Node energy consumption variations with WirelessHART and RPL in a Wireless Sensor Network

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Node energy consumption variation with the protocols WirelessHART and RPL in a Wireless Sensor Network – a study on different impacts on node lifetime

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Abstract

A wireless sensor network or WSN has three main components, the sensor node, the access point and a console. These components exist for the purpose of making the WSN function as we want to, collecting sensor values, monitoring shipments or tracking animals. Many articles concern themselves with the topic of energy consumption in sensor nodes or wireless sensor networks, which can be logical because the sensor node is in many cases only powered by a coin cell battery, and that replacement of the battery once deployed can in many scenarios be difficult.

This paper will further include a theoretical part concerning the technology behind a WSN such as the IEEE, the OSI model, Internet Protocol and routing in general. Furthermore, the focus will be on differentiating factors for the energy consumption in the wireless sensor nodes.

The protocols researched are WirelessHart and RPL. WirelessHart seem to be the choice when dealing with industrial wireless sensor networks where the nodes are fixed to a certain point where it is supposed to measure a value. RPL must be more flexible as thought to be applied in many different systems and aspects and the nodes running RPL can be dropped in for example terrain and be expected to form a network.

Energy consumption differences between the protocols will be calculated, discussed and compared. Further, the different aspects of energy consumption will be brought up and compared to the first calculations. The view point will also fall on the factor most influential for a nodes lifetime.

In order to provide the best comparison environment as possible, the theoretical example will be set up by both protocols utilizing the medium access control technology called time slotted channel hopping. We will also set up five nodes and an access point in a house to represent the seemingly growing interest for smart homes.

We acquired the technical specification of a Texas Instrument node and have used its numbers in this project, although the result could be applied to nodes that meet the same criteria as the TI node.

Preface

This paper is the final result of a 60 point masters project completed at the University of Oslo, Institute of Informatics. The work has been performed by Simon Vedel Johansen in the time period 2015-2018. The project has been supervised by Professor Josef Noll and Knut Øvsthus.

This thesis begun in 2016/2017 and its goals are to elaborate on the energy differentials in protocols in wireless sensor network and the differentiating factors concerning energy consummation.

The writing of this thesis has not been without challenges, but the author feels that these have been overcome and the paper provides a description of Wireless Sensor Network (WSN), WirelessHart, RPL, related technology and takes on the different energy usage aspects in a wireless sensor node.

The background research for this project has in the first phase been performed by studying WirelessHART, RPL, WSN and literature regarding related work in this field. In the second phase there has been excessive studying on energy consumption in WSN and several calculations in order to present comparisons on power usages.

The author Simon Johansen would like to extend a big thank you to P.hD student Andreas Urke for guidance through the project and offering constructive support and criticism during meetings.

The second big thanks go to the authors' significant other Helene Søiland. She has been there for emotional support, dinner making and other household duties during the authors writing hours.

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1 Introduction

A wireless connected network provides a solution to the different issues introduced with a wired connected network. Easy and quick set up, low cost and simple management is what's being advertised. A topic not so often advertised but frequently researched is the electricity or power consumptions in these wireless network units called nodes. A reason for this possible lack of advertising can be due to the vast differentiating power consumptions depending on an even vaster number of components.

In a wireless connected network the operators have an opportunity to choose between what software these nodes have installed. This software is referred to as protocols, and can be seen as a ruleset these components have to follow in order to function correctly. The focus is on the two protocols WirelessHart and RPL, and the different aspects of these protocols will be discussed in terms of energy consumption.

On the surface, some of these softwares mentioned can seem quite similar. The distinction between them is often how they choose to best route data traffic between nodes and the size of their header fields. To simplify for readers not so familiar in the field of wireless sensor networks, shortened WSN, a header can be seen as the captain of the packet. The captain of the packet knows where to go next at what the packet is supposed to do.

A wireless sensor network can contain a few tens to thousands of wireless units named sensor nodes [1, 4], and these nodes possess such a small storage space that they have to frequently send newly obtained information to a common collection point. This collection point goes under different names; sink, gateway, root, or access point. Figure 1 illustrates a simplified WSN.

The thesis will include comparison of the headers and other aspects varying the energy consumption impacts on a WSN. Furthermore, provide a conclusion and some guidance for optimization in a setup.

The rest of this thesis will be as follows. Chapter two will contain a description on what a wireless sensor network is and how a WSN will further be related in this thesis. Chapter three provides the theories and technologies related to this paper. Chapter fours main parts consist of timeslots, header sizes and a comparison as well as a discussion on the impact of these different sized headers. In chapter five, the nodes utilized for technical specifications are described. Chapter six focuses on a sensitivity analysis of nodes, how an indoor propagation model can be applied to this scenario and how the energy consumption varies from the different duty cycles. Chapter seven concludes this thesis and provides a brief discussion on the subjects.

