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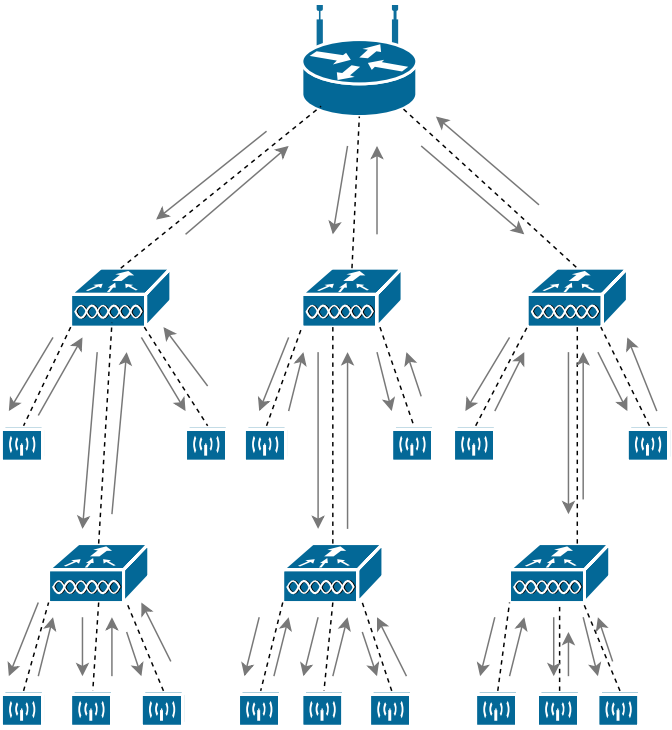

Reliable Wireless Sensor Networks in Smart Homes

Master of Science Thesis in Programme Computer Systems and Networks

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[Cover: Figure 5.1; the proposed round-robin algorithm as described in Chapter 5]

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Abstract

Wireless sensor communications play a key role in the emerging Internet of Things digital ecosystem. As the industry now gets ready to roll out the second generation of IoT-devices, effort is directed to fully standardize the protocol suite of wireless sensor networks, and assure full IP connectivity with devices. The protocols CoAP and MQTT are possible candidates for a highly functional application layer for the Internet of Things in terms of reliable transmissions and adherence to the less verbose attributes of wireless sensor networks where sleep cycles are utilized in an effort to keep the overall power utilization of end nodes low. Given these attributes, the protocols limit the number of messages sent to the minimum necessity in order to convey a current sensor value or actuating data. In neglecting other forms of communications, such as keep-alive correspondence, the element of uncertainty to whether devices are operational or not increases over time given the less verbose approach. This thesis aims to examine the need of basic communication between devices and server in Smart Home settings, in an effort to keep a updated state view of the network, and reduce this element of uncertainty while still trying to comply with the less verbose nature of constrained network environments. With a more immediate and up-to-date view of the network, the server is able to take action at a faster rate when devices in the network fail or are unable to communicate. This will make wireless sensor networks more applicable for soft real time systems where critical devices are used, such as wireless security systems. The thesis aims at providing an application level keep-alive algorithm, which can be independently operable, to serve as a viable option to keep a more up-to-date view of safety-critical devices in wireless sensor networks than offered by current protocols that are implemented in present-day operating systems for the Internet of Things such as RIOT OS and Contiki OS.

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Introduction

The Internet of Things (IoT) is the colloquial term for the interconnection of objects or "things", to the existing Internet infrastructure. These devices, usually small embedded computational devices, will transform our concept of Internet connectivity. By equipping objects such as cars, laundry machines, in-door heating systems, and even our-selves with Internet capabilities, the way that we will interact with these objects and how these objects will interact with each-other will change drastically.

In this new era of technology, it is expected that *Wireless Sensor Networks* (WSN) will play a key role in the information exchange between embedded devices and the Internet. However, wireless communications are not without obstacles and as we allow objects to become connected to the Internet, efforts must be taken to ensure reliable communication given any external impacts such as interference or absorption.

1.1 Purpose of the thesis

Future homes will be able to offer a range of different smart services, e.g. energy, utility, entertainment, medical, and security [1], all of which require a reliable way to transfer information and a way to detect abnormalities such as the disconnection of nodes or interference. All wireless networks are affected by interference which makes timed deliveries hard to achieve. As for wireless sensor networks, not only is it prone to interference, but the network could also experience changes in its topology. Nodes might crash, or be physically moved which will result in changes in the network's topology. Therefore, it is important to consider these asynchronous and dynamic factors in the network.

The purpose of this thesis is to examine and review the currently emerging proto-

cols and technologies together with the generally assumed uses of IoT in smart home environments and propose a method for addressing the *unknown state problem*, where embedded devices may be asleep for long duration of time in order to prolong their battery-life, but which introduces the uncertainty to whether the device is asleep, or if by any other means unable to communicate, such as due to device or link failure.

Some devices are meant to be purely event-driven, that is, they are only to communicate when an event has transpired, this include many detector type devices, such as intrusion detection and smoke detection. As such, other means needs to be taken to ensure that the devices are at full operational capacity when they are not actively transmitting, such as by a time-scheduled *keep-alive* function. With this however, other problems arises, such as how to maintain low battery-consumption among all devices in the network, as increased utilization of the wireless media will elongate wait times according to CSMA/CA.

1.2 Importance of study

The study of fault detection in distributed computing can be traced back to the early onset of computer networks and the the study of *Byzantine faults* [2]. These fundamental principles of fault tolerance and fault detection are immensely applicable for WSN, as wireless communications with battery-operated nodes are at high risk at being exposed to both communication and hardware malfunction.

Currently, a lot of research within the IoT field is carried out, both within academia and the industry sector. However, much of the development has been carried out independently where subtle differences in the implementations has introduced compatibility issues between operating systems for WSN, which may lead to sub-optimal performance in networks consisting of nodes that are running different operating systems [3] [4]. Also, as many of the protocols associated with IoT are not yet fully standardized, different implementations relying on different versions of the protocols' draft, could potentially cause interoperability issues [5].

This thesis presents the *unknown state problem* in Wireless Sensor Networks, and gives an abstract approach on combating the problem while adhering to the requirements and minimalist nature of WSN, and show how this could be implemented as an application layer algorithm, independently of the underlying operative system.

1.3 Previous works in the literature

Works on fault tolerance and fault detection in wireless sensor networks have previously been carried out by among others [6] [7]. A common denominator for these previous works are that they try to find algorithms that are both fault-tolerant as well

as energy efficient, as fault tolerance can not come at a high energy cost since long operation time by battery-operated nodes are of high concern. High redundancy, with the option of powering down the redundant nodes has been suggested [8] [9], but which would inadvertently lead to the higher installation cost and increased complexity of the network. Moreover, evaluation and efforts on fault tolerance mechanisms for WSN standards *IEEE 802.15.4* and *ZigBee* have been presented [10] [11].

Many approaches to achieving both energy efficiency and data consistency have been suggested. The *Alep* protocol suggested in [12], is an adaptive, lazy, and energy-efficient protocol that relies on aggregating data and delaying deliveries to reach energy-efficiency.

On the topic of safety-critical devices, [13] showcases a wireless fire-alarm setting, in where an alarm must be reported to a control station within ten seconds, detection of faulty nodes must occur within five minutes, and have a network lifetime of 3-5 years.

The authors at [14] show strategies for *heartbeat*-style failure detection where gossiping schemes with fixed message transmission rate are used for failure detection. The heartbeat-style gossiping schemes are proposed as routing protocol independent and make use of local broadcast to propagate a heartbeat counter. Due to this, information propagates slowly and at high cost. The paper acknowledge the fact that little research exists as to where probabilistically a lower bound should be drawn as to when to judge if a node has crashed. The suggested approach is robust, but the requirements on accuracy is an open issue, as the trade-off between higher accuracy results in increased latency for the failure detection system.

Another effort is the *Memento* system introduced by [15] that provides failure detection and symptom alerts, with limited bandwidth and power usage. Although effective, this more-advanced approach show considerable detection times when minimizing the false failure reports.

Still, the works of Meier [13] provides in-depth insight to the handling of safety-critical devices in WSN and introduces both a monitoring scheme as well as a forwarding algorithm that show results in simulation and implementation with high on-time delivery ratio, prompt failure reporting, and long network life time. The monitoring scheme called *DiMo*, is a distributed node monitoring scheme that maintains the network topology and monitors the health status of nodes. As such, *DiMo* does not rely on any routing protocol, but rather in an effort to increase efficiency and minimize energy consumption, the tasks of keeping a network topology and monitoring the health status of nodes is combined. This approach is suitable for a network that only consists of safety-critical devices, where no regular data traffic from other devices are expected. The algorithm monitors the network using observer nodes, which receives heartbeat messages from monitored nodes, and if it does not receive a heartbeat within a predetermined time, it will send a report message to the sink. The observer node will also

check the liveliness of the link towards the sink and as such the selection of observer nodes are alternated between relay nodes in the network to maximize network lifetime. Algorithm shows great reduction in the number of false positives reported as well as in the worst-case latency to report missing nodes compared to the *Memento* [15] algorithm. However, *DiMo* was designed with a target at five minutes as the maximum error reporting delay, and follows a rather uniformly time distributed detection time between the order of 30 seconds to 260 seconds. In the simulation-based evaluation, it was able to detect all missing nodes within five minutes, although very few were detected within the first 30 seconds.

1.4 Boundary of the thesis

The Internet of Things consists of many things, with Wireless Sensor Networks being present in smart grids, smart cities, industrial settings and others. This thesis will be focused on the home environment and *Smart Home* implementations, with an assumed number of nodes of about 10 to 100 nodes in a home WSN. As wireless sensor networks has many applications of use, of which implementation might be different to that of smart homes, it is important to make the distinction, as WSNs present in other settings and containing a greater number of nodes will have other concerns and difficulties to overcome.

1.5 Outline of the thesis

The outline of the thesis is as follows:

Chapter 2: Wireless Sensor Networks serves as a guide to the current technologies and protocols that have been developed to give a basis for IoT and Smart Home devices. The chapter focuses on the *IEEE 802.15.4* standard, the *6LoWPAN* networking protocol, the routing protocol *RPL*, and the application layer protocols *CoAP* and *MQTT*.

Chapter 3: Challenge presents the *unknown state problem* and investigates how the current protocols are set up to handle the obstacle of monitoring safety-critical devices given the energy-restricted nature of WSN.

Chapter 4: Methodology serves to illustrate which tools are used in the development of WSN and IoT devices. It describes the operating system programming approach to developing WSN software, how native programming is used to test software

and classifies the device types, which is used to build and test the proposed algorithm given in the subsequent chapters.

Chapter 5: Design of the proposed method provides an approach to the *unknown state problem* based on a *round-robin* message flow as to limit the total amount of messages required to carry out a *keep-alive* sequence. By utilizing end nodes to forward the keep-alive message to other end nodes, the total number of messages required per keep-alive round can be drastically reduced as compared to a fully centrally coordinated keep-alive sequence.

Chapter 6: Results gives the simulated results of the implemented algorithm introduced in the *Design Chapter* by using the *RIOT OS* as the base operating system, together with the virtual topology tool *Desvirt*. The simulation environment provides proof-of-concept for the algorithm and facilitates data on message complexity to be visualized.

Chapter 7: Discussion investigates the possible obstacles and short-comings of the designed algorithm in accordance to the specification of wireless sensor networks. Items such as power consumption and security is discussed. By the end of the chapter some open issues are mentioned.

Chapter 8: Conclusions delivers some concluding remarks about the thesis.

2

Wireless Sensor Networks

The Internet of Things can be deployed using any Internet capable technology, such as Wi-Fi, Ethernet, or cellular networks. These technologies are all well established and fully functional for Internet communications and as such are suitable to be a part of the backbone of the Internet of Things. However, the requirements of the Internet of Things differentiate from the current use of PCs, laptops, smart phones and other peripherals that are connected to the Internet.

Firstly, for general Internet use the increase of bandwidth has been a corner stone in development of the services associated with the web 2.0, such as streaming media, cloud storage, and remote applications. For the Internet of Things however, the individual bandwidth requirement per device is low, as most devices will only collect and send sensory data, or receive actuating data [16].

Secondly, IoT devices do not require a user interface as what is normally expected when working with connected devices. Rather, IoT devices are capable to function and make decisions without human intervention. Devices may collect data, the data might then be processed by some application and a suitable action could then be executed accordingly to some pre-configured algorithm or self learned pattern recognition software.

As a third differentiating factor, the scale of the Internet of Things will be much greater than that of current connected devices, which will require an Internet backbone capable of handling a large amount of devices. The Cisco Internet Business Solutions Group (IBSG) predicts that the number of connected devices could be as high as 50 billion by 2020 [17], of which a majority is assumed to be small and constrained devices. Other estimates include Gartner's [18], which predicts there to be a total of 4.9 billion connected things in 2015, and total of 25 billion by the year 2020. With all IPv4 addresses being exhausted [19], the rapid expected growth of the Internet of Things means that the roll-out of IPv6 is ever so important in order to accommodate for the

Internet of Things.

Wireless Sensor Networks usually consists of a number of battery powered sensor and actuator devices, which are typically constrained in terms of storage and processing power. For example, there exists a number of different devices with dimensions comparable to that of common circulating coin or less, equipped with as little as 1 kB of RAM and 8 kB of flash memory [20]. These types of devices are known as *sensor nodes*, or in some cases as *motes*.

Wireless communication has the advantage of being easy to implement in already constructed buildings, as it requires no extra installation of wires. As devices are not bound by wires, they can also move freely around the building, making wireless communication ideal for wearable items and other none stationary devices.

This chapter will focus on a subset of technologies and protocols used with Wireless Sensor Networks, many of which are still undergoing development. Table 2.1 shows the protocols in accordance to the general Internet Protocol layer categorization model.

