**IEEE P802.15**

**Wireless Personal Area Networks**

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| Project | IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs) | |
| Title | **TG10 / Technical Guidance Document** | |
| Date Submitted | [14th May, 2014] | |
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| Re: | [TG10 TGD] | |
| Abstract | [Full version of the TGD - Working document] | |
| Purpose | [Document Accompanying TG10 Calls for Proposals] | |
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# Overview

Devices that implement the IEEE Std. 802.15.4 are widely deployed and support a variety of applications. The new PHYs and features added in the IEEE 802.15.4g and 802.15.4e amendments (the Smart Utility Network) enable support for smart metering applications operating over longer distances in a Neighborhood Area Network. The use of mesh network topologies is an essential characteristic of these applications, which enables range extension and reliability improvements.

Mesh networks are a class of network topologies where individual nodes have multiple neighbors within communication range. Packets traverse the mesh in multiple hops between nodes. Packets can be forwarded through the mesh along a number of possible paths. Nodes make dynamic decisions of which neighbor to forward a packet to, based on knowledge of the current set of available paths, and metrics related to congestion and signal quality.

Mesh networks may implement packet routing at layer 3 (IP routing), or at layer 2. One approach to layer 3 routing is specified in the RFC 6550 family (IPv6 Routing Protocol for Low-Power and Lossy Networks - RPL). RPL addresses some issues with IP routing over wireless networks such as 802.15.4, but there are still reasons that routing at layer 2 may be preferable. Routing at layer 3 tightly couples the network’s overall IP architecture to the routing, which has implications in IP hop counts, multicasting, fragmentation, and overall efficiency. Routing at Layer 2 enables a mesh network to look more like a single network segment to IP and higher layers.

In many ways, a layer 2 mesh looks like an 802.1 bridge (or a collection of bridges). However, the intended use cases for the 802.15.10 Layer 2 Routing amendment diverge from the design assumptions of 802.1 bridging.

One example is the design philosophy of low-energy, constrained resource network devices that are generally seen in the 802.15.4 family. Low power is implemented in these ways: 1) Low data rates resulting from relatively simple radio physical layers, and 2) MAC layer design to optimize for very low duty cycle operation and extended sleep time.

The combination of these two principles with a multi-hop topology can result in significant delays in forwarding a frame through multiple nodes in a network. Data rates for 802.15.4 range from less than 1 Kbps to over 27 Mbps. In some 802.15.4 PHYs, packet lengths up to 2047 octets are supported, along with data rates in the low kbps range. Transmitting a maximal length packet at the minimum rate would require over 1 S. Even when more practical packet lengths and data rates are considered, the additional delays for synchronizing sleep cycles and multiple hops could easily result in end-to-end delays exceeding several seconds.

This upper bound on packet delivery through the bridged network exceeds the design expectations of 802.1, which call for end-to-end reply within 2 S.

The possibility of delays exceeding 2 S will need to be considered as existing bridging mechanisms specified in 802.1 are considered for application in 802.15.10.

Due to the limited bandwidth of 802.15 networks, the use of broadcast and multicast for establishment and maintenance of bridging operation should be carefully considered, and minimized when possible.

The essence of this amendment is that it must be able to inform flow control and routing using only the information from the MAC and PHY layer. It may optionally supplement it with information from layers 3 and above.

## Methodology for comparison

The methodology is based on a consensus approach to defining a minimal set of features, characteristics, performance and constraints to be considered when making a proposal.

This document provides:

* A functional view of the L2R characteristics, in the form of specific parameters which define externally verifiable performance and interoperability considerations;
* Performance requirements which characterize the Layer 2 routing with any required MAC information elements.

In preparing proposals, this can be used as a framework to produce a concise summary of the characteristics of each given proposal, and will allow the group to see the similarities and differences in submitted proposals.

# Definitions

## Conformance Levels and Requirements Language

The conformance level definitions used in this document follow those in clause 11.2.2 of the IEEE Style Manual.

SHALL: A key word indicating mandatory requirements to be strictly followed in order to conform to the standard; deviations from shall are prohibited (shall equals *is required to*).