2 Wireless Sensor Network (WSN)

2.1 General WSN

Wireless connected network devices have certain advantages over the wired solution in networks, for instance; deployment is in many cases simpler, a significant cost reduction from wired networks and the size of the network takes up less space than a wired connected network would [25]. In case of environmental inconvenience on set up, networks relying on cable set up can in some cases be impossible while wireless technology enables users to quickly set up a network. “The “care free” feature and convenience of deployment make a wireless network more cost-efficient than a wired network in general [25].”

As mentioned in the introduction, the general wireless sensor network can contain a few to thousands wireless units named sensor nodes [1, 4]. These nodes possess such a small storage space that they have to frequently transmit newly obtained information to a common collection point. This collection point goes under different names (sink, gateway, root, access point etc.) and will be referred to as “Access Point” in this paper.

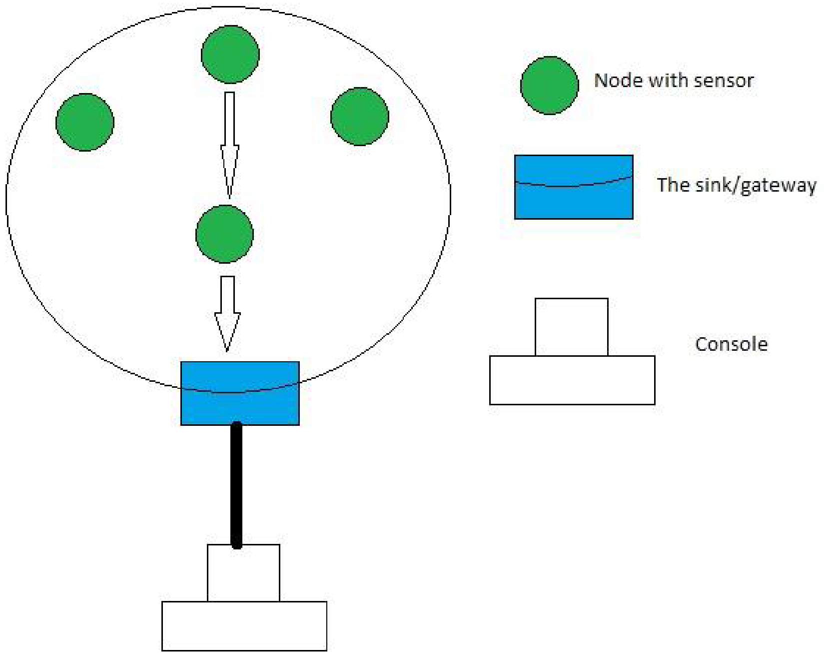

Figure 1: Illustrates a simplified Wireless Sensor Network

A WSNs three main elements are [9]:

- Nodes

- Access Point (sometimes called gateway or root)

- Console

The node is an electronic unit with several key components: a sensor, a microprocessor, a memory, a battery, and a transceiver to communicate with the rest of the network. The node is compatible with many micro sensors which tasks is to sense (motion sensor or gas “sniffer”), measure (temperature incline or fluid level) or collect environmental information (temperature, air quality, etc.) [3, 4]. The sensor is small with restricted processing and computational power. Additionally, it has a small storage space but is favorable for its more economical side compared to traditional sensors. Nodes utilize the transceiver to communicate with other nodes by means of radio waves. Figure 2 present a general view on the architecture of a node.