The *IEEE 802.15.4* standard is a *Physical* and *Data link* layer correspondent for WSN, representative for *Ethernet* using twisted pair cable, or to that of 802.11 (Wi-Fi) for *Wireless Local Area Network*. The *Network* layer equivalent is the *6LoWPAN* protocol, which is *IPv6 over Low power Wireless Area Networks*, and to supply routing capabilities, the routing protocol *RPL*. For the *Transport* layer, both *TCP* and *UDP* can be used, however, due to the low-power consumption features of WSN, where nodes are able to enter sleep mode for long duration of time, it has been argued that *TCP* is less suitable to be used in WSN [21]. Finally, this thesis work has chosen to look at the *Application* layer protocols *MQTT* and *CoAP*, which are both light-weight protocols suited for WSN.

Layer	**Protocol**		
Application	MQTT	MQTT-SN	CoAP
Transport	TCP	UDP	
Network	6LowPAN with RPL		
Physical and MAC	IEEE 802.15.4		

Table 2.1: A representation of the technologies and the corresponding layer.

2.1 IEEE 802.15.4

The *IEEE 802.15.4* standard specifies the *Physical* (PHY) layer and the *Media Access Control* (MAC) for *Wireless Personal Area Networks* (WPAN)[22] and corresponds to the first layer given in the model in Table 2.1. It was defined in 2003 by IEEE to fill

a gap in existing wireless network standards. IEEE constructed the standard with the following set of criteria [22]:

- Very low complexity
- Support for multiple-node networks
- Ultra low power consumption
- Low data-rate
- Relatively short communication range
- Using unlicensed radio bands
- Low Cost

With these criteria the standard is set aside from other wireless standards such as the *802.15.1* (Bluetooth) which is intended for point-to-point communications and not for multiple-node networks, and from the *802.15.3* which is designed as a High Rate WPAN.

Primarily, the 802.15.4 standard is devised for very low power consumption, making it possible to make use of battery-powered devices which are totally wireless (equipped with neither network or power cables) for easy and cost-efficient installations.

2.1.1 Data rate and range

The standard has a maximum data-rate of 250 kbit/s depending on which modulation scheme and frequency band that is used. The range is dependent on operating environment as well as output power of the antennas, which usually is kept low in battery-operated devices to conserve power. Typical ranges are above 200 meters for outdoor uses and about 30 meters in indoor uses depending on factors such as absorption, reflection and diffraction due to walls and other objects [22].

2.1.2 Frequency bands

The IEEE 802.15.4 defines two different PHYs, one to be used with regional bands and one PHY for the global 2.4 GHz frequency band. The two original regional frequency bands are 868.0-868.6 MHz for Europe which only has one channel numbered as 0 and the 902-928 MHz for North America which is divided in to ten channels numbered 1 to 10. Since the original specification, more regional frequency bands has been added through amendments to the standard to be used in China and Japan. The worldwide band of 2400-2483.5 MHz is divided into 16 channels numbered 11 to 26. As the global

2.4 GHz band is commonly used for other communication systems, such as Wi-Fi, Bluetooth and cordless phones, it is important to choose a suitable channel, as to avoid potential disturbances from other communications.

2.1.3 Transmission and power saving features

Most of a node's power usage will correspond to the amount of time it spends on listening or transmitting data [23] [24] [25]. IEEE 802.15.4 make use of very low duty cycles to keep the transmission times short. A duty cycle is defined as the time interval for when the node is transmitting or is actively listening on the network, which is then followed by a long interval of no transmission or listening. By making the duty cycles short, and the time intervals between the transmitting and listening phase long, power is conserved, as the node is able to enter a low-power sleep mode between duty cycles. As a direct consequence of this, nodes are not able to receive transmissions while in sleep mode, messages intended for sleeping nodes are therefore stored, and later retrieved by the receiving node by sending a request message for incoming messages when it enters the duty cycle.

2.1.4 Security

The standard has built-in security services, as it can optionally use *Block Cipher Mode* to encrypt the traffic. It can be configured to either use *Counter Mode* (CTR) or *Cipher-block Chaining* (CBC) with AES, but key management must be provided by higher layers. The 802.15.4 frames contains *Frame Control Fields* and sequence numbers and as such, these cryptographic mechanisms will provide the security services of *Data Confidentiality*, *Data Authenticity* and *Replay Protection* when in use.

Using a link-layer level security has the advantages of being hardware realisable and being network protocol independent. However, link-layer security will only provide security on a hop-by-hop basis, meaning that every node that the message passes through must be a trusted node, and if the message leaves the 802.15.4 network the link-level security will no longer be available, thus an end-to-end security can not be achieved purely by using link-layer security.

2.1.5 Device types and device classes

Nodes are divided into *Device Types* according to their functionalities and into *Device Classes* according to their capabilities.

Device types

There must be one and only one **PAN Coordinator** in an 802.15.4 network. The PAN Coordinator assigns a PAN ID to the network, and assigns itself a short address. It handles requests from other devices which wishes to join the network and assigns them a short address. It is also responsible of performing an energy scan to select the most suitable channel to use for communications. Depending on the topology used, it also relays all or some of the messages sent. In practice, the coordinator is the edge of the network, and bridges the network towards the Internet. Given that the coordinator make use of another network interface which may or may not be incapable of supporting sleep mode, and given the communication flow of 802.15.4 networks, which in some cases does not support the PAN coordinator to enter sleep-mode, this device type requires more power usage than other nodes in the network, making it less suitable to run on battery.

The **local coordinator**, also known as the router, is a device capable of relaying messages from and to other nodes. In a network there can exist many local coordinators, each with the capabilities of handling requests when other nodes wishes to join the network or relay their messages.

The **end devices** are nodes connected to either a PAN Coordinator or Local Coordinator, which are not able to relay other nodes messages. Usually, these are low-power consuming devices, which have a high sleep to work ratio, and are only set to wake up to handle incoming messages or transmit data. In essence, these end devices can be battery-powered with a very long battery-operating time [26].

Device classes

The device class **Full Function Device** (FFD) is capable of being a PAN coordinator or a local coordinator as well as an end device. All PAN coordinators and local coordinators must be an FFD.

The device class **Reduced Function Device** (RFD) has a simpler subset of the 802.15.4 protocol, with restricted processing and memory resources, making it incapable to act as a PAN coordinator or local coordinator.

2.1.6 Superframes

The standard has the optional functionality of using *superframes*. The superframe is defined by the PAN coordinator which transmits network beacons where the interval between the beacons is divided into 16 equally sized time slots. Such a network is referred to as a beacon-enabled network. There is also another mode where the superframe is enlarged by an inactive period, allowing for the coordinator to enter low-power mode during the inactive period.

2.1.7 Contention Access Period & Contention Free Period

Any device that wishes to communicate in a beacon-enabled network will do so during the *Contention Access Period* (CAP) between two beacons. All devices are using slotted CSMA/CA, which does not guarantee timed transmissions. There is however a function, named *Guaranteed Time Slots* (GTS) which takes place during a period known as the *Contention Free Period* (CFP) which the coordinator may choose to use. The coordinator may allocate up to seven GTSs in a CTS which takes place right after the CAP. In the CFP, the coordinator may allocate a certain GTS for one specific device, making that device the only device allowed to communicate during that GTS. This guarantees that the device will always be able to communicate during its GTS in every superframe. The use of GTSs is suitable for nodes which require low-latency or a specific amount of data bandwidth.

Device to coordinator

In beacon-enabled networks, a device that wishes to send a message first needs to listen for the network beacon. When the device receives a beacon, it becomes synchronized with the beacon-enabled network. The device will then transmit its message to the coordinator using slotted CSMA/CA or simply send the message during its allocated GTS if in use.

In a nonbeacon-enabled network however, the nodes will simply engage in unslotted CSMA/CA whenever it wishes to transmit a message.

Coordinator to device

As an end device might be in sleep-mode, the coordinator can not simply transmit a data message to the device. In a beacon-enabled network, the coordinator will indicate that there is a data message pending for a device in the network beacon. End devices are not obliged to listen to every network beacon, so the coordinator will keep the data message and the indication in the network beacon until the device receives the beacon. When the device receives the network beacon, it will transmit a *Data Request* message to the coordinator, using slotted CSMA/CA, after which the coordinator will send the data message to the device.

For nonbeacon-enabled networks, the coordinator will store the data message and wait for the device to make contact. Devices will periodically send a *Data Request* message to the coordinator, to which the coordinator will respond with an acknowledgment frame indicating whether there is a pending message, in which case it will transmit the data message using unslotted CSMA/CA.

2.1.8 Frame size

802.15.4 only support a maximum frame size of 127 bytes. After accounting for the frame header, and optional link-layer security, even less is available for the layers above. This requires that the upper layers are well-suitable for small frame size transmissions, in order to avoid unnecessary link-layer fragmentation. Also, when considering that the protocol should attain ultra low power consumption, every extra byte that is required to be transmitted due to protocol-specific headers, can be directly translated in to a higher power utilization. For example, the IPv6 header is 40 bytes long, which would leave little space left for the application data and thus requiring more frames to be sent if the application data is larger than the available space left after applying the headers.

2.1.9 Topologies

Every 802.15.4 network must consist of at least two devices, of which one and only one must be a PAN coordinator. IEEE 802.15.4 networks can be build as either Peer-to-Peer or as star networks shown in Figure 2.1.

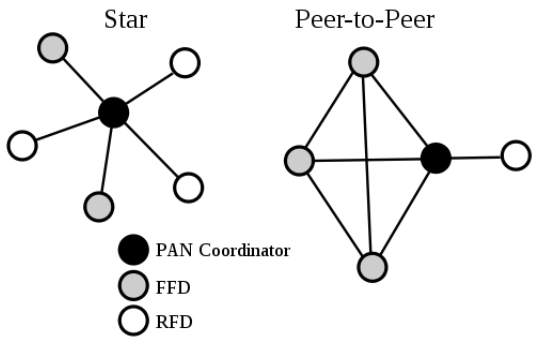


Figure 2.1: IEEE 802.15.4 Star and Peer-to-Peer topologies.

Star topology

Star Topology is a network type where a central PAN coordinator is directly connected to all other devices which are end devices. All messages must be send to the coordinator, which will then relay the message to its final destination. The disadvantages with this kind of topology is that the coordinator becomes one central point of failure, if the coordinator fails, no other messages can be delivered as there is no alternative route. Also, the coordinator might become a bottleneck and cause congestion if there is a large number of end devices. The network is also limited in physical size, as any end device must be in radio vicinity of the PAN coordinator.

Peer-to-Peer

Peer-to-Peer, also known as mesh topology makes it possible for devices to communicate directly. Devices that are not within range can communicate with each other by relaying the messages through intermediate devices, without the use of the PAN coordinator. This reduces the bottleneck effect on the PAN coordinator as well as the

message complexity. Since devices do not need to be directly connected to the PAN coordinator, the physical range of the network can be much larger compared to a Star Topology network. However, as nodes may route and handle messages that do not originate from themselves or for which they are the end destination, these local coordinators will consume more power. Not all devices are required to relay messages, and relay paths can be calculated and recalculated according to preferences such as battery-level.

Other topologies are possible, although not part of the IEEE 802.15.4 standard, they may be implemented on higher layers by other protocols, such as 6LoWPAN.

2.1.10 Acknowledgments

Frames can be sent with or without acknowledgment request. If the *Acknowledgment Request* flag is set for a frame, the sender will wait for a predetermined amount of time for the corresponding acknowledgment to be received.

If the transmission was indirect, that is, a data message that was preceded by a *Data Request* message, and no acknowledgment was received, the coordinator will not retransmit the frame, but the frame will remain in the transaction queue of the coordinator and will only be sent if the coordinator receives a new data request command. If such a command is received, the originating device will then retransmit the frame.

For direct transmissions, i.e. from device to coordinator, the device will repeat the transmission of the frame if it does not receive the acknowledgment. The number of times that it will retransmit the frame is set in a variable (definable in the range of 0 to 7 times, with the default value being 3 times). The retransmission will only be attempted if it can be completed within the same portion of the superframe, that is, the CAP or GTS in which the original transmission was made. If this is not possible, the retransmission will be delayed until the same portion of the next superframe. If the device has still not received an acknowledgment after its maximum amount of retransmissions, the MAC sublayer will consider the transmission failed and will notify the next upper layer of the failure.

2.2 6LoWPAN

Using an Internet Protocol with 802.15.4 networks has many advantages. Resources within the network will be available on the Internet without the need of translations. Already well-proven and readily used protocols such as UDP, TCP, HTTP, FTP and so forth can be used directly, which makes development easier.

Given the presumed growth of the number of connected devices, the only reasonable option to comply with IP technology and have adequate amount of address space for IoT is to make use of IPv6. Clearly, the Internet backbone must support IPv6 fully in

order to accommodate with the increased quantity of connected and address-requiring devices. Even so, the usage of IPv6 in WSN presents some obstacles as to comply with the constrained and minimalist nature of the underlying architecture.

The IPv6 specification [27] requires that links support a *maximum transmission unit* (MTU) of at least 1280 bytes. This pose a problem since IEEE 802.15.4 has a maximum frame size of 127 bytes, of which a considerable part is used for the frame overhead and optional security features. For example, using the AES-CCM-128 security implementation for 802.15.4 could leave as little as 81 bytes for the upper layers [22].

In regards to this, the *IPv6 over Low power Wireless Personal Area Networks* (6LoWPAN) [28] specification was formulated as a means to facilitate IPv6 networking on constrained devices running 802.15.4. 6LoWPAN is in essence IPv6, with a few modifications in order for it to run in Wireless Sensor Networks where the frame size is much smaller than the minimum MTU of IPv6.

2.2.1 IP header compression

The IPv6 header is 40 bytes long, add to that the 802.15.4 MAC header, and a header for the transport protocol, such as the UDP header and the effective payload of one frame cold be as little as 33 bytes when link-security is used. Obviously, the ratio of payload to header information is not that effective when low frame sizes are used. Instead, 6LowPAN makes use of a variable sized header to improve this ratio. Link-local IPv6 addresses are compressed according a loss-less compression principle, where any parts of the address which could be calculated from the context, are omitted [29]. The compression is purely loss-less compression, and therefore a stateless compression, requiring no devices to keep a record of the compressed data.