SHOULD: A key word indicating that, among several possibilities, one is recommended as being particularly suitable, without mentioning or excluding others; that a certain course of action is preferred but not necessarily required; or, that (in the negative form) a certain course of action is deprecated but not prohibited (should equals *is recommended that*).

MAY: A key word indicating a course of action permissible within the limits of the standard (may equals *is permitted to*).

# Abbreviation and acronyms

CIS Customer Information System

CPU Central Processing Unit

CSL Coordinated Sampled Listening

DR Demand Response

HAN Home Area Network

KMP Key Management Protocol

L2R Layer 2 Routing

MAC Medium Access Control

MIC Message Integrity Check

NAN Neighborhood Area Network

NIST National Institute of Standards and Technology

PAR Project Authorisation Request

PHY Physical layer

QoS Quality of Service

RIT Receiver Initiated Transmission

RF Radio Frequency

TMCTP TV White Space Multi Cluster Tree PAN

TSCH Time Synchronised Channel Hopping

# General requirements

* Use information from MAC and PHY Layer to inform flow control and routing
* This differs from route-over where flow control is derived from information at Layer 3.
* Will not alter the PHY or MAC functionality
* The addition of Information Elements to facilitate the exchange of PHY and MAC information may be considered.
* Support for multi-hop networks in linear topology for greatest range.
* Using 802.15.4g for one-to-many and many-to-one topologies. Supporting monitoring applications, with low duty cycle.
* Support for commercial building automation, interior lighting control, street light control, and similar applications
* These applications have requirements for peer to peer topology (switches or sensors to lights). Many-to-one and one-to-many relationships are required, as well as multicast to support groups of lights. Linear topology is also required for strings of lights. There is sometimes a requirement for mobility to support hand-held controls. There is a requirement for relatively low latency (100mS) for direct manual control of lights. This must be accomplished while maintaining low energy consumption. MAC functionality first defined in 802.15.4e as well as 6TISCH may be applicable. Gateways to building management systems (possibly using 802.3 or 802.11) may be required.

## Summary of PAR

### Scope

This recommended practice identifies protocols that route packets in a dynamically changing 802.15.4 network (changes on the order of a minute time frame), with minimal impact to route handling. The result is an extension of the area of coverage as the number of nodes increase.

### Purpose

This recommended practice facilitates the routing of packets in dynamically changing wireless networks. Specifically it provides for automatic handling of route related capabilities such as:

* Route establishment
* Dynamic route reconfiguration
* Discovery and addition of new nodes
* Breaking of established routes
* Loss and recurrence of routes
* Real time gathering of link status
* Allowing for single hop appearance at the networking layer (not breaking standard L3 mechanisms)
* Support of broadcast
* Support of multicast
* Effective frame forwarding

## High level requirements

* One-to-many and many-to-one topologies
* Support for multiple “concentrator” or gateway functions at the edge
* Support large numbers of hops
* Support for pre-described routes
* Support for route diversity
* Support scalability for large networks
* Multicast support
* Support for device mobility within the network
* Quick Rejoin Capability/Mechanism
* Flow control and routing functions, including congestion management and prioritization (message or path) are able to function using only information from MAC and PHY Layer services. Use of information from other layers is not precluded.
* Support for route optimization and stale node purging
* Support for round trip delays through the entire network exceeding 2 seconds.
* Routing and networking functionality are scalable to operate on devices with limited memory and processing capability.
* Support for routing and network formation implemented in a distributed manner. This does not preclude source routing. Support for storing and non-storing nodes.
* Support for operation with minimal energy consumption and low (RF) power devices
* Multicast support
* Support for “sleepy nodes”, “sleepy routers”, and low duty cycle routers
* Security Aspects
* Must be able to work w/just MAC layer security and compatible w/ KMP (including 802.1x, etc.) mechanisms
* Joining Control
* Quick Rejoin Capability/Mechanism

## Defined behaviors

The defined behaviors should support the following in 802.15.4:

* 802.15.4 2006 and forward
* Non-beacon networks
* Information Elements (not necessarily all of them)
* TSCH
* CSL, RIT
* TMCTP
* All PHYs except for those described in the 15.4F amendment
* Routing between different PHYs

# Use cases/applications

## Use case/application 1 - Smart Metering (HAN and NAN)

The NIST Knowledgebase defines the metering use case as follows:

“Advanced metering infrastructure (AMI): Currently, utilities are focusing on developing AMI to implement residential demand response and to serve as the chief mechanism for implementing dynamic pricing. It consists of the communications hardware and software and associated system and data management software that creates a two-way network between advanced meters and utility business systems, enabling collection and distribution of information to customers and other parties, such as competitive retail suppliers or the utility itself. AMI provides customers real-time (or near real-time) pricing of electricity and it can help utilities achieve necessary load reductions.”

AMI (Smart Meter) use cases include (see doc. # 15-13-0564-00-0010 for details):

* **A Bulk Meter Readings**
* **On Demand Meter Reading from CIS**
* **Remote Programming of Smart Meter**
* **Remote Meter Firmware Update**
* **Meter Remote Connect Disconnect**
* **Outage Notification**
* **Outage Restoration Notification**
* **Real Time Price HAN Messaging**
* **Last Gasp Message**
* **Direct Load Control Event**
* **DR HAN Pricing & Event Customer Opt-Out**
* **AMI Network**
* **DR HAN Device Provisioning**
* **Plug In Electric Vehicle (PEV) Charging at Premise**



## Use case/application 2 - Smart City - Street Lighting/Parking/Meters…

A smart city is considered as one which improves the quality of life of people by leveraging modern communication infrastructure and sustainable economic development. Wireless sensor networks are considered a specific technology to help to create smart cities.

Smart City use cases include:

* **Traffic System**
* Traffic Signal Control
* Parking Guidance System
* Street Light Control
* Real Time Traffic Messaging (board or in car)
* **Environment Monitoring**
* Pollution Monitoring
* Noise Mapping
* Disaster Notification
* **Municipal Administration**
* Water Leak Detection
* Garbage Collection System
* **Structure Monitoring**
* Bridge Monitoring
* Tunnel Monitoring
* Building Monitoring
* **Irrigation Optimization**
* Park Management
* Smart Agriculture
* **CEMS, BEMS, HEMS (City, Building, Home Energy Management Systems)**
* Sustainable Subsistence System
* **Smart Lighting**
* Intelligent Use for Energy Saving
* Control for Personal Use
* Control for Commercial Use

## 

## Characteristics of use cases/applications

Characteristics used in describing the use cases include:

* Data flows
* Topologies
* Routing strategies
* Management
* Communications domains
* Latency vs. QoS vs. reliability
* Power saving

Routing strategies to be focused on include:

* Proactive
* Reactive

Context of the network topology:

* Mesh in particular

# Functional requirements

## Deployment architecture

It should be possible to operate as a self-contained network, without connection to the internet or external network. A self-contained network should offer similar levels of security to that provided when connected to an external network.

It should be possible to merge an independent subnet into a larger network when connectivity between them becomes available, providing both are using similar operating parameters. The merge operation should ideally take place without outside intervention. It should be possible for a network to operate as a number of independent subnets in the event of failure of parts of the network.

## Mesh Topology Discovery

The proposal should provide a method to relearn the network topology in response to changes in the presence of devices, changes in connectivity between devices and changes in the quality of the links between devices as determined by the relevant routing metric(s).

* *The proposal shall enable automatic topology learning, including the status and quality of links between devices*

The proposal may provide a method to trigger relearning as a consequence of an external stimulus.

## Mesh Routing Protocol

The route established between devices will depend on the network topology and routing metrics.