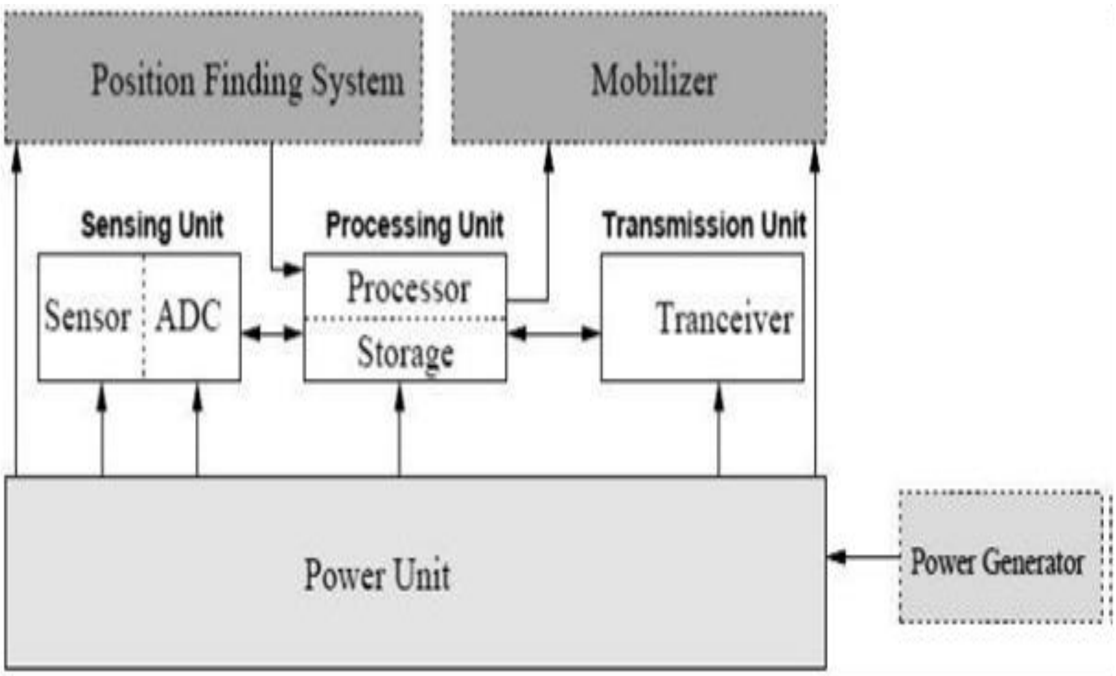

Figure 2: Sensor nodes common architecture [4]

Because of the limitations in a nodes resource and memory, and often distribution in locations difficult to access, a transceiver is implemented for wireless transfer of data to an access point. An access point can be a node with additional storage space and energy reserve or a computer [3]. The access point is mandated with the responsibility of keeping all the information received from the nodes or forwarding all the received data to a station. A station can be a relaying unit, relaying the information to a computer, or a computer console where data become possible to collect, process, analyze and present to an end user.

Figure 3 gives an overview of the sensor applications. A sensor network can be used to monitor hospital patients, animals, environment (such as weather, temperature or pressure), factories, machines or security detection. Another area of use for a WSN is tracking. One can track animals, vehicles, humans or, in a military context, enemies.

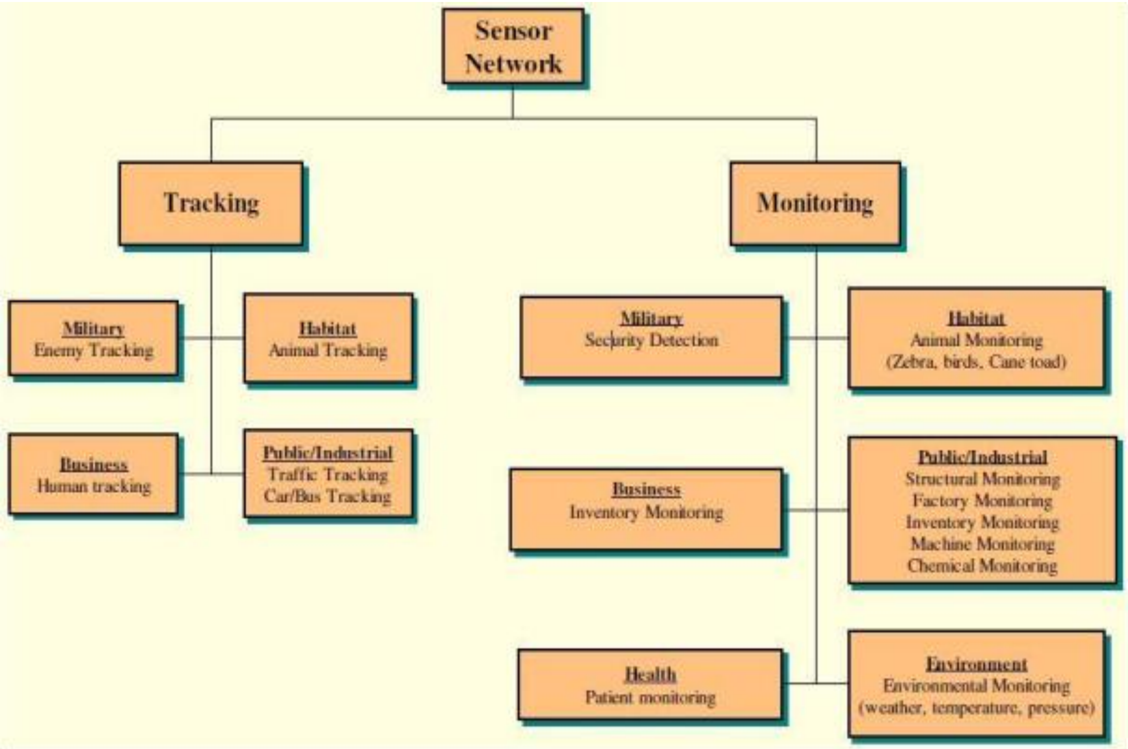

Figure 3: Overview of sensor applications [3]

A practical example can be when nodes are deployed in the forest or in the city, where they immediately will begin to locate each other and collect requested information to form a network. After the sensor network is up and running the nodes begin their next assigned task which in many cases is information gathering. The intention behind these information accumulations can be diverse, however the two major reasons is tracking and monitoring. The next paragraph will contain information regarding the energy consumption of the nodes and how different applications cause various energy consummations.