2.2.2 Fragmentation

As IPv6 has a minimum restriction of 1280 bytes for the MTU, 6LoWPAN must be able to handle IPv6 packets of at least this size. This is solved by making use of fragmentation. An IPv6 packet will be divided into a multitude of fragments, where the first fragment will carry a header containing the size of datagram and a datagram tag. Every subsequent fragment will then carry an offset, indicating its place in the fragmentation, and the datagram size and tag. The fragments will be stored by the receiver for up to 60 seconds in order to receive all fragments for reassembly[29].

2.3 Routing with RPL

As nodes only covers a limited range, routing is often required. As for all wireless links, *Low power and Lossy networks* (LLN) are affected by the environment, where acts such

as starting a microwave can cause disturbances or physical changes such as doors or furniture being moved can cause absorption and reflection, making links temporarily or permanently unreliable.

The need for an IPv6-based routing solution for wireless sensor networks was recognized by the IETF in 2008 with the formation of the working group ROLL (*Routing Over Low power and Lossy networks*). The working group found that existing routing protocols such as OSPF, IS-IS, AODV, and OLSR were not satisfying in their current form to the specific requirements of LLNs.

The working group has since focused on developing an architectural framework for IPv6 routing in LLNs, which considers the lossy characteristics of such a network and the low-power and modest hardware specifications of nodes. Another important aspect is the scalability, as LLNs could potentially have a very large number of nodes.

The group acknowledged the fact that that there is a wide scope of application areas for LLNs, and that the routing requirements differs according to the application area. As such, as their first order of business the group defined the routing requirements for a set of areas: Urban [30], Building [31], Industrial [32], and Home Automation [33] sensor networks.

Following this, the "*Ripple*" routing protocol (RPL) [34] was introduced along with specifications on routing metrics [35], objective functions [36] and security.

2.3.1 DODAG build up

RPL is a pro-active routing protocol and its key fundamental lies in the build up of the DODAG (*Destination Oriented Directed Acyclic Graph*). The process of building up the graph starts with the RPL root, which usually coincides with the LBR (*LoWPAN Border Router*). A set of ICMPv6 messages are used to exchange graph information, namely DIS (*DODAG Information Solicitation*), DIO (*DODAG Information Object*) and DAO (*DODAG Destination Advertisement Object*).

The root will advertise its existence on the network by using a DIO message and neighbouring nodes will process the DIO message based on pre-configured rules. The node can choose to join the graph or not according to these node-specific rules. If the node decides to join the graph it will have a route towards the RPL root, known as the "parent". It will also compute a "rank" of itself in the graph, which will indicate its position within the graph as shown in Figure 2.2.

If the node is configured as a router, it will forward the DIO message, which it will modify according to the rank of the node, to its neigbouring nodes. However, if the node is configured as a "leaf node", it will only join the graph, without forwarding any DIO messages. This process will continue until the whole network is converged, that is, until every router and leaf node in the vicinity of another graph-connected node has received the DIO message and processed its information. Every graph-connected node will as such have a routing entry with a parent towards the RPL root and data packets

will be able to flow upwards in the graph. Depending on the Objective Function used by a node, a node could be configured with either one or more than one parent.

If a new node wishes to enter the graph after its convergence, the node will send a DIS message which solicits graph information from its neighbouring nodes, which will cause the neigbours to send out a DIO message.

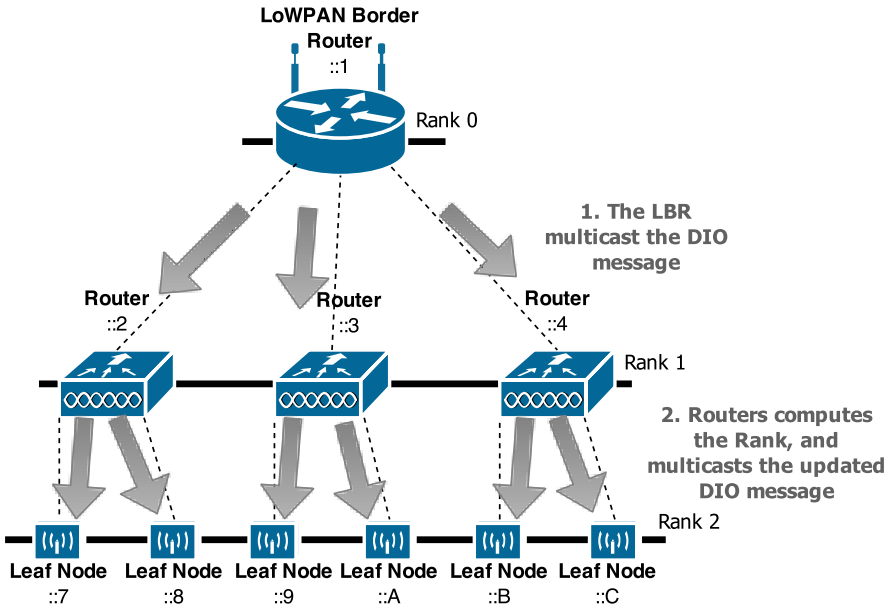


Figure 2.2: The "rippling"-like distribution of the DIO message in RPL.

Reversely, for traffic to be able to travel downwards in the graph, a routing state is required at every node. The DAO message is used to advertise reachability towards the leaf nodes. Whenever a node joins the DODAG, it will send a DAO message to its parent, containing information of underlying nodes. DAO messages can also be requested by a node or the root by an indication in the DIO message.

When a node receives a DAO message, it will add the entries to its routing table, append any other routes that it knows of to the DAO message, and send the message to its parent. This is known as "storing mode", and could be used when nodes have enough memory to store the routing tables. Contrary, RPL also supports "non-storing mode", where nodes will not store any routes, but merely forward the DAO message upwards in the graph. In a network using the non-storing mode, a data packet will have to travel all the way up to the RPL root where the routing table is stored, the root will then calculate the path and store this path in the source routing header of the packet, and send it to the next-hop node. Each node along the path will then examine the source routing header and send the packet towards the corresponding child node.

Although non-storing mode requires less memory from nodes, the source routing header will cause the packet size to increase, which will lead to more power and

bandwidth consumption.

2.3.2 Multi-topology routing

RPL has the added functionality to perform *multi-topology routing* (MTR). Basically, using different instances, multiple DODAGS can be constructed over the same physical topology, and associated with its own instance id. A node can belong to several instances simultaneously, and traffic could be directed using different instances according to the traffic type. For example, non-critical traffic can be routed to avoid battery-powered nodes, whereas critical traffic could be routed along the path with the least amount of latency. Other parameters that could be taking into account when building up multiple DODAGs are reliability, link-encryption support, battery-level, and link color.

2.3.3 Routing metrics and Constraints

Routing metrics and constraints [35] are used by RPL in an elaborated decision making routing strategy to select the best available path according to set specifications. Metric is a scalar quantity such as latency, battery-level, or reliability and could be either node or link based. Constraints however, is a non-scalar criterion which is used to specify which links and nodes that can be used when choosing the path, for example to only include non-battery powered nodes in the path or links that can support encryption.

2.3.4 Timers

Whereas regular routing protocols usually make use of periodic keepalive messages to keep the routing tables up date, RPL needs to consider the energy-saving principles of LLNs and therefore limit the number of control messages sent. Instead, RPL implements a self-regulating mechanism known as the "*trickle timer*" [36].

The trickle algorithm uses a variable timer that is the result of the current stability of the network. Events, such as loops, or when a node joins or moves within the network, are treated as inconsistencies in the network and will cause the timer variable to decrease, giving rise to a higher frequency of DIO messages. In contrary, the lack of inconsistencies in the network will allow the trickle timer to increase and subsequently less DIO control messages will be sent.

As the trickle timer is implemented locally, any area of the network that exhibits inconsistencies will have a higher rate of control messages in its vicinity, whereas other areas without inconsistencies will have a lower rate of control messages.

2.3.5 Local and Global repairs

RPL has graph repair mechanisms that allows nodes to take action to repair the graph in case of link or node failures. If a node is unable to communicate with its parent, so that it has no other route in the upward direction of the graph, it can initiate a *local repair*. In a local repair, the node will try to find another parent, by sending out RPL control messages.

This could however cause the graph to diverge from its most optimal configuration, which is why a *global repair* is sometimes necessary. A global repair can only be initiated by the RPL root and will rebuild the DODAG completely, at the high cost of the number of messages required by such an action.

2.3.6 Security in RPL

As security adds an extra level of complexity and therefore adds to the requirements on the hardware, it is not always feasible or desired to include elaborate security features within the RPL implementation. However, there exists security features in RPL which are available as optional extensions [34].

RPL has through these extensions three security modes; "*unsecured*", "*pre-installed*", and "*authenticated*". In the unsecured mode, RPL messages are sent without any security. For the pre-installed mode, a pre-installed key is used which allows the nodes to process and generate RPL messages within an RPL instance. In the authenticated mode, nodes are required to obtain a key from an authentication authority if it joins the instance as a forwarding node.

2.4 Transport layer protocols

Since 6LoWPAN gives wireless sensor networks IP connectivity, both TCP [37] and UDP [38] may be used with 6LoWPAN networks. TCP however, has been often been claimed as unsuitable for WSNs due to the specific requirements of the protocol [21]. As TCP is a connection-oriented protocol, a connection involving the three-way handshake must first be set up before transferring any data. As sensor data is usually only one value, corresponding to at most a few bytes of data, the overhead carried by TCP is large in comparison to the data sent. The handshake procedure will also prolong the transmission of the data, causing sensor data to arrive to its destination later than if UDP was used. One option to reduce the overhead of the three-way handshake and improve on the data latency, is to keep the connection open between transmissions. This however, requires a constant exchange of keep alive messages, which would require a node to wake up from sleep mode to keep the connection alive, even if it has no sensor data to send. This is not desirable when nodes are battery-powered and strive to keep their awake/sleep ratio as low as possible in order to conserve power.

UDP comes with its own set of disadvantages, for example, UDP offers no flow control or congestion control, which might cause dropped datagrams in a congested network. Also, UDP contains no ACK mechanism.

In conclusion, one can argue that neither TCP nor UDP are suitable for WSNs, however, as UDP is such a rudimentary protocol, carrying only a mere 8 byte header, it makes up for its shortcomings due to its simplicity, as the extra functionalities of TCP comes at the price of a higher complexity. Any shortcomings of UDP, such as reliability and the lack of an ACK mechanism could be left to the Application Layer to optionally implement.

2.5 Application layer protocols

Common application layer protocols such as HTTP and FTP have not been constructed for constrained environments in mind, as little effort has been made to keep the overhead small. For WSNs, which are restricted in terms of bandwidth, energy, and hardware, the need to keep the overhead low and the overall simplicity in terms of complexity to the minimum viability, supersedes the approach of making communication easily read by humans.

Two of the most discussed application protocols for Internet of Things deployment are MQTT and CoAP [39]. Both are open standards which has been constructed with constrained devices in mind. They are fundamentally different from each other, as a different approach to communication has been taken for MQTT and CoAP respectively. MQTT is a client-server setup, and make use of a so called broker which acts as a server, whereas CoAP is a server-client setup, where every node that runs CoAP is a server by its own.

2.5.1 CoAP

The *Constrained Application Protocol* (CoAP)[40] developed by the CoRE (*Constrained RESTful Environments*) IETF group is a transfer protocol similar to HTTP, but designed for constrained devices. Rather than using TCP, CoAP relies on UDP for transport.

According to its specification [40], CoAP has the following main features:

- Web protocol fulfilling M2M requirements in constrained environments
- UDP [RFC0768] binding with optional reliability supporting unicast and multicast requests.
- Asynchronous message exchanges.
- Low header overhead and parsing complexity.

- URI and Content-type support.
- Simple proxy and caching capabilities.
- A stateless HTTP mapping, allowing proxies to be built providing access to CoAP resources via HTTP in a uniform way or for HTTP simple interfaces to be realized alternatively over CoAP.
- Security binding to Datagram Transport Layer Security (DTLS) [RFC6347].

Message type

CoAp has two message types, the request message and the response message, with fixed-size header, an optional Type-Length-Value for further options, and a payload. The payload size is bound by the underlying datagram length of UDP.

Uses

In contrast to HTTP, CoAP has a built-in subscription and publishing mechanism, known as observation, which allows clients to subscribe to resources and receive updates when changes occur. Clients can do a resource search on available resources by accessing the URI `/.well-known/core` on a CoAP server, which returns a list of the available resources.

Quality of Service

Messages can be marked as "*confirmable*" or "*nonconfirmable*", a confirmable message must be acknowledged whereas nonconfirmable messages are "*fire and forget*".