*For the proposal:*

* *A protocol and algorithm using MAC addresses shall be defined for dynamic auto-configuration of MAC-layer data delivery paths between devices in L2R networks*
* *There shall be no logical limit to the number of hops within a route*
* *The routing protocol shall employ mechanisms to avoid creating routing loops*

## Extensible Mesh Routing Architecture

* *The proposal shall define a protocol architecture that allows alternative path-selection metrics and/or routing algorithms to be used, based on application requirements.*
* *The proposal may provide multiple path-selection metrics or routings algorithms that are available for use by the network. Each device shall detect or be informed of which method is to be used.*
* *The proposal shall describe a signaling scheme provided to indicate which metric or combination of metrics is in use within the network*
* *The proposal shall describe how the scheme is extensible to cope with the introduction of other metrics in the future.*

The scheme should provide a means of specifying the order that metrics are applied in the case where multiple metrics are used together in determining the routing decision.

*For the proposal:*

* *It shall be possible for the application or other higher layer to determine the path selection metrics or routing algorithms to be used within the network.*
* *It shall be part of the network formation process to establish the path selection metrics or routing algorithms to be used in the network.*

It may be possible for the path selection metrics or routing algorithms to be changed or updated during the lifetime of the network.

## Mesh Broadcast Data Delivery

* *The proposal shall enable MAC-layer broadcast or multicast data delivery across the L2R network*

## Mesh Unicast Data Delivery

* *The proposal shall enable MAC-layer unicast data delivery across the L2R network*

## Route discovery

* *The proposal shall support at least one technique for route discovery. The technique supported may be proactive or reactive in nature*

The proposal may allow a mix of reactive and proactive route discovery techniques to be present in the network.

It should be possible for the route discovery or route maintenance process to optimize the path of a route based on a metric or combination of metrics. If appropriate, it should be possible to use the data flow over a route as part of the maintenance process for that route.

## Low power operation

The proposal should not preclude the use of devices with limited energy capacity (e.g., energy harvesting, coin cells). The proposal should not preclude the use of techniques such as receiver duty-cycling to reduce the power consumption of all devices in the network.

* *The proposal shall support the use of sleeping end and sleeping routing devices*

## Mesh Security

* *The proposal shall allow the network to operate both secured and unsecured but not at the same time*
* *The security modes of the proposal shall consist of “secured with MIC” or “secured with MIC and encryption” (the use of encryption without a MIC is prohibited)*
* *The proposal shall apply security to the link layer*
* *The proposal shall specify a means to authenticate the identity of a node as part of the network joining process*

The proposal should specify a mechanism whereby security material can be delivered securely to an authenticated node.

* *The proposal shall, wherever possible, use existing methods for authentication, distribution and management of security material*

The proposal should specify a mechanism whereby the security material in a node or group of nodes can be changed or withdrawn. The mechanism should allow the update of security material to be selectively applied, in order to remove previously authenticated but now untrusted devices from the network.

The proposal should specify a method to ensure sleepy devices can maintain communications even when security material has been changed while they have been asleep.

## Routing Metrics

The routing decision may be a result of applying a combination of metrics.

* *The proposal shall base the decision on which link to use to route a packet on at least one routing metric*

## Radio-Aware

Multi PHY interfaces should be supported. Example parameters which may be utilized include data rate, packet size, signal strength, link quality.

* *The proposal shall define at least one radio-aware routing metric for use by the routing protocol(s)*

## Device-Aware

Proposals are encouraged to take advantage of the devices awareness as to its current state and capabilities, such as:

* Energy constraints - remaining energy in battery, duty cycling
* Memory constraints - buffer space availability

## Network-Aware

Proposals may optionally take advantage of available network information.

## Bridge-Aware

Proposals may optionally take advantage of information which may exist regarding routes between bridges or gateways within the network, linked via an external connection implemented in other standards (802.11, 802.1…) which may provide a more advantageous route than routes which exist entirely within the network.

## Discovery and Association

* *The proposal shall enable devices to discover and associate with an L2R network*
* *The proposal shall include mechanisms for identification of a target network*
* *The proposal shall provide a method for joining the target network which will allow the joining device to be authenticated and admitted to the network and provides for the establishment of security material between the joining device and those already on the network*

## Frequency Agility

The proposal should support a method whereby the network can change operating frequencies either as a result of detecting interference or as a result of the underlying MAC configuration.