A node can be powered by either a battery or from an uninterrupted power source, but maybe the most used is battery power nodes. It is in these nodes energy conservation becomes most critical as they may be in intricate locations and exchanging battery is deemed challenging. The size of nodes makes it difficult for regular batteries to be attached and usually a coin cell battery is chosen. Some benefits using a coin cell battery is the small size, relatively economical and simple accessibility. On the other hand, a downside to a coin cell battery is the low total energy and small voltage size (compared to other batteries). A visual representation of a coin cell battery can be seen below in figure 4.

Figure 4: Coin Cell battery [45]

The basics of a WSN have in this chapter been briefly described. When the nodes have obtained a piece of information it transmits this to the access point for storage, thus when a console connects to the access point an operator can retrieve the necessary information. The appliance of WSNs simplifies; data logging, alarms/event detection and data collection.

In wireless sensor networks the need for an efficient routing protocol to route traffic as effortlessly as possible have become a critical issue due to the limitations set by the nodes size [4]. As mentioned, the election of battery is impacted by the size of the node. Further, the size and battery power does not fit well with a big antenna so this has to be small in size as well. With a small antenna one will likely not get the desired range and could have to compromise on certain aspects of the WSN. Maybe you have to add another node as a relay node or find other means of transmission from the node in order to sustain communication with the node. Protocols designed to handle these concerns exists and will be mentioned further down, chapter 3.3.

2.2 WSN in relation to project

In the case of this thesis and to give a visual representation on how a WSN can look like, figure five is provided. The circles are nodes and the square is the access point. Nodes are placed in a house with walls and floors. This house has three floors, basement, first floor and second floor. The access point is placed in the basement alongside node E, while node C and D are placed on the first floor and node A and B are placed on the second floor.

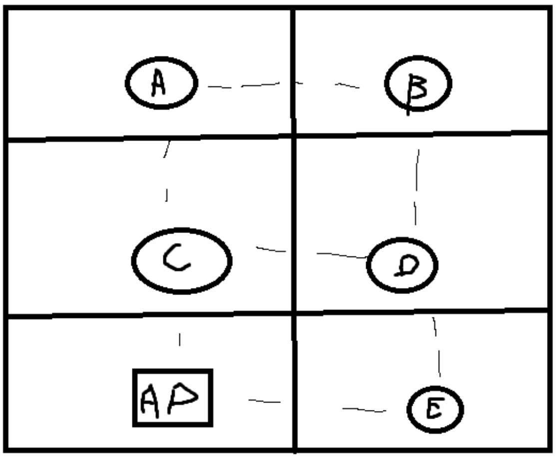

Figure 5: Simple illustration of nodes places inside a house

The main task in this project will be to compare energy consumption variations in the nodes and a big part of that will be to compare protocol headers of the two protocols WirelessHART and RPL. When we talk about WSN, nodes and energy consumptions it is important to mention the terms duty cycle, retransmission, node distance and packet size. These aspects are looked at later in this paper and will be discussed and calculated on.

It is in the authors mind that the sensor nodes in this network is connected to radiators and thermometers and have a task of upholding the temperatures decided by the house holding.

Physical simulation and measuring would be possible for this thesis but different circumstances led to a theoretical approach on the project. Many aspects of a WSN will be mentioned and discussed in attempt to shed light on different variables and situations to have in mind when managing wireless sensor nodes. The nodes utilized are described in chapter 5, we use only the nodes technical specification and the desired lifespan of a node is five to ten years. This paper will calculate node power consumption and discuss factors damaging the lifespan.

3 Factors influencing energy consumption

This chapter contains mainly three parts; (1) the subsection “Standards” main focus is on the IEEE802.15.4 but a description on other related subjects will also be addressed. (2) the subsection on routing will explain the basics of routing and how routing is related to a WSN. (3) on the third and last subsection of this chapter the two routing protocols WirelessHart and RPL will be addressed as an example on protocols suitable in a WSN, and is also in later chapters used to describe how different routing protocols affect the energy consumptions of a node. These subjects are covered in attempt to give a comprehensive view over the necessities in wireless communication. A wireless sensor network is an example where all these subjects are highly relevant and there are wireless devices, described more in chapter 2 about WSN.

When we want devices with network connection capabilities to connect, they need a common talking ground. They must route traffic over the same protocol. When we decide on a routing protocol we must have a standard on top.

3.1 Standards

A standard or standardization is a technical specification that describes how different objects should be defined in an unambiguous manner [23]. An example on a standard is the Universal Serial Bus (USB) or in the field of communication technology IEEE 802.15.4. Because of standards, different products from different vendors can cooperate [22]. This ensures competition between businesses, which leads to the down keep of product prices for consumers, and simplifies further development. In the case of network communication, if we did not have standards, the development would be rather restricted because our research would work on our systems but no other systems.