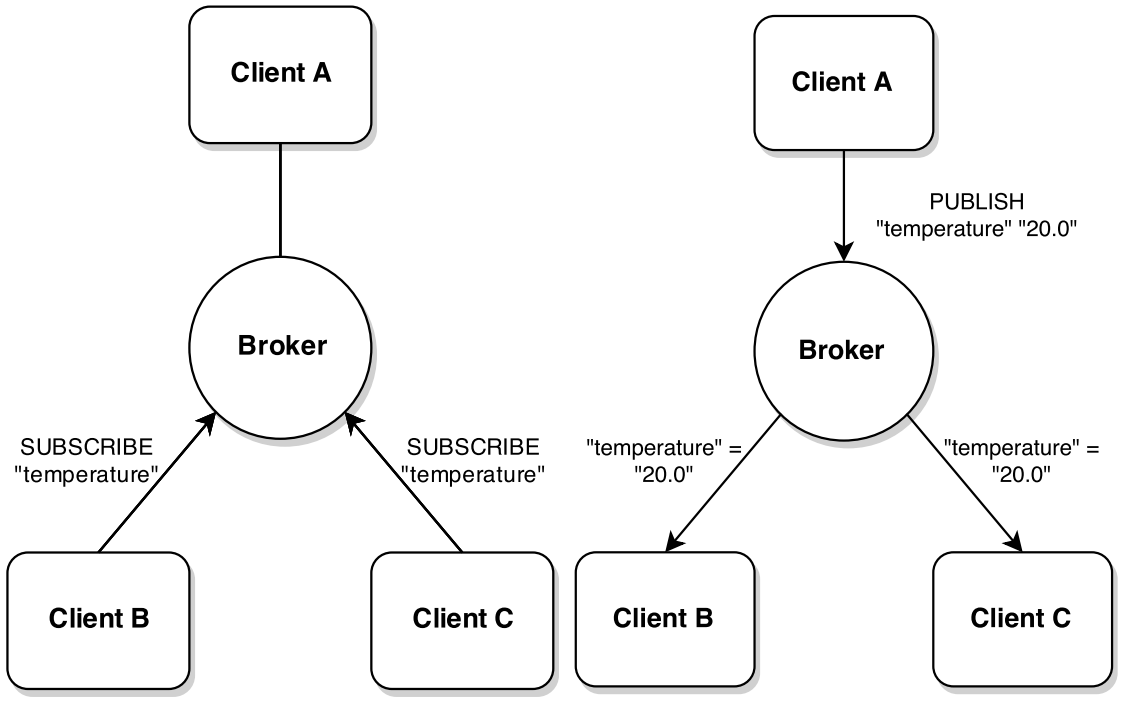
Security

As CoAP is a UDP protocol, TLS is not available since it requires a TCP connection. However, the similar DTLS [41] (*Datagram Transport Layer Security*) can provide security for UDP, with support for AES and RSA. It has been showned in [42] that CoAP with DTLS offers full protection against eavesdropping and man-in-the-middle attacks.

Another means to secure CoAP is with the use of IPsec, which unlike DTLS operates directy at the network layer. As such, the CoAP implementation can be kept intact, as IPsec is transparent to the application layer. However, IPsec requires support from the underlying IP stack, which is not necessarily present in the IP stacks designed for constrained devices.

2.5.2 MQTT

MQTT[43], formerly enlarged as *Message Queue Telemetry Transport*, is a lightweight publish/subscribe messaging protocol originally developed by IBM but has since become an open standard managed by OASIS.



(a) Subscription (b) Publishing

Figure 2.3: Two subscriptions followed by an one-to-many publication.

Architecturally, MQTT is set up as a client/server model, where every sensor is a client which connects to a server, known as a broker. Clients distribute their sensory data by publishing their data to the broker. A specific sensor data type is known as a topic, and other clients can choose to subscribe to these topics by messaging the broker. When a device publishes its data to the broker, the broker will distribute the data to all the clients which has chosen to subscribe to the specific topic. This model of publisher and subscriber allows for MTQQ clients to communicate *one-to-one*, *one-to-many* as well as *many-to-one* and *many-to-many*, as graphically visualized in Figure 2.3.

Topics are sorted hierarchically, like the directories of a file system. For example, a temperature sensor located inside a kitchen freezer could have the topic path `kitchen/freezer/temperature`. When subscribing to topics, wildcards can be used to observe a whole tree structure of publishing clients. The wildcard + will match any single directory, whereas the wildcard # will match any number of direc-

tories. As such, subscribing to the topic `kitchen/+/temperature` will match `kitchen/freezer/temperature` as well as `kitchen/fridge/temperature`, but not `kitchen/temperature` or `kitchen/dishwasher/wateroutlet/temperature`. The # wildcard must be the final character of a subscription, and will match any depth level, i.e. the subscription `kitchen/#` would match all the previous examples.

Quality of Service

MQTT has three levels of assurance for delivery when publishing topics. These *Quality of Service* levels are *At most once* (Fire and Forget), *At least once* (Acknowledged delivery), and *Exactly once* (Assured delivery).

With *At most once* delivery, the message is delivered with the best efforts of the underlying layers. No response is expected and no retransmissions are carried out. The client will publish the message to the broker and then simply delete the message. The message will arrive to the broker either once or not at all.

For *At least once* delivery, an acknowledgment is expected by the client. If the client does not receive the acknowledgment within a specified time range, the client will resend the message and mark the retransmission as a duplicate. This guarantees that the message is received at least once. The subscribe and unsubscribe type messages sent by clients use the *At least once* QoS level.

The *Exactly once* delivery is the highest level of delivery assurance, as it makes sure that no duplicate messages are delivered. The client append a message ID to the message as it is published, which the broker will include in its acknowledgment. The client will then confirm the acknowledgment, and broker will end the delivery by returning one last acknowledgement. The client stores the message until the last step of the communication flow, in the case of communication loss. This QoS level is the most heavy level in terms of network traffic, as it requires a minimum of 4 messages to complete the delivery.

Last Will and Testament

MQTT has a mechanism known as *Last Will and Testament*, which is a custom message that the client can send to the broker. This message would then be sent to subscribers if the connection between the client and broker is severed, as a mean to notify the subscribers when a device has disconnected.

Security

The MQTT connect message contains fields for username and password, however, the standard does not specify how they should be used. In fact, the standard does not specify any security related features of MQTT, even so, it is possible to implement

security notions such as authentication and authorization of clients by the server as well as encryption algorithms such as AES and DES, but as it is not built-in to the protocol, it would have to be independently implemented.

MQTT-SN

MQTT is designed to be a lightweight protocol, however, it requires a TCP connection between the client and broker, which needs to be kept open at all times. This is not desirable for a constrained device in a message loss prone network such as 802.15.4 as nodes are not able to enter sleep mode for longer amounts of time. Also, as topic names are usually descriptive (e.g. `kitchen/fridge/temperature`) and sent in full, the topic string itself will account for an unnecessary proportion of the small message size of 802.15.4.

MQTT for Sensor Networks (MQTT-SN) [44], previously abbreviated as MQTT-S, is a UDP implementation of MQTT which has addressed these issues when using MQTT in 802.15.4 networks. MQTT-SN has been design to be as similar as possible to MQTT, while being more adapted towards WSN environments. Instead of using topic names in the PUBLISH messages, MQTT-SN replaces the topic name with a two-byte topic id which is acquired in a registration procedure with the broker. There is also support for sleeping clients, where clients are allowed to enter a sleeping state to conserve power. The client notifies the broker that it is entering a sleeping state and the broker will buffer messages destined for the client until it receives notification that the client has woken up.

3

Challenge

There are many reasons for why communication between nodes within a network could fail. Power failures, either from depletion of the battery source or interruption in the external power supply could cause the node to be unresponsive. Interference, such as electromagnetic disturbances or physical blockages of the transfer media path could cause dampening of the signal to the extent that communications could fail. Software errors and hardware failures are other factors that could cause nodes to not function properly.

For some of these factors precautionary measures could be taken, for example, a node could monitor its own battery status, and in the case of low battery level, notify the server that its power source is running low. Even nodes with external power supplies would be able to monitor its own power supply and send a notification in the event of a power outage, given that the node is equipped with a back-up power source, such as a capacitor providing enough power to send the notification.

Other factors are harder to take preventive measures against, such as interference in the transfer media in an uncontrolled environment, which includes just about any environment except for a laboratory setting.

As such, there may be no advanced indication whereas the node will fail to convey its information, and no indication for the receiving part to what caused the failure.

A common denominator for these factors are that they could be caused unintentionally due to natural causes, improper maintenance etc, or be caused intentionally by an adversary with mischievous intentions. It is therefore important that when communications fail to treat it as a possible attack to the network and in extension as an possible attack to what the sensor network is monitoring or controlling which could potentially lead to breaking and entering, loss or damage of properties, health repercussions or other unforeseen effects.

3.1 Fault detection

Detecting faults in WSN can be divided into two types of detection techniques, either *self-diagnosis* or *cooperative diagnosis*. With self-diagnosis, a node itself can detect the onset of a fault, such as energy depletion, by monitoring its battery level. A node may also use self-diagnosis to deem links faulty given that it does not receive any messages within a predetermined time[7]. However, in the onset of an unpredictable fault, such as hardware failure, cooperative diagnosis is necessary in order to detect the fault. In cooperative diagnosis, active or passive measurements are taken by nodes to supply fault detection for other nodes in the network.

3.2 Detecting network abnormalities

As wireless sensor networks are intentionally constructed to be operable with constrained devices, message exchange is designed to be kept to a minimum in order to minimize power-usage. That is, a node will usually not communicate unless a change has occurred that would require it to send a message. Such an event could be caused by the change of one of the nodes sensory value, a timer associated with a communication action running out or an incoming message which require a response, such as an acknowledgment. Otherwise, a node may choose to enter sleeping mode for extended period of times, and essentially be invisible to the network.

This induces the problem of uncertainty, as the server is unable to know if the absence of communication is due to the node choosing not to communicate or if the node is incapable of relaying its message due to link or node difficulties.

The only way to detect that nodes are still functioning is for the node to actively communicate its present on the network. Only then can the server know that the node was alive and operable at the time it sent the message.

Intrinsically, the sole solution to scale down the time frame for which a server may be in this uncertain state before receiving reassurance to whether the node and link is functional, is to introduce a periodical message flow, i.e. a *keep-alive* connection.

3.3 Timed communication features by layer

As visualized in Chapter 2 Wireless Sensor Networks, the communication flow in WSNs could be categorized according to the general TCP/IP-Model. Each layer has features for detecting failed and non-delivered/received transmissions.

3.3.1 Physical layer and media access control

The IEEE 802.15.4 standard has the optional feature of acknowledged message, as explained in Subsection 2.1.10. Also, in beacon mode, a message, i.e the beacon frame, is distributed in a timely manner to the nodes. However, this beacon is designed to let the end nodes communicate, either according to GTS (Guaranteed Time Slots) or access contention, in an effort to extend sleeping cycles and lower power usage. An end node could simply choose not to communicate, and no action will be taken by the 802.15.4 layer to investigate whether the node is still active on the network.

3.3.2 Network layer

As 6LoWPAN is an adaptation layer for IPv6 responsible for header compression and fragmentation, no effort is taken by the 6LoWPAN protocol to assure delivery and by extension detect if a node is unresponsive.

RPL

The trickle algorithm [36] is set to run according to a defined interval which depends on three configuration parameters: the minimum interval size, the maximum interval size, and the redundancy constant.

The minimum interval size is a time unit, whereas the maximum interval size is a number that specifies the number of doublings of the minimum interval size. For example, if the minimum interval size is set to 100 milliseconds and the maximum interval size is set to 16, then the maximum interval size will specify the time $100 * 2^{16}$ milliseconds, which is approximatively 109 minutes. The redundancy constant is used to suppress timed transmissions, so even if the node is bound to transmit the DIO message according to the defined interval, it must also meet the requirements of the redundancy constant, if not, the transmission will be suppressed.

The algorithm will strive to reach the maximum interval size by increasing the defined interval incrementally when the network is consistent. When inconsistencies are detected by the node, the trickle timer will be reset, and will cause the defined interval to be set to the minimum interval size.

As such, an RPL DODAG that exhibits no inconsistencies, will allow the timers to reach the their maximal potential which equates to long period between RPL control messages.

The *Home Automation Routing Requirements in Low-Power and Lossy Networks RFC 5826* [33] which laid out the requirements that RPL should meet in Home Automation settings states that:

> ...Since wireless and battery operated systems may never reach 100% guaranteed operational time, healthcare and security systems will need a management

> layer implementing alarm mechanisms for low battery, report activity, etc.
>
> For instance, if a blood pressure sensor did not report a new measurement, say five minutes after the scheduled time, some responsible person must be notified.
>
> The structure and performance of such a management layer is outside the scope of the routing requirements listed in this document.

Which entails that RPL has not been designed to in any way manage or investigate node and link abnormalities. Rather, RPL will strictly provide routing according to its specification given best effort.

3.3.3 Transport layer

UDP is a connection-less protocol and does not offer any build-in mechanism for assuring that nodes are alive [38].

On the other hand, TCP is a reliable protocol that establishes a connection using a three-way handshake [37]. The connection itself could be kept-alive using the TCP keep-alive feature. For most systems the keep-alive timeout is set to 7200 seconds, but it could be adjusted downwards to detect disconnected nodes earlier on. Using the keep-alive feature of TCP might be an option if a TCP connection is used for regular communication with the nodes. However, there exist an inclination to not use TCP for WSNs since the the nature of a TCP connection inhibits nodes to go to sleep for longer amounts of time. As such, CoAP and MQTT-SN has been designed to run on UDP rather than TCP, and to use TCP solely for its keep-alive feature would require a connection between every node and the server, and the total amount of messages needed for the keep-alive feature would also have to include the number of messages associated with setting up the TCP connection.

3.3.4 Application layer

There is multitude of application protocols that could be used for WSNs. This thesis however has chosen to focus on the protocols MQTT and CoAP given that they have been directly geared towards Wireless Sensor Networks and the Internet of Things.

MQTT

According to the MQTT standard [43], it states that *[if] ... the Server does not receive a Control Packet from the Client within one and a half times the Keep Alive time period, it MUST disconnect the Network Connection to the Client as if the network had failed.* The standard also has a non normative comment, which reads as *The actual value of the Keep Alive is application specific; typically this is a few minutes. The maximum value is 18 hours 12 minutes and 15 seconds.* The keep alive time interval is measured in seconds, expressed as a 16 bit word. Therefore, the lowest time unit for sending keep

alive messages would be 1 second, and the lowest time for a non-functioning device to be discovered and disconnected would be 1.5 seconds.

Such a time frame might be sufficient in certain applications, however, each message is sent as a unicasted ping request from the broker and followed by a unicasted ping response from the client, which would give rise to $\sum_n^N 2d_n$ messages per time frame, where N is the number of nodes and d_n being the depth of the node.

Message authenticity could be validated with encryption provided by TLS in MQTT, or with DTLS for MQTT-SN. The Ping request message has no payload, and there is no nonce in the header, but there is room for independent implementation using other flags and remaining length. This could open up for replay attacks if the ping response does not differentiate and TLS or DTLS is not in use and underlying layers are not providing encryption and authentication.