## Transmit Power control

The proposal may support a method to vary the transmit power of a node based on the proximity of other devices in a network in order to reduce the chance of packet collisions in a busy, dense network.

## Network Acknowledgement

The proposal should provide a means for the sender of a multi-hop transmission to ensure that the message reached its intended recipient. In the case of multiple recipients, there may be no indication of the success or otherwise of the transfer.

* *The proposal shall include a notification mechanism if the message is to a single recipient*
* *The proposal shall, if a notification mechanism is present, enable the notification mechanism on a per-transfer basis*

## Addressing modes

*For the proposal:*

* *64-bit extended addressing shall be supported by the routing protocol*
* *If present, the protocol shall allow the use of short addresses when establishing routes between source and destination devices*
* *If short addresses are required to be used in the network, a mechanism for allocating or choosing short addresses shall be provided as part of the network joining process*
* *If short addresses are used there shall be a mechanism provided to detect and resolve the allocation or choice of duplicate short addresses across the whole network*

## Quality of Service

The proposal should provide a method which allows data with different properties to be treated differently by the routing algorithm. As an example, it should be possible to route traffic with latency-critical properties over lower-latency paths while other traffic may be directed over other paths (more hops, poorer links), or to provide a means to allow higher-priority messages to be transmitted before lower-priority messages over the same link.

## Changes to the MAC and PHY

* *The proposal shall not require modifications to the 802.15.4 PHY or MAC layers with the exception of additional Information Elements to facilitate the exchange of PHY and MAC information*

## Multiple Entry and Exit points

The proposal should support the use of multiple ingress and egress points for data within the network if required by the application(s).

*For the proposal:*

* *Devices shall implement a method to select the most appropriate entry/exit point for their communications with entities outside the network*
* *If a device becomes unable to communicate with an entity outside the network at the required quality of service using its preferred entry/exit point, it shall be possible for the device to find an alternative entry/exit point (if one exists) and begin to use that*
* *It shall be possible for devices to use different entry/exit points to communicate with different external entities*

It may be possible for the protocol to use connections external to the network between ingress and egress points as part of the route between devices within the network (backbone routing).

# Performance requirements

## Scenario for performance requirements comparison

The following simplified scenario has been defined for the purposes of the Call for Preliminary Proposals (CfPP). As such, the scenario has locked down several aspects, some which may be in conflict with the requirements in the TGD. Proposers are reminded that proposals shall support all aspects of the TGD, even though the scenario to be used for comparison during the CfPP phase has tied some of those down. For the Call for Final Proposals (CfFP) a more extensive scenario(s) will be defined.

CfPP Scenario

Network Size & Formation

PAN coordinator is at the center of the grid

During CfPP use 11x11 and 33x33 node networks (99x99 will be added during CfFP)

Assume ~static size of network

Network has already been initialized and all nodes are on the network

Neighbor Range

Nodes have visibility of 3 grid points from itself (neighbor consist of 28 nodes around the node)

Packets are subject to loss through contention or collision

Traffic Pattern

Max. of 1 packet at the PAN coordinator every sec. for upstream traffic

127 byte packet lengths are to be used

No Downstream or peer-to-peer (this will be specified for the CfFP)

(for CfFP the PAN coordinator will send data to each node – specifying the size of packets in bytes and the rate in packets/sec)

Route Update

A random terminal is going off the network every 5min and remains off the network for 10min

Route updates every 1min for 11x11

Route updates every 10min for 33x33

## Memory usage and required memory resource

The proposal may use different techniques within the same network to provide routing decisions when the amount of memory available at some nodes is at a premium. The proposal should provide methods to optimize the use of memory dedicated to routing by promoting re-use. It should be possible to remove routes and reuse the memory based on a number of factors such as amount of available memory, amount of traffic using a route, lifetime, and priority. It should be possible to protect and maintain particular routes while others are allowed to be removed.

* *The proposal shall allow the amount of memory per node used for routing to be configured, in order to allow a mix of devices with different memory sizes to be present in the network.*

Considering also needs to be given to minimum complexity implementations and devices.