A standard within communication technology determines the functions and which protocols that can be utilized by the network needed for communication in certain environments. IEEE 802.15.4 is an example on such standard, it enlists detailed specifications on what type of supported device, frame structure, data transfer model, superframe structure, robustness, security and power consumption considerations [24]. The development of this standard was done considering the limited power supply available in relatively small wireless devices which usually are battery powered.

3.1.1 The OSI model

In order to give an abstract description of the network communication process we use a model called the Open Systems Interconnection or better known as the OSI model [25]. It is a reference model made to provide a path for nonproprietary protocol development and the architecture is defined in terms of a number of blocks in order to simplify the perspective. The blocks are called layers and each layer is responsible for doing its part of the network task and offer services to the higher layers. For a visual example see table 1.

	Layer Name	Description
7	Application	Performs services for the applications used by the end users.
6	Presentation	Provides data format information to the application. Informs layer 7 about encryption or file format.
5	Session	Manages sessions between users. This layer synchronizes web sessions, voice and video conferences in the web.
4	Transport	Defines data segments and number them at the source, transfers the data, and reassembles the data at the destination-
3	Network	Creates and addresses packets for end-to-end delivery through intermediary devices in other networks.
2	Data Link	Create and addresses frames for host-to-host delivery on the local LANs and between WAN devices.
1	Physical	Transmits binary data over media between devices. Physical layer protocols define media specifications.

Table 1: The OSI model with layer number, layer name and layer description

Data begins in the application layer and is passed down to each lower layer to be encapsulated with supported data. When the data reaches the physical layer, layer one, it is sent out on the media. Data arriving at the destination is decapsulated and passed up through each layer. Because it is just a reference model, manufacturers have the liberty to make protocols and products that combine functions of one or more layers. The IEEE 802.15.4 utilizes this model by using only layer one and two, data link and physical (PHY). Layer two, the data link layer, is divided into two sublayers, Logical Link Control (LLC) and Medium Access Control (MAC) [26]. Table three illustrates how this looks.

<table>
<tr><th colspan="3">OSI Model</th></tr>
<tr><td>Layer 7</td><td colspan="2">Application</td></tr>
<tr><td>Layer 6</td><td colspan="2">Presentation</td></tr>
<tr><td>Layer 5</td><td colspan="2">Session</td></tr>
<tr><td>Layer 4</td><td colspan="2">Transport</td></tr>
<tr><td>Layer 3</td><td colspan="2">Network</td></tr>
<tr><td rowspan="2">Layer 2</td><td rowspan="2">Data Link</td><td>Logical Link Control (LLC)</td></tr>
<tr><td>Medium Access Control (MAC)</td></tr>
<tr><td>Layer 1</td><td colspan="2">Physical</td></tr>
</table>

Table 2: The OSI model with detailed layer two

The OSI reference model is not the only protocol stack, a more relevant model may be the five-layer Internet protocol stack. It is divided into five layers, instead of seven as in the OSI model, the application layer, Transport, Network, Data Link and Physical layer. A graphical comparison is provided in figure 6.

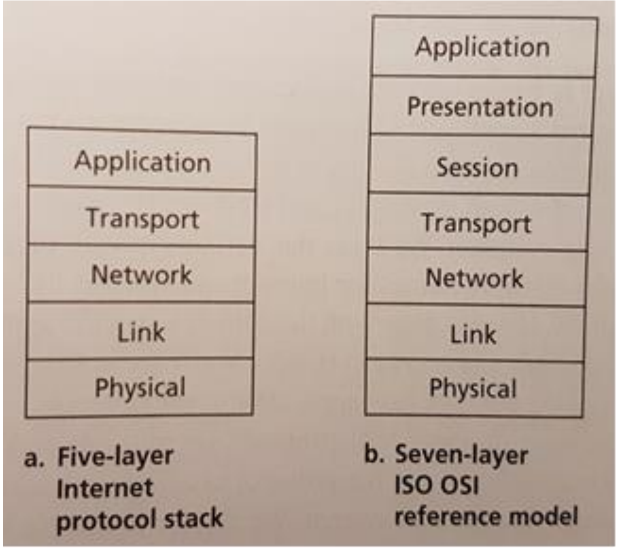

Figure 6: Visual representation of five layer vs seven layer protocol stack

Layer one, the physical layer, provides an interface between the MAC sublayer and the physical medium [24]. The medium can be physical (copper wire, fiber optics or coaxial cable) or wireless (2.4GHz radio, specifications of bands in table 3). The essential task for the physical layer is to move individual bits from the source to the destination [28]. Some other tasks the physical layer is responsible for is:

- Activation and deactivation of the transceiver, it can be in three different states: transmitting, receiving or sleep [24].