CoAP

There is no keep alive feature in the original CoAP specification. However, the observe feature of CoAP, which is comparable to the subscribe/publish feature of MQTT, has the option to use a "freshness" timer. Essentially, this observe feature could be used to observe whether the node is alive, so even though the value has not changed, the CoAP server will communicate its current state, to keep the value "fresh" among its observer. If the associated Max-Age option of a value has expired, the value can no longer be trusted and observers would have to conclude that the CoAP server or link are no longer functional.

Comparable to MQTT-SN, DTLS would provide message authenticity and anti-replay for CoAP as well.

3.4 Importance of a consistent continuous view of the network

IEEE 802.15.4 is generally considered to be focused on low power usage, where it make use of different duty cycling techniques to limit the time a node will power on its radio transceiver to either transmit or receive transmissions. It has been shown that the radio transceiver is the component within a node that usually consumes far more power than the other components [23] [24] [25], and the overall best way to prolong the battery power of a device is to limit the usage of the radio transceiver. Essentially this means that nodes might have to wait before being able to receive or transmit, in order to conserve power and that the overall transmission should be kept low. That is, a node should only transmit when it actually needs to convey new information. For example, if a node is set to communicate a sensor value periodically, it will disregard

this periodicity if the sensor value has not changed, the receiving part will simply assume that the last recorded value is still valid.

This imposes a problem if a node is unable to transmit a new sensor value, caused by any event that inhibits the node to send its message or for the receiving part to receive it. The receiving part will then assume an incorrect value for the sensor node giving rise to an inconsistent view of the network.

In some applications the sporadic inconsistent view of the network is of little concern. For example, if a temperature sensing node fails to transmit a new value it will simply transmit the value at a later stage. For logging purposes and for action which are based upon data sets recovered from sensing nodes over a longer period of time, transient transmission problems causing the occasional drop or postponed arrival of sensing data is to be expected and of no serious concern.

Table 3.1: Table showing possible outcome in case of node or link failure.

Node Type	Outcome
Intrusion Detector	Burglary, Home-Invasion
Heart Rate Monitor	Death
Smoke Detector	Property Damage, Loss of life

In some circumstances the need of keeping at least a partial view of the network continuously consistent is necessary even with the associated drawbacks of increased network and power usage. For example, health care and security nodes, such as heart rate monitors, intrusion and smoke alarms, are inherently critical as in the event of a non-delivered or late-delivered message from such nodes could have severe repercussions as seen in Table 3.1.

Both CoAP and MQTT have features to protect against this, using a freshness timer and a Last Will of Testament respectively. The timers associated with these features are both variable according to the protocols, making it possible to detect an inconsistent view of the network within a predefined time. However, both these features relies on direct communications between the node and the observer/server, which will give rise to a large amount of keep alive messages, resulting in higher bandwidth and power usage for the network.

3.5 More precise problem description

Given a wireless sensor network running 802.15.4, where a multitude of different types of nodes are present, such as periodical sensor nodes, actuating nodes, and safety-critical nodes, the requirement is to keep a highly continuously consistent view of the safety-critical nodes. In a smart home setting, it is assumable that a wide range of

devices will run on 802.15.4 technology in the future, some of which will be safety-critical. It is therefore desirable to make use of an algorithm that can keep a highly consistent view of safety-critical devices while other non-safety-critical devices are present. As such, a common communication set can be shared between all devices and the specific consistency monitor algorithm can be implemented as an application level algorithm, making use of a shared routing protocol among all nodes. Such an algorithm will be adaptive as it does not depend on specific underlying functionalities such as MAC, or any specific operating system and can be implemented in a wide range of systems.

The algorithm will be designed as a rudimentary monitoring system, where focus is to minimize the number of messages required to detect any faulty links or nodes, and to keep the message size as small as possible, in an effort to minimize the total energy consumption in the network. As faults are expected to happen very seldom, it is not required by the algorithm itself to identify the source of the fault, rather, if any fault is detected by the algorithm, further investigative measurements could be launched by other instances.

Regarding the possibilities of false positives, the algorithm should have the option to reinitialize the probing of the network an arbitrarily number of times, before reporting the possible fault to a higher instance, in order to avoid a high degree of false positives. The number of times reinitialization is required for a certain false positive ratio will be specific to the actual implementation of the network, as interference and other influencing factors will be highly per installation specific.

As the detection time for faults is crucial for safety-critical nodes in order to avoid the possible outcomes given in Table 3.1, the responsiveness of the algorithm is of high concern. Ideally, the algorithm should be able to identify a possible fault within a time frame which is much shorter than what can be provided by the protocols CoAP and MQTT in their default configurations. It should be noted that since the algorithm will only be designed to detect the presence of faults, not to identify the nature or location of the fault, more time needs to be allocated in order to identify which node or nodes are affected by the possible fault before appropriate measurements can be taken.

The algorithm will be evaluated given its ability to detect the presence of any faults in the direct communicative path between any safety-critical node and the sink. With variable timers as to how often the algorithm should execute the monitoring scheme, a total number of messages per time unit required can be calculated and a rough estimation of the required energy usage for a certain setup can be given.

As the level of responsiveness that can be acquired by the algorithm correlates with the energy budget that has been allocated to the algorithm, the thesis will illustrate the coherence between increased responsiveness and the increase in energy levels required to maintain a certain level of responsiveness.

As a concluding evaluation, a comparison of results and differentiating factors to

the other similar approaches *DiMo* [13] and *Memento* [15] for fault detection in safety-critical networks will be made.

4

Methodology

There exists a number of different approaches to developing software for wireless sensor network devices. This chapter explains the common approach of using operating system programming to develop software for constrained devices in the IoT field. This approach has become the norm when programming for sensor nodes, as the usage of a base operating system greatly reduces the need to duplicate functionality and simplifies the porting of software across different hardware platforms. Moreover, energy-efficiency when communicating as well as compatibility between nodes can be increased as the underlying architecture of the operating system can be shared across different types of nodes.

Also, in effort to speed up development and testing, the native approach to programming with operating system, which will be used when constructing and testing the algorithm in the subsequent chapter, is explained in this chapter together with how virtual topologies can be used for native devices to simulate high-depth networks. Further, it is explained how network data can be analyzed for both the native port and hardware nodes using a packet analyzer. To conclude the chapter, a clear presentation of the different device types that will be used when constructing the algorithm is also given.

4.1 Operating system programming

The Operating System Model [45] is a programming model where code is programmed for a certain operating system kernel, which in turn will compile the code to machine code for the intended target hardware. Code written for a certain operating system kernel can be reused and applied to other kinds of hardware which the operating system support. In contrary, when writing code for a certain platform, specific APIs and

libraries are used to compile the code to machine code, making the code non-portable to other platforms. As such, the operating system model is preferable as it is more portable as well as less cumbersome, as it provides a higher abstraction layer to work with.

4.1.1 Contiki OS

Contiki [46] is an operating system developed by among others the *Swedish Institute of Computer Science* (SICS). It consists of a kernel and libraries, as well as a set of processes. Contiki is developed in C, and all applications developed using the OS is written using a subset of C. It is event-driven where processes are implemented as event handlers.

Modules such as RPL, CoAP, and support for 6LoWPAN are present, making programming using Contiki a much simpler task compared to head on microcontroller programming.

Contiki also comes with its own full-fletched Java-based simulator known as Cooja. It will run Contiki programs that has been compiled natively for the host CPU, or compiled for microcontroller emulators. With this simulation tool the user is able to view a fully simulated network of nodes, with timelines, loggers and communication flow. As such, Contiki provides an easy way of developing applications without the need of actual node hardware.

4.1.2 RIOT OS

RIOT [47] aims to avoid redundant developments and maintenance costs, by supplying a unifying operative system that will work on a wide spectrum of hardware.

RIOT OS is programmed using standard C and C++, provides multi-threading and has real-time capabilities. It is designed to be energy-efficient, modular and use a small memory footprint. Development is ongoing with a current support for a range of different platforms. A comparison between Contiki OS and RIOT OS can be viewed in Table 4.1.

Table 4.1: Comparison of the Contiki and RIOT operating systems [47].

OS	Min RAM	Min ROM	C Support	C++ Support	Multi-Threading	Real-Time
Contiki	<2kB	<30kB	Partial	No	Partial	Partial
RIOT	~1.5kB	~5kB	Yes	Yes	Yes	Yes

4.2 Native programming

Both Contiki OS and RIOT OS support native programming [48] [49]. The native platform emulates the hardware needed for nodes and allows the node to run with the complete software stack of the node OS on a regular UNIX-like desktop, comparable to that of virtual machine solutions such as Virtualbox and VMware. The benefits of using the native port is that no actual node hardware is needed, as everything is simulated and run within a regular Linux distribution. As hardware is emulated, the programmer is not restrained by physical limitations of nodes such as RAM and ROM size during development. Node communications are allowed to flow within a controlled environment, without disturbances such as noise. Native programming allows for fast development and testing as these can both be done using the desktop machine, compared to programming directly for hardware as this requires the compiled code to be uploaded to the nodes.

4.3 Virtual topologies

Network support for native nodes are given through TAP interfaces. A TAP interface is a virtual network device that simulates a link layer device. TAP devices are bridged to allow for inter-device communications.

Tools such as *Desvirt*[50] can be used to create more complex virtual topologies, which allows you to specify custom links between nodes and define a loss rate for those links. As such, topologies with multi-hop communications can be defined as visualized in Figure 4.1.

4.4 Analyzing data

Since the virtual TAP interfaces simulates a real network interface, it is possible to use packet analyzers such as Wireshark to analyze the network flow in real time. In order for Wireshark to be able to parse packets correctly sent over TAP interfaces by RIOT's native nodes, a Wireshark dissector is required[1].

Analyzing data from real nodes requires a sniffer, which is a node that is able to forward all packets received to another interface, usually a serial interface such as USB which would be connected to a desktop computer were the packets can be analyzed with e.g. Wireshark. Sniffer software are an essential part of analyzing real network traffic and software for sniffers is included within the Operating Systems Contiki and RIOT. The sniffer could be put anywhere in the network, but it will only be able to

[1] `https://github.com/RIOT-OS/RIOT/tree/master/dist/tools/wireshark_dissector`

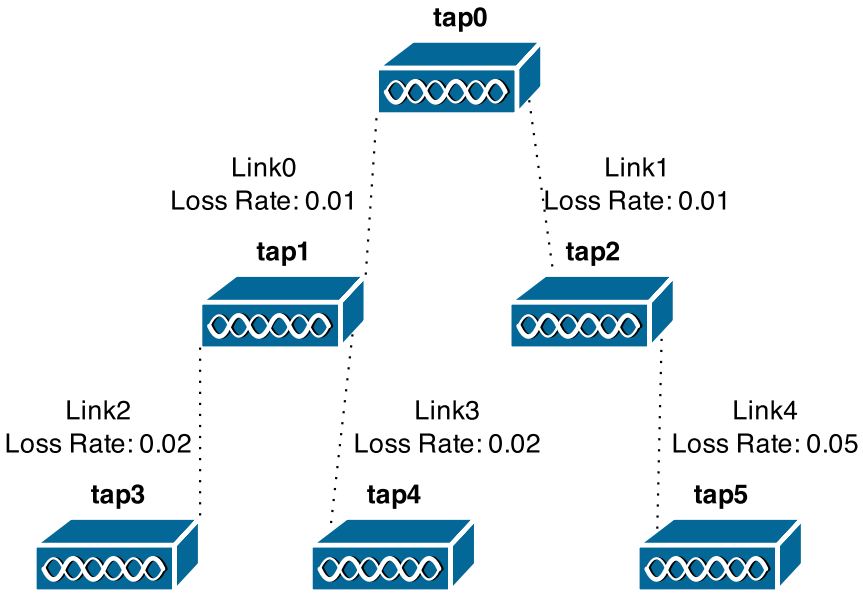


Figure 4.1: A virtual topology with six TAP interfaces and five links with customizable link loss rate.

forward packets which it is physically able to receive, making direct communications from far-away nodes invisible to the sniffer. Multiple sniffers could be used in order to fully cover a large 802.15.4 network in order to analyze all packets.

4.5 Devices

The devices within an 802.15.4 network can be divided into different categories depending on their function and place within the network. Depending on which type a device belongs to, different software and hardware can be applied.

4.5.1 Border router

The Border Router connects the 802.15.4 network with the Internet, usually over ethernet or Wi-Fi, and depending on the nature of the connection to the Internet and the rest of the local network, the border router might act as a MAC-bridge which forwards 802.15.4 packets to the ethernet interface. In other arrangements, and where IPv6 is not available, the border router could also be used for tunneling the traffic using IPv6 to IPv4 tunneling software. The border router, although not by requirement, is a suitable device to act as the RPL router and the PAN coordinator in a 802.15.4 network.

4.5.2 Local coordinator

Local coordinators are devices within the wireless sensor network that are capable of forwarding and relaying frames from other devices in the network. In order for a network to extend spatially, so that all devices are not in direct communicative distance to the border router, local coordinators are required to relay traffic. The local coordinators themselves may also act as a functional device, sending sensory data or acting on received control data. However, due to that a local coordinator is relaying traffic from other devices, it will inherently be receiving and transmitting at a higher rate compared to end devices, and as such will have lower sleep to awake ratio, or in some cases, be configured to never enter sleep mode. This naturally affects the power utilization of the device, making local coordinators less suitable to be run as battery-powered devices, compared to end devices.

4.5.3 End device

The end device is at the edge of the 802.15.4 network. Only traffic intended for the end device is sent to device, as the end device lacks any forwarding capabilities. Depending on the functionality of the device, the end device can enter sleep mode for extended periods of time to conserve power. As such, the end devices are well-suited to be equipped with batteries as their overall power utilization is low or very low, allowing for the device to be operable using a battery source for a long duration of time.