* *Proposals shall support the use of devices with only hundreds of bytes of inner memory for the processer.*

## Calculation cost

Calculation costs affect both the energy consumption and propagation delay of the application data.

* *Proposals shall allow for devices to work with the network size and delay requirements described in the use case(s).*
* *Proposals shall allow for devices to work with the energy consumption requirements described in Section 7.9.*

## Control traffic overhead

Control traffic should be minimized.

* *Proposals shall specify the mechanisms to minimize the use of network capacity for control traffic.*

The route acquisition overhead depends on the type of routing. It is defined according to the table below.

|  |  |
| --- | --- |
| **Routing method** | **Overhead for route acquisition** |
| **Proactive:** table-driven. The routes are computed automatically and independently of packet arrivals. (E.g.: DSDV, OLSR) | Typically needs to initialize routing information prior to network operation and maintains the information while the network operates, and updating following link status changes. |
| **Reactive:** on-demand, triggered when a node has a packet to send to unknown destination. (E.g.: AODV, DSR) | A node initiates route discovery prior to sending a packet when the node doesn’t have the route information for the next hop. |

Proposal may use approaches other than the proactive or reactive. A hybrid approach may also be considered/proposed.

* *A proposal shall describe the control traffic overhead (in bytes) for the following cases:*
* *Control traffic when initializing network*
* *Control traffic when updating network*
* *Control traffic when sending data packets*

## Recovery time of link failure

* *Proposals shall describe how the network will detect when local a link failure occurs and how they will attempt to recover for the use cases covered in the proposal, including the time required to recover from the link failure, for the scenario described in Section 7.1.*

## Scalability to network size

The solution should be able to scale in complexity, proportionally to the size of networks being supported.

* *Proposals shall state how the complexity scales with the size of the network, to support the uses cases being covered in the proposal.*

## End to End packet loss ratio

Packet loss ratio and throughput have a dependent relation. These values are dependent on node density, link budget and environmental parameters. The combination/balance of packet loss ratio and throughput should be appropriate for the targeted use case(s).

* *Proposals shall specify the End to End packet loss ratio presumed and related parameters for the use cases covered in the proposal and the scenario described in Section 7.1.*

## End to End data delay

End to end delay and packet throughput also have a dependent relation. These values are dependent on node density, link budget and environmental parameters. The combination/balance of end to end delay and packet throughput should be appropriate for the targeted use case(s).

* *Proposals shall specify the End to End delay and related parameters for the use cases covered in the proposal and the scenario described in Section 7.1.*

## Energy Consumption and life time of battery operated network

Battery operated coordinators, routers and end devices may exist on the network. It is important to understand the impact of routing on the battery life for each of these types of devices.

* *Proposals shall support devices on the network with duty cycles that support the network lifetime requirements described in Section 4, including the uses cases described in Section 5.*
* *Proposals shall include battery life estimations for coordinators, routers and end devices for the scenario described in Section 7.1, with the exception that all routers are sleeping, with a 1% active duty cycle, and there are no end devices.*

An example representation conveying the expected life time of a battery operate device on the network may look like the description below.

Typical parameters for RF power consumption and the battery life associated with those parameters when using an AA battery are as follows:

Consumption of RF+CPU： 40mA in active

　 10µA in sleep

AA alkaline battery： 2000mAh

Battery Life of Routing Device: 0.5 years

For final proposals additional scenarios will be described.

# Regulatory considerations/aspects

Characteristics of supporting Layer 2 Routing may impose limitations or restrictions on MAC and or PHY characteristics, or impose limitations or restrictions on supporting Layer 2 Routing for a particular MAC or PHY in a particular region, due to regulations.

* *Proposals shall adhere to all regional and global regulations for those PHYs in which this draft is targeted to support the Layer 2 Routing capability.*
* *Where, due to regulations, different solutions need to be provided, the relevant regulations giving cause, the differences in the regulations and their impact shall be covered along with the differences in solutions provided.*