- Clear channel assessment (CCA) for Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), it is performed by utilizing carrier sense, energy detection or both.

The bits are transferred through the link in different ways depending on the protocol, and the protocols in layer one is dependent on which transmission medium that is used. An example they use in [28] is that Ethernet has many physical-layer protocols: one for twisted pair copper wire, another for coaxial cable, another for fiber and so on.

The link layer, layer two, provides services that enable the network layer to move packets from source to destination. These services depend on the specific link-layer protocol which is employed over the link [28]. Reliable delivery over one link is an example on a provided service. Ethernet, WiFi and IEEE802.15.4 are examples on link-layer protocols. As mentioned, the data link layer is divided into two sublayers, Logical Link Control (LLC) and

Medium Access Control (MAC). “The LLC sublayer provides multiplexing mechanisms that make it possible for several network protocols (IP, IPX, Decnet and Appletalk) to coexist within a multipoint network and to be transported over the same network medium. It can also provide flow control and automatic repeat request (ARQ) error management mechanisms. The LLC sublayer acts as an interface between the media access control (MAC) sublayer and the network layer [27].” The MAC sublayer provides an interface between the LLC and the physical layer; it also offers the two services; the MAC data service and the MAC management service [24, 26]. The MAC data service makes it possible to transmit and receive MAC protocol data units across the physical layer data service [30]. Some of the MAC sublayer functions are to support channel access, frame validation, and acknowledge frame delivery.

Band	868MHz	915MHz	2.4GHz
Frequenzy (MHz)	868-868.6	902-928	2400-2483.5
Chip rate (kchips/s)	300	600	2000
Number of channels	1	10	16
Modulation	BPSK	BPSK	O-QPSK
Data rate (kb/s)	20	40	250
Symbol rate (ksymbols/s)	20	40	62.5
Symbol type	Binary	Binary	16-ary orthogonal

Table 3: Details on the different bands

3.1.2 LR-WPAN

IEEE 802.15.4 is a standard that define the physical layer (PHY) and medium access control (MAC) sublayer specifications for networks named low-rate Wireless Personal Area Networks (LR-WPAN) [30]. To describe LR-WPAN as they do in [30]; it is a simple, low cost communication network that allows wireless connectivity in applications with limited power and flexible throughput requirements. The essential tasks of these networks are simple installation, dependable data transfer and fair battery life while maintaining a simple and adaptable protocol. The standard targets devices in a LR-WPAN, a general characteristic of these devices is; low power consumption, low cost, low data rate, low complexity and operation within 10 m (POS – personal operating space) [24, 30]. A 802.15.4 device can be one of two types; (i) a full-function device (FFD), this device is capable of serving as a coordinator (a coordinator is a device in a LR-WPAN that support synchronization services to other devices in the LR- WPAN) or a personal area network (PAN) coordinator. Or (ii) a reduced-function device (RFD), this device is not able to serve as a coordinator or a PAN coordinator and is intended for simple applications. A device is given this status because they do not require sending large amount of data and they associate only with a single FFD at a time. FFDs aid RFDs by supporting objectives such as network coordination, packet forwarding, interfacing with other types of networks, etc [32]. A WPAN must include one FFD, working as a PAN coordinator [30]. An IEEE 802.15.4 network can consist of one-hop neighbors or, if the range exceeds POS, multi-hop neighbors. As listed in table 3, wireless links utilizing 802.15.4 can operate on three frequency bands; (i) data rate on 250 kbps in the 2.4 GHz band, (ii) data rate on 40 kbps in the 915MHz band and (iii) data rate on 20 kbps in the 868 MHz band. It is assigned 27 channels in 802.15.4, 16 of which is allocated to the 2.4 GHz band, 10 is to the 915 MHz band and the last channel is assigned to the 868 MHz band.

The IEEE 802.15.4 LR-WPAN may operate in one of two topologies depending on requirements from the applications: the peer-to-peer topology or star topology, illustrated in figure seven. In the star topology the communication between devices and a single central controller is established and is called the PAN coordinator. Some examples of applications that favor this topology are home automation, PC, toys, games and personal health care.