5

Design of the proposed method

As mentioned, the only way to make sure that a node is still functioning properly is for that node to actively communicate on the network. In the absence of communications from the node, the node will be in an unknown state from the viewpoint of the border router, as to whether the node is functional and communicative, or faulty or in any other way unable to communicate.

By using *keep-alive* messages with associated timers, it is possible to limit the time in which the node is in this unknown state. Timers could be set arbitrarily and when such a timer run out, the node could be either assumed non-functional, or further actions could be taken to verify its current state in the network. As wireless communications are prone to message loss, it is important to consider that timers might run out due to delays or interference in the network, which could either be intermittently present or of a more permanent nature. As for the decision unit, any missed timer deadline should be treated as a potential malfunction of the node in question, however, further investigation by the server should be taken to ensure that the node in question is not available, to avoid a potential false positive. Further investigations could include an arbitrarily number of rounds of keep-alive traffic, during which intermittent delays and interference will have time to recede.

One important aspect is how an increase in message exchange will affect the overall performance of the network, as a smart home WSN might include many different types of sensor and actuating nodes, which will all share the network with the safety-critical nodes. Aspects such as the power usage of the nodes, the general throughput and delays in the network needs to be considered not only for the safety-critical part of the network, but for the network as a whole.

5.1 Method proposed in the thesis

Rather than a direct router to node communication flow, a *round-robin* approach was chosen, were nodes will take part in distributing the keep-alive message to its adjacent node neighbours.

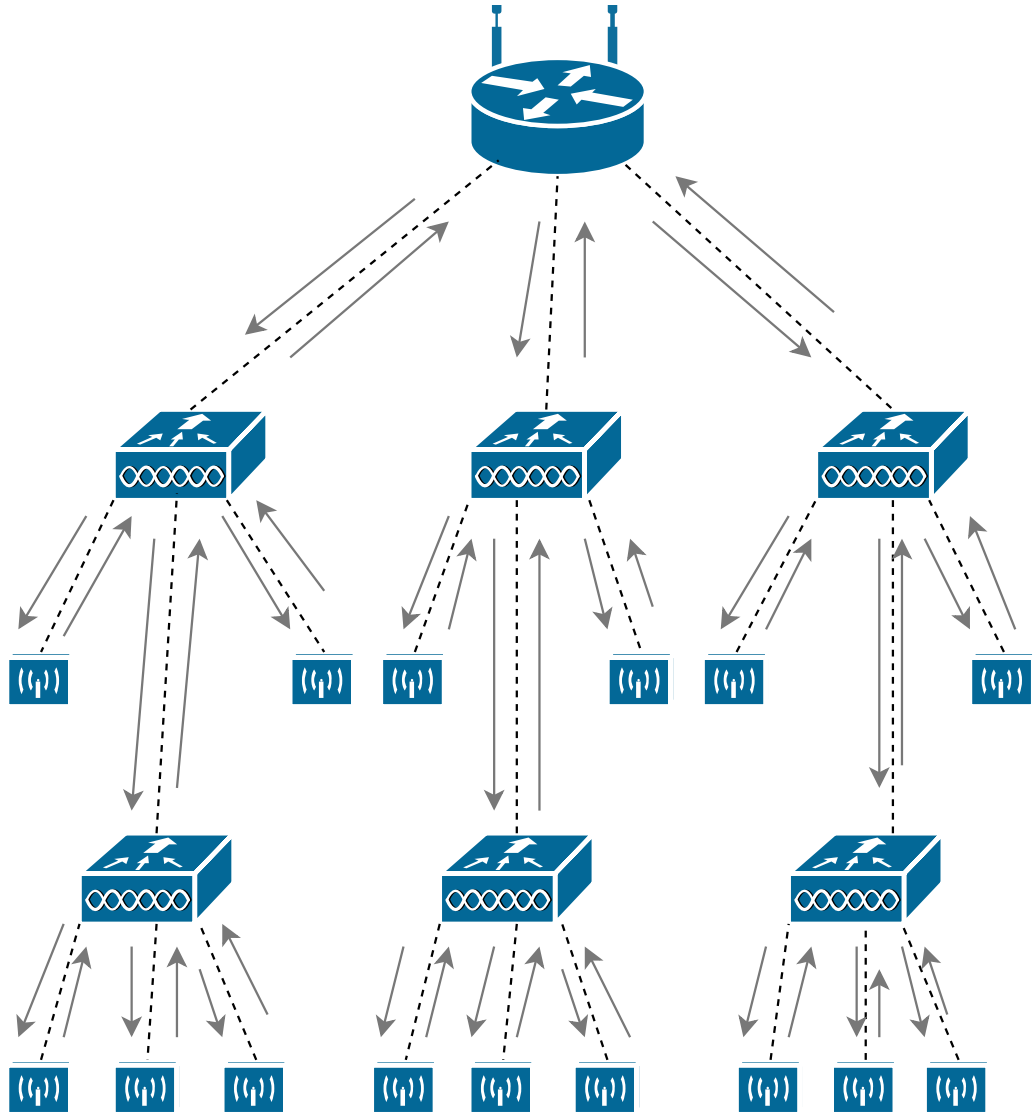


Figure 5.1: The round-robin keep-alive message flow.

Instead of every node sending keep-alive messages to the main server, safety-critical nodes, for example intrusion alarm nodes, form a logical ring and the keep-alive message pass through each and every node in the logical ring and then concludes

by being sent back to the server. This would severely diminish the amount of messages required to be sent in a larger wireless sensor network where many local coordinators and end devices are present at depths greater than one from the border router. For instance, given the network illustrated in Figure 5.1, a round robin approach would optimally give rise to a total of 42 messages per keep-alive round. In comparison, if a direct server to node keep-alive approach was taken, messages would have to pass through multiple local coordinators multiple times, as every node would be independently communicated with.

5.1.1 Time aspect

Generally, this approach will be able to make the decision whether a node is unreachable or not within a much smaller time range than the typical timer values of RPL, MQTT and CoAP. It should act quickly enough so that the possible negative outcomes given in Table 3.1 could be counteracted given manual or automatic response.

For example, for the critical device types mentioned in Table 3.1 appropriate response to node or link failure should be initialized in the matter of seconds, rather than minutes or even hours which could be the case if relying on the keep-alive or freshness features of other protocols such as CoAP and MQTT.

Fast response is of high concern especially when it comes to medical devices monitoring vital values, as it has been shown that the survival rate drops incrementally with time when patients go untreated for life threatening conditions such as cardiac arrest [51].

The exact time unit for when a decision can be made to whether a fault is present or not will be highly installation and purpose specific, as a number of factors need to be justified for the specific setting.

These factors that needs to be considered when choosing a certain degree of responsiveness include but are not limited to *a*) **energy-efficiency**, the number of messages sent per unit of time can be directly linked to the overall energy-consumption of the system, *b*) **false positives**, which are more likely to occur as the wait time before decision making on fault detection is decreased. Furthermore, *c*) **inherent cost** associated with the negative outcomes due to node or link failure, for example property loss or loss of life, needs to be accounted for when deciding on the responsiveness of the system. Also, *d*) **other applications** present on the network needs to be considered, as rapid keep-alive monitoring may cause latency in other parts of the system, such as sensor data reporting. Therefore, it is important to evaluate the necessity of rapid fault detection on a per application basis, as different safety-critical systems may adhere to different levels of what is considered fast response. For example, health monitoring nodes that are monitoring vital signs may be considered as more pressing and of higher concern than other safety-critical systems such as smoke detector nodes in an uninhabited building.

5.1.2 Message complexity

As there is no requirement from the algorithm to pinpoint the location of the fault, i.e. for the server to be able to tell which node or link is responsible for the fault, no information of participation from nodes needs to be carried in the message itself. This functionality would however be rendered mute, as the algorithm relies on the absence of return messages to detect fault, and as such, any information carried in the message would be unattainable for the server in the case of an undelivered message. As such, the message length can be kept short, with the only requirement that the message from each round should be unique, as to avoid stored messages from previous rounds to intervene with a current keep-alive round, causing a false negative. Since messages are sent from end node to end node, the total amount of messages required for every node to announce its continued presence on the network can be reduced to the total amount of uplinks for the safety-critical sub-topology times two. The safety-critical sub-topology is defined as all safety-critical nodes uplinks as well as the uplinks of any local coordinator which has any safety-critical node as its descendants.

5.1.3 Algorithm description

The communication exchange presupposes that every end node has a defined variable for its *next neighbour*, which could either be defined as another end node or as the server. Also, the server has a defined variable for the end node that will be the first node to participate in the keep-alive round. The message flow of the proposed algorithm is described by the following procedures:

INIT: The server initiates the keep-alive round by creating and storing a nonce. It will then send a message containing the nonce to the first node in the keep-alive round which has been previously defined by the server. The server will at this point start a timer.

FORWARD: Any node that receives the keep-alive message will relay the message to its *next neighbour* which is the node next in line to receive the message. This will be repeated by every node partipating in the algorithm until the message reaches the last of the participating nodes in the predefined list of nodes. This node will then relay the message to the server, using the predefined variable *next neighbour*.

RESET: If and when the server receives the message, it checks the message nonce with the stored nonce for the round, and if it matches, the server will reset its timer and then re-initiate the algorithm according to *INIT*.

If the server fails to receive the message before the timer runs out, or the nonce received can not be matched with the stored nonce, the round will be considered as

failed and one or more of the following actions may be taken *a*) the algorithm may be **repeated** an arbitrarily number of times before one of the other actions are chosen in order to let potential intermittent interference surpass, this will counteract the possibility of false positives on account of time; *b*) an **investigating** algorithm could be activated, in order to find which node in the keep-alive list did not fulfill its relay; or *c*) the algorithm can **choose to report** the failed keep-alive to a higher instance, such as an alarm event.

:

6

Results

An algorithm as described in Chapter 5 was constructed using the RIOT operating system and tested successfully using the native platform. With the use of the virtual topology tool *Desvirt* [50], a virtual network with static link loss was constructed to accommodate for high-depth network simulation. The results show that a distributed round-robin algorithm is possible to construct with the RIOT operating system and is operational in a simulated network environment.

6.1 Simulated network topology

The simulated topology used for the simulation of the algorithm consisted of the PAN coordinator, from which the algorithm was initiated, a local coordinator, which relayed the keep-alive messages to and from the end nodes. Two end nodes included in the keep-alive algorithm were added to the topology. With this, three links with a statically configured link loss were set up to allow for communications between devices. The links were configured so that the two end nodes would have the local coordinator as their parent, and any message exchange between the PAN coordinator and the end nodes would therefore be routed through the local coordinator as visually described in Figure 6.1.

6.2 Message complexity

The particular topology visualized in Figure 6.1 is one of the most rudimentary topologies that would still benefit from a round-robin keep-alive algorithm. Given a regular ping request/ping response approach by the PAN coordinator, where every node is

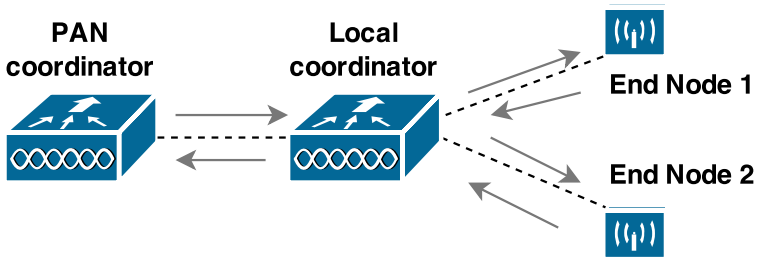


Figure 6.1: The simulated topology where the two end nodes are distanced from the PAN coordinator through the intermediary of a local coordinator.

independently probed, a total of eight messages per round would be transmitted in order to successfully verify the status of the links and the two end nodes. The proposed algorithm in this thesis, would only require a total of six messages per round, as the end nodes relay the keep alive message to the next end node rather than that the PAN coordinator issues ping requests for every end node. Therefore, for this topology there is a message reduction of 25% less messages using the round-robin approach rather than a regular ping request/ping response approach. For other topologies, where more end nodes and local coordinators are present at higher depths in the topology, even greater reductions in message number can be achieved. For example, for the network topology exemplified in Figure 5.1 in Chapter 5 a reduction of 46% less messages could be achieved.

6.3 Responsiveness

Given that the algorithm was tested solely in simulation, it is hard to predict actual responsiveness of a real set up. Generally however, it can be said that the number of end nodes participating in the keep-alive round will directly relate to the responsiveness of the system. For every extra end node that is added to the keep-alive round, more time is required as more messages are sent, as the messages sent are strictly dependent on the previous messages. That is, before a node is able to relay its keep-alive response, it must first receive an incoming keep-alive message from another end node or the PAN coordinator.

6.4 Energy-efficiency

Given the simulation result, little can be said about the predicted energy consumption of the algorithm. As energy-efficiency depends heavily on the MAC-protocol in use, and as there is currently no method of analyzing energy consumption at runtime for the RIOT OS [1], no results can be obtained on energy consumption given the simulation setting.

However, crude estimates of energy consumption based on the number of messages sent can give a rough guideline to actual energy consumption. The authors in [52] estimates the energy consumption for a number of primitive tasks given a specified sensor node platform. Their estimations include a 1.6 mJ energy consumption for packet reception, and a range of 2.1 mJ to 3.5 mJ for packet transmission. Naturally, other energy consumption factors are present, such as *clear channel assessment* and any associated backoff-periods but these are minuscule in comparison given that the network is not heavily congested. For the current consumption of the microcontroller, radio transceiver, and any present sensor hardware, of which are not directly linked to the receiving, handling, or transmission of proposed algorithm messages, it shall not be counted towards the energy consumption of the proposed algorithm. This because if a safety-critical node network were to be set up without the proposed algorithm, current draw associated with keeping the node operational, such as the energy consumption of the microcontroller, would still be present. Given that that the algorithm is purely event-based, that is, the algorithm is not invoked by the end nodes unless a keep-alive message is received and no timers that are associated with the algorithm are present at the end nodes, it can be assumed the algorithm itself will not provoke any passive energy consumption by the end node.

