetDefaultPIB parameter set to TRUE. The DLNE shall collect the data on the wireless environments and neighbour networks by requesting that the MAC sublayer performs an energy detection scan and an active scan in succession. The DLNE issues the MLME-SCAN.request primitive with the ScanType parameter set to ED and the ScanChannels parameter set to the ScanChannels parameter of the DLN-START-NETWORK.request primitive. On receipt of the results via MLME-SCAN.confirm primitive, the DLNE shall select the channels, whose energy levels are beyond an acceptable level, at most the number of channels specified in the HoppingSequenceLength parameter of the DLN-START-NETWORK. request primitive. The DLNE issues the MLME-SCAN.request primitive with the ScanType parameter set to ACTIVE and the ScanChannels parameter set to the ScanChannels parameter of the DLN-START-NETWORK.request primitive. On receipt of the results via MLME-SCAN.confirm primitive, the DLNE shall review the PANDescriptorList parameter. The DLNE collects the information on the neighbour IEEE 802.15.4-2011 PANs: the PAN identifier, channel number and channel page, superframe specification, and the time at which the beacon frame was received. The DLNE collects the information on the neighbour IEEE 802.15.4e-2012 PANs: the PAN identifier, superframe specification, DSME superframe specification, channel hopping specification, time synchronization specification, and beacon bitmap.