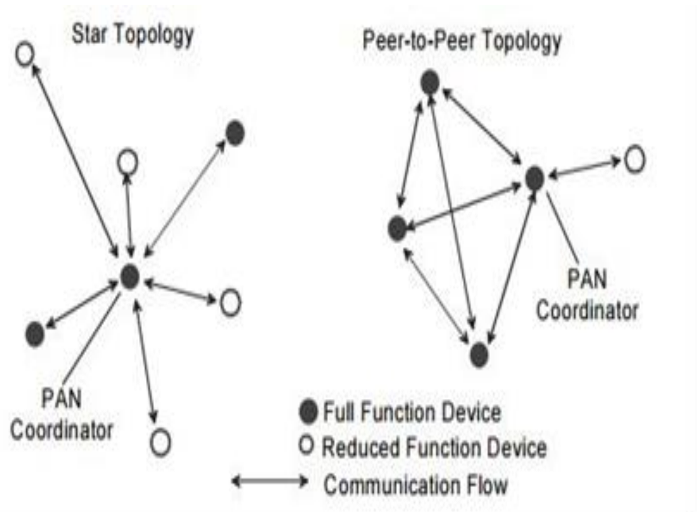

Figure 7: Star and peer-to-peer topology [30]

In a star topology all devices must communicate with or through the PAN coordinator but in the peer-to-peer topology any device may communicate with any other device as long as they are in range. By setting up a peer-to-peer topology a more complex network formation implementation is possible, for example mesh network topology. Applications that will favor a peer-to-peer solution would be industrial control and monitoring, WSN, assets and inventory tracking and security.

The 802.15.4 LR-WPAN utilizes a channel access mechanism called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [30], this mechanism attempt to ensure that a packet from the source arrives at the destination.

3.1.3 Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)

The avoidance of collisions is an important part since collisions lead to packet loss, which leads to retransmissions and that in turn to higher energy consumptions. CSMA/CA is in other words a mechanism to improve the probability of successful data transmission. A brief description on the steps of CSMA/CA follows. When a device wants to transmit data frames or MAC commands it must check to see if the medium is idle or busy in order to reduce collisions. By waiting a random time, then checking the medium it can ensure to a certain degree that a collision won’t happen. This time is often referred to as the backoff time interval. If the device detects that the medium is busy it will wait another random period, but if the medium is idle it will transmit the data. Depending on the network configurations the 802.15.4 LR-WPAN can use two types of channel access mechanisms. These are called (i) nonbeacon-enabled PANs using unslotted CSMA/CA and (ii) beacon-enabled PANs using slotted CSMA/CA. In an unslotted CSMA/CA the waiting time is a random time interval as for the slotted CSMA/CA the waiting is a random number of time periods.

3.1.4 Internet Protocol and 6LoWPAN

IP will be explained before 6LoWPAN and IPv6 in an attempt to bring the best view possible on the subject.

In order for a protocol to be considered a layer three, network layer, protocol it has to define routing and logical addressing [35]. The only network layer protocol that is widely used today is the Transmission Control Protocol with Internet Protocol (TCP/IP), specifically IP. Internet Protocols primary task is the routing of packets from source to destination and because of the possible large traffic load the network has to manage the IP routing processes simple. IP is called a connectionless protocol because it does not require a message or overhead agreement prior to packet transmissions. IP alone do not provide error recovery which will lead to packet loss if a host/router IP process is unable to deliver a packet. The correlation between IP routing and IP addresses is explained in [35]; IP routing relies on the structure and meaning of IP addresses, and IP addressing was designed with IP routing in mind.

The layout of an IP address (IPv4) is written as dotted-decimal notation, 192.156.97.15 is an example on how it can look. Each number can vary from zero to two hundred and fifty five (0-255). With that in mind and the layout being how it is we have an opportunity to calculate how many possible host we can assign to an IP address, it is 16’843’002. An IP address is necessary if a device needs to communicate with the use of TCP/IP. If a device obtains an IP address and have the appropriate software and hardware the transfer of IP packets is possible.

TCP/IP groups IP addresses in sets of consecutive addresses, these are referred to as IP networks. IP addresses that belong to a group must not be separated by a router, if an address is separated can it be natural to place it in another group. The intension of practicing this IP address grouping is to make routing as simple as possible. A great example used in [35] is the resemblance of IP addresses and postal addresses. If Ola lives in Norwaystreet 1, it is reasonable to assume that another person lives right besides Ola in Norwaystreet 2. So if the postal service know where Norwaystreet is, the delivery of a packet will not be difficult.

The name mostly referred to for IP addresses used in today’s networks is IPv4, Internet Protocol version four, and IPv6 is slowly implemented to support the lack of addresses. But before writing about the differences between v4 and v6, a brief explanation of v1, v2, v3 and v5 will be covered. According to [36, 37] IPv1, 2 and 3 belong to the TCP/IP protocols earlier versions and that IPv4 is the first standalone version of the IP protocol. Internet Protocol version five was an experimental TCP/IP protocol called the Internet Stream Protocol, this protocol was never finished because increase in bandwidth lead to the possibility of streaming over IPv4.

Internet Protocol version six (IPv6) is the new version of the Internet Protocol. It is the Internet Protocol version fours (IPv4) successor [38]. The difference between v4 and v6 is mainly divided into five categories:

- Expanded addressing capabilities: The mayor visual change of the Internet protocol is the layout. It has gone from looking like 192.156.57.19 (IPv4 address example) to looking like 2001:0db8:85a3:08d3:1319:8a2e:0370:7344 [39] (IPv6 address example). The change of layout is not only visual, it has an increased in size from 32 bits to 128 bits [38]. Due to this increased size, IPv6 can support simpler auto-configuration of addresses, more levels of addressing hierarchy and a greater number of addressable nodes.