As such, using the energy estimations given by [52] it can be deducted that the participation by a node in the algorithm would infer a estimated energy consumption of 3.7 mJ to 5.1 mJ for receiving and relaying the keep-alive message for one individual node. The rate of which a node receives keep-alive message is directly proportional to the total energy consumption of the algorithm, due to the cascading procedure of the algorithm. Since the responsiveness of the algorithm can be deduced to the timers associated with the algorithm, i.e. the time-frame before a keep-alive round is deemed as failed and the wait-time for re-initiating the algorithm, the total energy consumption of the algorithm can be directly linked to the rate of which messages are sent and consequently the responsiveness of the algorithm.

[1] `https://github.com/RIOT-OS/RIOT/wiki/SWP14` [ACCESSED 2015-06-12]

6.5 False positives

The rate of false positives can be calculated given the number of messages per round and the static link loss per link as visualized in Figure 6.2. It shows that given the criteria that the algorithm would be operating in a home environment with a range of 10 to 100 safety-critical nodes present, the rate of false positives quickly becomes intolerable as more links are introduced in the network with the given static link loss of 0.01, 0.02, and 0.05. To combat this, multiple rounds can be executed before a failure is allowed to be acted on, as to limit the number of false positives. Figure 6.3 shows the failure rate when three consecutive rounds are executed, given that all three rounds fail to complete. This shows that the algorithm is vulnerable to scaling, as it only takes one link failure for the whole round to fail. Another angle of attack to minimize the amount of false positives is by using subgroups, where the algorithm would run independently for a limited subset of the total amount of safety-critical nodes. In such case, the rate of failure could be reduced, at the total cost of a few extra messages.

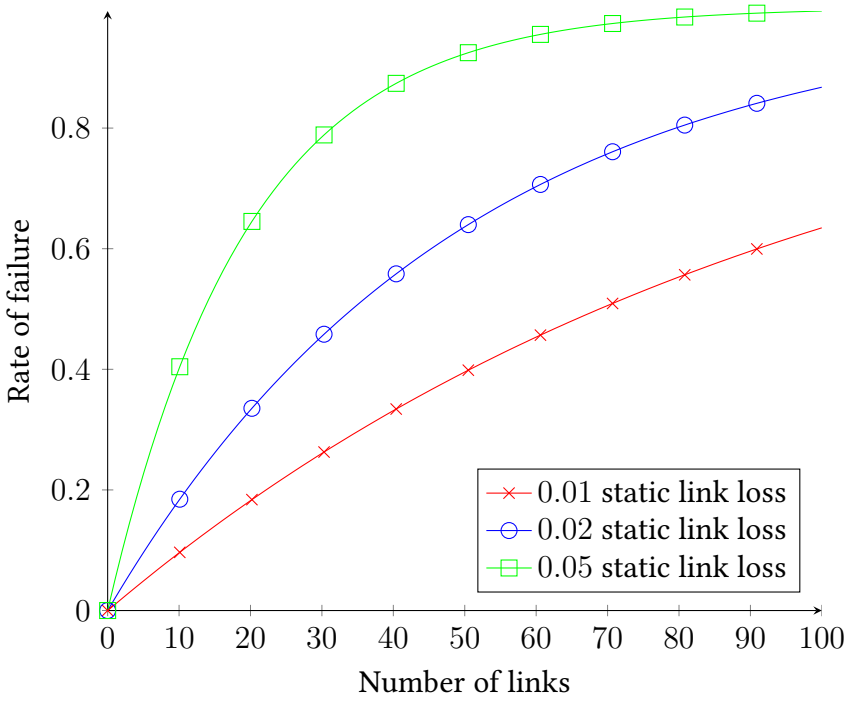


Figure 6.2: Probability of failed round

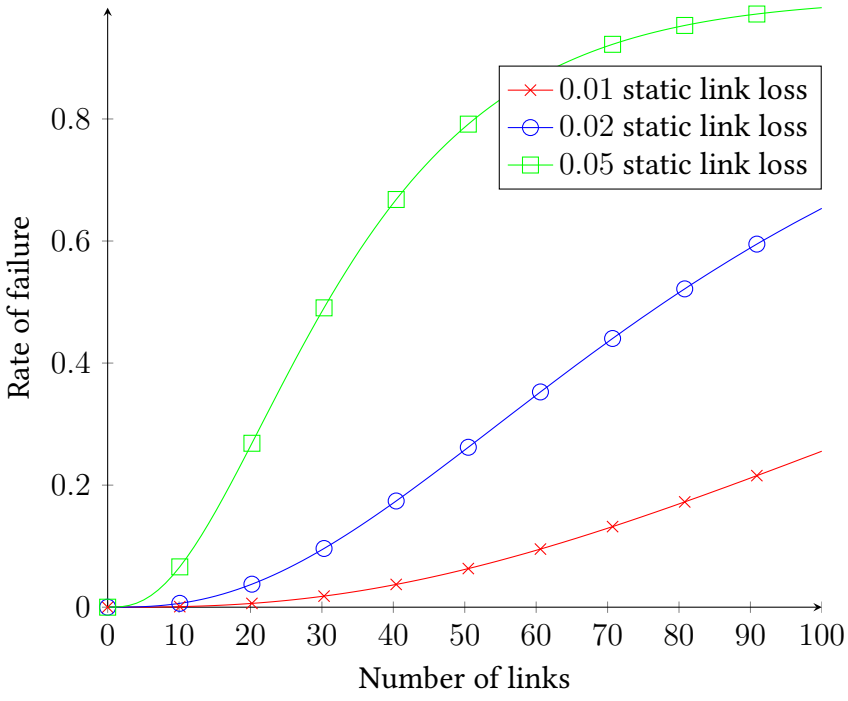


Figure 6.3: Probability of failure for three consecutive rounds

7

Discussion

Few conclusions can be drawn from the results of the simulation as to how the algorithm would perform in a real network environment. Other than confirming the functionality and proper implementation of the algorithm, a real network setup or a more advanced simulation is required in order to analyze the algorithm in a dynamical environment. As such, there is a number of concerns that could not be addressed due to the nature of running simulated nodes in a simulated network environment.

Moreover, authentication was left out in the algorithm that was implemented. As authenticity is of high concern in order to verify the correctness of received keep-alive messages, it is of high importance that either the algorithm itself can provide the necessary authentication, or that underlying layers are able to provide it.

7.1 Energy consumption

Low energy consumption is of major concern for wireless sensor networks. Generally, this is achieved by allowing battery-powered devices to enter sleep mode and implementing features such as duty cycles and message buffering. In accordance to this, any extra information that needs to be sent or received by battery-powered nodes, will affect power utilization negatively.

As such, the keep-alive algorithm proposed in Chapter 5, will severely affect the power consumption of the network, even though efforts has been taken to limit the total amount of messages required to complete one round of algorithm.

There are a number of approaches to further limit the power usage. Arguable, the most effective method to decrease the energy utilization required by the algorithm is to limit the number of devices that are regarded as safety-critical devices and therefore

not being a part of the round-robin algorithm.

One important aspect to consider is that not only will the safety-critical devices that are part of the round-robin algorithm suffer from higher power utilization, but also any other nodes that are within communication distance of any of the critical devices within the keep-alive algorithm, as CSMA/CA will force nodes to first perform a *clear channel assessment* (CCA) by listening for activity on the channel and if present, postpone their transmission. For beacon-enabled networks however, this can be circumvented by using *Guaranteed Time Slots* (GTS). Another approach to minimize wait time and collisions, and in extension energy consumption is a multi-channel approach, made possible by either equipping devices with multiple hardware transsceivers, or to make use of a scheduling algorithm in order to synchronize channel change between nodes [53] [54] [55]. For deployment, the choice of MAC protocol is paramount, as it is one of the most influential factor for energy-consumption and latency when implementing an algorithm such as the one proposed. There exists a wide number of MAC-protocols [56] and many elements needs to be considered as to how the overall performance of the network will come to be, including power utilization for non-safety-critical nodes present in the network.

7.2 Authentication

Authentication is an important step in order to confirm that the nodes are in fact operational and communicative. Without authentication the network becomes vulnerable to *man-in-the-middle* attacks. Link-level authentication can authenticate links, but this requires trust from all devices in the message path. Therefore, without top-level authentication every device that relay keep-alive messages, i.e. the local coordinators, are required to be trusted devices. If end-to-end authentication is used, there's no need to trust intermediate devices and given the authentication, this will guarantee that every intended node took part in the keep-alive round.

7.3 Multi DODAG for safety-critical devices

As explained in subsection 2.3.2, multiple DODAGs can be created with RPL, giving the option to choose between multiple routing strategies. Therefore, it would be possible to create an instance of RPL strictly for safety-critical devices, allowing timers to be set according to the need of the safety-critical devices, while routing for other non-safety-critical devices could be maintained by another instance of RPL. By defining the parameter *maximum interval size* of the trickle algorithm to a low time unit in accordance to the need of safety-critical devices, RPL could be set up to mimic much of the functionality of the proposed algorithm. RPL is however not designed with a

constant interval in mind as the trickle algorithm will strive to increase its interval size in the absence of inconsistencies in the network. Also, as the DIO messages are initiated by the local coordinators, and any detected inconsistencies are reported by the local coordinators upwards to the RPL root, this would require a level of trust from the local coordinators, which could be gained by using one of the security modes of RPL, such as the "authenticated" security mode. However, many of the current implementations of RPL for WSN only support the "unsecured" security mode, making RPL a nonviable option for networks where safety-critical devices are present and full trust is non-achievable for local coordinators.

7.4 Direct inter end node communications

One may argue that in order to limit the power usage, a direct communication flow between neighbouring end nodes would be beneficial as it would decrease the number of messages sent. This approach however is not recommendable as RPL follows a strict upwards or downwards message flow and due to the sleeping nature of end nodes, where in order to send a message directly between end nodes would require both nodes to be awake at the same time, which could potentially lower the sleep ratio of end nodes and in extension increase their power usage. Also, using such an approach may cause the message flow to deviate from the safety-critical devices' natural path to the root, as visualized in Figure 7.1, and as such would fail to test whether certain links are viable for communication.

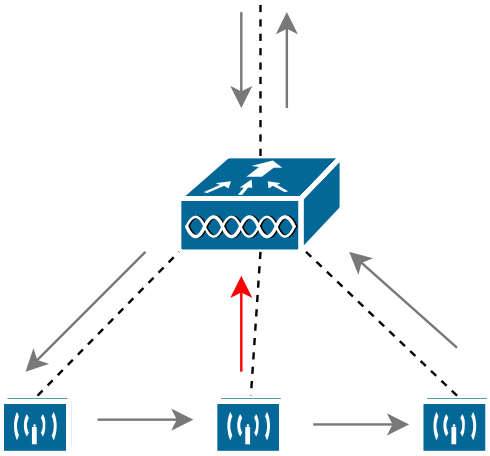


Figure 7.1: Inter end node communication would fail to test the direct upward link for intermediate end nodes (*shown in red*).

7.5 Related works

In comparison to other methods of fault detection in WSN, like *DiMo* [13] proposed by Meier, the approach chosen in this thesis is not a stand-alone implementation, as it relies on the routing protocol RPL for routing. *DiMo* is able to provide monitoring for safety-critical nodes at competitive energy consumption and low false-positive rate, however the maximum tolerable delay of reporting errors is set at five minutes. In the given configuration, with the addition of the alarm reporting protocol Dwarf, Meier concludes that the network lifetime would exceed operational time of three years. In *Memento* [15], with its similar approach with periodic heartbeats, the authors advocates the reuse of other protocols messages, such as periodic routing advertisements or sensor samples to be used for failure detection. Unfortunately, the choice of aggregating messages as to not increase the message load close to the sink, has the inadvertent effect of increasing the latency of the system. For the approach in this thesis, which is fundamentally different from the *DiMO* and *Memento* approach, as it relies on a round-robin approach, has the given advantage of being light-weight in comparison, as nodes are only instructed to forward a message to a neighbour, rather than monitor neighbours heartbeat messages. The main disadvantage with this round-robin approach however, has to do with scaling, as every node added to the algorithm will cause the round-robin ring to enlarge and as such, more time is needed to complete the round-robin sequence. As the algorithm was designed with smart homes in mind, the number of safety-critical nodes in a network may be limited to a small number of nodes, for which a tolerable latency can be achieved. However, if a large number of nodes participates in the round-robin sequence, the latency of the system may cause the overall responsiveness to fall outside of acceptable levels.

7.6 Open issues and future works

As the network topology simulation tool *Desvirt* only supports static link loss, it fails to sufficiently simulate a real wireless network topology where dynamical link loss is present. As such, only a speculative evaluation of how the algorithm would perform in a real environment can be made. The simulation tools used in the work, the native platform for RIOT OS and the network topology tool *Desvirt* have no mechanism for simulating power consumption, and as such no conclusions can be drawn whether the algorithm is a viable option for battery-powered nodes or if the power usage is simply too excessive for battery-powered units.

One major issue for the algorithm proposed by the thesis is the long convergence time in the onset of a global repair by the RPL protocol. As the algorithm relies on RPL for routing, the algorithm itself is very simplistic and carries a small code footprint, but as such, it relies on RPL for routing and the timers associated with RPL are influential

to the responsiveness of the proposed algorithm. This means that when RPL is called to perform local and global repairs more frequently, such as when safety-critical nodes are non-stationary, the responsiveness of the proposed algorithm may be heavily affected. This might however be combated by using a separate RPL DODAG for safety-critical nodes where the RPL associated timers has been adjusted accordingly.

Therefore, the author proposes that the algorithm should be tested in a real environment where dynamical interference is present and with a range of typical WSN hardware, in order to evaluate if the algorithm is feasible for implementation in areas where WSN are present, such as Smart Home environments. With a real environment set up, hard numbers can be gathered on how well the algorithm performs under a certain hardware set up. Interesting figures, for instance latency, energy consumption and the rate of false positives, could then be compared to other keep alive algorithms for wireless sensor networks, such as the heart beat algorithms[13][15].

8

Conclusions

This thesis has presented the issue of keeping a continuously consistent view within Wireless Sensor Networks while still trying to adhere to the minimalist and low energy principles of WSN. The thesis proposes an algorithm that make use of a round-robin approach where end nodes are relaying a keep-alive message to other end nodes, in order to minimize the number of messages required to keep a continuously consistent view of safety-critical nodes and links.

As for wireless communications, it is not currently possible reach the same reliability and response level as a closed circuit system, but wireless sensor networks have the advantage of being both cheaper and easier to install compared to a closed circuit system. As such, an approach where safety-critical devices are managed in a wireless sensor network rather than a closed circuit system may be realizable in homes or other areas where cost is of a major concern. The comparative cost of such an installation compared to that of a closed circuit system might be that modest that a wireless sensor network approach to security should rather be compared to a non-security premise than a closed circuit system as a wireless security approach can offer some security at a comparably small investment.

Issues exists, such as finding a suitable algorithm to fine-tune the variables used by the proposed algorithm, in order to reach a fast-response system where the number of false positives are kept low.

Bibliography

[1] M. R. Alam, M. B. I. Reaz, M. A. M. Ali, A Review of Smart Homes—Past, Present, and Future, IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews) 42 (6) (2012) 1190–1203.
URL http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6177682

[2] L. Lamport, R. Shostak, M. Pease, The Byzantine Generals Problem, ACM Trans. Program. Lang. Syst. 4 (3) (1982) 382–401.
URL http://doi.acm.org/10.1145/357172.357176

[3] J. Ko, J. Eriksson, N. Tsiftes, S. Dawson-haggerty, A. Terzis, A. Dunkels, D. Culler, ContikiRPL and TinyRPL: Happy Together, in: In Proceedings of the workshop on Extending the Internet to Low power and Lossy Networks (IP+SN 2011, 2011.

[4] J. Ko, J. Eriksson, N. Tsiftes, S. Dawson-haggerty, M. Durvy, A. Terzis, A. Dunkels, D. Culler, Beyond Interoperability: Pushing the Performance of Sensornet IP Stacks, in: In Proceedings of the International Conference on Embedded Networked Sensor Systems (ACM SenSys, 2011.

[5] I. Ishaq, D. Carels, G. K. Teklemariam, J. Hoebeke, F. Van den Abeele, E. De Poorter, I. Moerman, P. Demeester, IETF standardization in the field of the Internet of Things (IoT): a survey, JOURNAL OF SENSOR AND ACTUATOR NETWORKS (2) (2013) 235–287.
URL http://dx.doi.org/10.3390/jsan2020235

[6] F. Araújo, L. Rodrigues, On the Monitoring Period for Fault-Tolerant Sensor Networks, in: C. Maziero, J. Gabriel Silva, A. Andrade, F. de Assis Silva (Eds.), Dependable Computing, Vol. 3747 of Lecture Notes in Computer Science, Springer Berlin Heidelberg, 2005, pp. 174–190.
URL http://dx.doi.org/10.1007/11572329_15

[7] H. Liu, A. Nayak, I. Stojmenović, Fault-Tolerant Algorithms/Protocols in Wireless Sensor Networks, in: S. C. Misra, I. Woungang, S. Misra (Eds.), Guide to Wireless Sensor Networks, Computer Communications and Networks, Springer London, 2009, pp. 261–291.
URL http://dx.doi.org/10.1007/978-1-84882-218-4_10

[8] G. Călinescu, I. Măndoiu, A. Zelikovsky, Symmetric Connectivity with Minimum Power Consumption in Radio Networks, in: R. Baeza-Yates, U. Montanari, N. Santoro (Eds.), Foundations of Information Technology in the Era of Network and Mobile Computing, Vol. 96 of IFIP — The International Federation for Information Processing, Springer US, 2002, pp. 119–130.
URL http://dx.doi.org/10.1007/978-0-387-35608-2_11

[9] S. Chessa, P. Santi, Crash Faults Identification in Wireless Sensor Networks, Comput. Commun. 25 (14) (2002) 1273–1282.
URL http://dx.doi.org/10.1016/S0140-3664(02)00030-0

[10] S. B. Attia, A. Cunha, A. Koubâa, M. Alves, Fault-tolerance mechanisms for ZigBee wireless sensor networks, 2007.

[11] R. Alena, R. Gilstrap, J. Baldwin, T. Stone, P. Wilson, Fault tolerance in ZigBee wireless sensor networks, in: Aerospace Conference, 2011 IEEE, 2011, pp. 1–15.

[12] K. Sha, W. Shi, On the effects of consistency in data operations in wireless sensor networks, in: Parallel and Distributed Systems, 2006. ICPADS 2006. 12th International Conference on, Vol. 1, 2006, pp. 8 pp.–.

[13] A. Meier, Safety-Critical Wireless Sensor Networks, Ph.D. thesis, SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH (2009).

[14] S.-C. Wang, S.-Y. Kuo, Communication strategies for heartbeat-style failure detectors in wireless ad hoc networks, in: Dependable Systems and Networks, 2003. Proceedings. 2003 International Conference on, 2003, pp. 361–370.

[15] S. Rost, H. Balakrishnan, Memento: A Health Monitoring System for Wireless Sensor Networks, in: Sensor and Ad Hoc Communications and Networks, 2006. SECON '06. 2006 3rd Annual IEEE Communications Society on, Vol. 2, 2006, pp. 575–584.

[16] T. S. Rappaport, Y. Zhuang, J. Cappos, R. McGeer, Future Internet Bandwidth Trends: An Investigation on Current and Future Disruptive Technologies (2014).

[17] D. Evans, The internet of things: How the next evolution of the internet is changing everything, CISCO white paper 1.

[18] Gartner, Gartner Says 4.9 Billion Connected "Things" Will Be in Use in 2015, 2014.
URL http://www.gartner.com/newsroom/id/2905717

[19] L. Smith, I. Lipner, Free pool of ipv4 address space depleted, Number Resource Organization. Retrieved 3.

[20] Wikipedia, List of wireless sensor nodes — Wikipedia, The Free Encyclopedia, [Online; accessed 8-March-2015] (2015).
URL http://en.wikipedia.org/w/index.php?title=List_of_wireless_sensor_nodes

[21] C. Wang, K. Sohraby, B. Li, M. Daneshmand, Y. Hu, A survey of transport protocols for wireless sensor networks, IEEE network 20 (3) (2006) 34–40.

[22] IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs), IEEE Std 802.15.4-2011 (Revision of IEEE Std 802.15.4-2006) (2011) 1–314.

[23] A. J. Odey, D. Li, Low Power Transceiver Design Parameters for Wireless Sensor Networks.
URL http://dx.doi.org/10.4236/wsn.2012.410035

[24] E. H. Callaway, Wireless Sensor Networks: Architectures and Protocols, CRC Press, Inc., Boca Raton, FL, USA, 2003.

[25] I. Stojmenovic, Handbook of Sensor Networks: Algorithms and Architectures, Wiley Series on Parallel and Distributed Computing, Wiley, 2005.

[26] E. Nataf, O. Festor, Online Estimation of Battery Lifetime for Wireless Sensors Network, ArXiv e-prints.

[27] S. Deering, R. Hinden, Internet Protocol, Version 6 (IPv6) Specification, RFC 2460 (Draft Standard), updated by RFCs 5095, 5722, 5871, 6437, 6564, 6935, 6946, 7045, 7112 (Dec. 1998).
URL http://www.ietf.org/rfc/rfc2460.txt

[28] J. Hui, P. Thubert, Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks, RFC 6282 (Proposed Standard) (Sep. 2011).
URL http://www.ietf.org/rfc/rfc6282.txt

[29] G. Montenegro, N. Kushalnagar, J. Hui, D. Culler, Transmission of IPv6 Packets over IEEE 802.15.4 Networks, RFC 4944 (Proposed Standard), updated by RFCs 6282, 6775 (Sep. 2007).
URL http://www.ietf.org/rfc/rfc4944.txt

[30] M. Dohler, T. Watteyne, T. Winter, D. Barthel, Routing Requirements for Urban Low-Power and Lossy Networks, RFC 5548 (Informational) (May 2009).
URL http://www.ietf.org/rfc/rfc5548.txt

[31] J. Martocci, P. D. Mil, N. Riou, W. Vermeylen, Building Automation Routing Requirements in Low-Power and Lossy Networks, RFC 5867 (Informational) (Jun. 2010).
URL http://www.ietf.org/rfc/rfc5867.txt

[32] K. Pister, P. Thubert, S. Dwars, T. Phinney, Industrial Routing Requirements in Low-Power and Lossy Networks, RFC 5673 (Informational) (Oct. 2009).
URL http://www.ietf.org/rfc/rfc5673.txt

[33] A. Brandt, J. Buron, G. Porcu, Home Automation Routing Requirements in Low-Power and Lossy Networks, RFC 5826 (Informational) (Apr. 2010).
URL http://www.ietf.org/rfc/rfc5826.txt

[34] T. Winter, P. Thubert, A. Brandt, J. Hui, R. Kelsey, P. Levis, K. Pister, R. Struik, J. Vasseur, R. Alexander, RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks, RFC 6550 (Proposed Standard) (Mar. 2012).
URL http://www.ietf.org/rfc/rfc6550.txt

[35] J. Vasseur, M. Kim, K. Pister, N. Dejean, D. Barthel, Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks, RFC 6551 (Proposed Standard) (Mar. 2012).
URL http://www.ietf.org/rfc/rfc6551.txt

[36] P. Levis, T. Clausen, J. Hui, O. Gnawali, J. Ko, The Trickle Algorithm, RFC 6206 (Proposed Standard) (Mar. 2011).
URL http://www.ietf.org/rfc/rfc6206.txt

[37] J. Postel, Transmission Control Protocol, RFC 793 (INTERNET STANDARD), updated by RFCs 1122, 3168, 6093, 6528 (Sep. 1981).
URL http://www.ietf.org/rfc/rfc793.txt

[38] J. Postel, User Datagram Protocol, RFC 768 (INTERNET STANDARD) (Aug. 1980).
URL http://www.ietf.org/rfc/rfc768.txt

[39] D. Thangavel, X. Ma, A. Valera, H.-X. Tan, C.-Y. Tan, Performance evaluation of MQTT and CoAP via a common middleware, in: Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2014 IEEE Ninth International Conference on, 2014, pp. 1–6.

[40] Z. Shelby, K. Hartke, C. Bormann, The Constrained Application Protocol (CoAP), RFC 7252 (Proposed Standard) (Jun. 2014).
URL http://www.ietf.org/rfc/rfc7252.txt

[41] E. Rescorla, N. Modadugu, Datagram Transport Layer Security Version 1.2, RFC 6347 (Proposed Standard) (Jan. 2012).
URL http://www.ietf.org/rfc/rfc6347.txt

[42] S. Jucker, Securing the Constrained Application Protocol, Master's thesis, ETH Zurich (2012).

[43] IBM/OASIS, MQTT Version 3.1.1, [Online; accessed 2-November-2014] (2014).
URL http://docs.oasis-open.org/mqtt/mqtt/v3.1.1/mqtt-v3.1.1.html

[44] A. Stanford-Clark, H. Truong, MQTT for sensor networks (MQTT-S) protocol specification (2013).
URL http://mqtt.org/new/wp-content/uploads/2009/06/MQTT-SN_spec_v1.2.pdf

[45] M. O. Farooq, T. Kunz, Operating systems for wireless sensor networks: A survey, Sensors 11 (6) (2011) 5900–5930.

[46] A. Dunkels, B. Gronvall, T. Voigt, Contiki - A Lightweight and Flexible Operating System for Tiny Networked Sensors, in: Proceedings of the 29th Annual IEEE International Conference on Local Computer Networks, LCN '04, IEEE Computer Society, Washington, DC, USA, 2004, pp. 455–462.
URL http://dx.doi.org/10.1109/LCN.2004.38

[47] E. Baccelli, O. Hahm, M. Günes, RIOT OS: Towards an OS for the Internet of Things, INFOCOM'2013 (2013) 2453–2454.
URL http://hal.inria.fr/hal-00945122/

[48] F. Österlind, A sensor network simulator for the Contiki OS, SICS Research Report.

[49] O. Hahm, E. Baccelli, H. Petersen, M. Wählisch, T. Schmidt, Simply RIOT: Teaching and Experimental Research in the Internet of Things, in: 13th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN 2014), ACM, Berlin, Germany, 2014.
URL https://hal.inria.fr/hal-01058634

[50] DES-Testbed, desvirt, https://github.com/des-testbed/desvirt (2015).

[51] S. IG, W. GA, F. I. BJ, et al, Improved out-of-hospital cardiac arrest survival through the inexpensive optimization of an existing defibrillation program: Opals study phase ii, JAMA 281 (13) (1999) 1175–1181.
URL +http://dx.doi.org/10.1001/jama.281.13.1175

[52] K. Jalsan, K. Flouri, G. Feltrin, Energy Consumption Estimation for Wireless Sensor Network Layout Optimization, in: Ubi-Media Computing and Workshops (UMEDIA), 2014 7th International Conference on, 2014, pp. 238–242.

[53] E. Toscano, L. Lo Bello, Multichannel Superframe Scheduling for IEEE 802.15.4 Industrial Wireless Sensor Networks, IEEE Transactions on Industrial Informatics 8 (2012) 337–350.
URL http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6009195

[54] N. Abdeddaim, F. Theoleyre, F. Rousseau, A. Duda, Multi-Channel Cluster Tree for 802.15.4 Wireless Sensor Networks, IEEE, 2012, pp. 590–595.

[55] S. Chantaraskul, Multi-channel Utilization Algorithms for IEEE 802.15. 4 based Wireless Network: A Survey, Engineering Journal 17 (3) (2013) 119–126.

[56] P. Suriyachai, U. Roedig, A. Scott, A Survey of MAC Protocols for Mission-Critical Applications in Wireless Sensor Networks, Communications Surveys Tutorials, IEEE 14 (2) (2012) 240–264.