- Header format simplification: In order to reduce the processing cost of packet handling and limit the bandwidth cost of the IPv6 header some of the IPv4 header fields have been made optional or dropped.

- Improved support for extension and options: The change of IP header encoding enables more effective forwarding and better flexibility in the area of future introduction of new options.

- Flow labeling capability: Labeling of packets which belongs to a particular traffic “flow” is a new added capability. With this label the sender has the opportunity to request a special handling, such as “real-time” service and non-default quality of service (QoS)

- Authentication and privacy capabilities: Extensions are specified for IPv6 in order to support data integrity, authentication and data confidentiality. Data confidentiality is optional.

In order to send and receive Internet Protocol version six (IPv6) packets, in a WSN environment, a protocol designed for such a task have to be applied. This is where the Internet Protocol version six over Low power Wireless Personal Area Networks (6LoWPAN) protocol comes in.

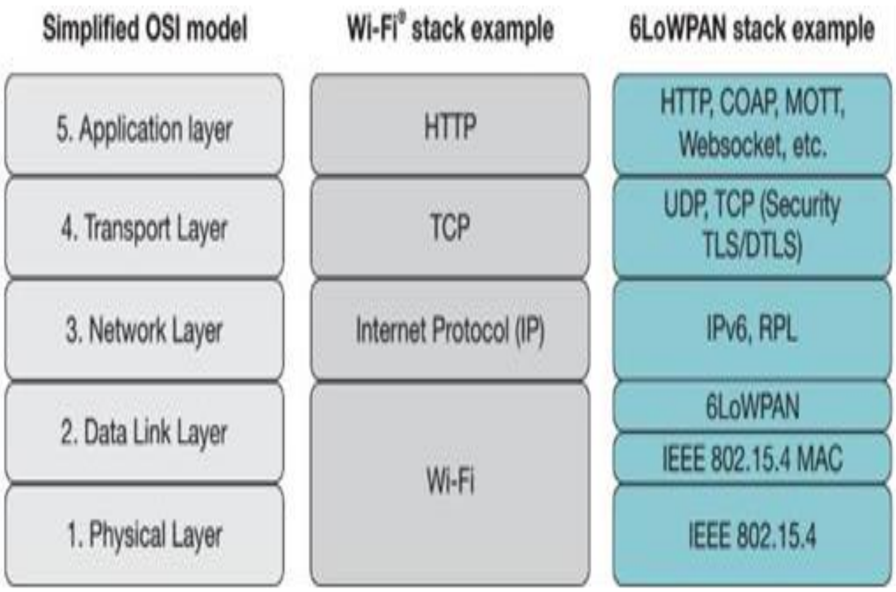

Figure 8: OSI stack, WiFi stack and 6LoWPAN stack together for visual explanation [34]

6LoWPAN is a definition on how to layer IPv6 packets over low data rate, low power, small footprint radio networks [31]. 6LoWPANs main objective is to carry IPv6 packets on top of low power wireless networks, in general on top of IEEE802.15.4. This protocol presents an adaption layer between the network layer and the data link layer, illustrated in table four [33]. The introduction of this adaption layer enables transmissions of IPv6 datagrams over IEEE802.15.4 radio links by providing adaption from IPv6 to IEEE802.15.4 [34]. For visual representation of the different stacks, see figure 8.

Layer name
Application
Transport
Network
6LoWPAN adaption
Data link
Physical

Table 4: Simplified OSI model with 6LoWPAN included as a sixth layer for visual representation [34]

An IPv6 network example is illustrated in figure seven and this figure includes the network topology for a 6LoWPAN network, a low-power mesh network [34]. A 6LoWPAN network cannot use the function of the Internet unless it has an access point acting as an IPv6 router. A 6LoWPAN network is in figure three connected to the IPv6 network through an edge router, this router is responsible for handling three actions. (i) The exchange of data between the Internet, alternatively other IPv6 networks, and 6LoWPAN devices, (ii) the exchange of local data between devices inside the 6LoWPAN and (iii) maintenance and generation of the radio subnet, the 6LoWPAN network. 6LoWPAN networks will according to [34] typically operate on the edge, acting as stub networks. Since it is seen as a stub network it is reasonable to assume that traffic towards the network has its destination at one of the devices inside the

6LoWPAN. This does not mean that a 6LoWPAN only can be a stub network, the 6LoWPAN can connect to other IP networks through more than one edge router that forwards data packets between different medias. The connection to another IP network is provided through Ethernet, Wi-Fi or cellular (3G or 4G).

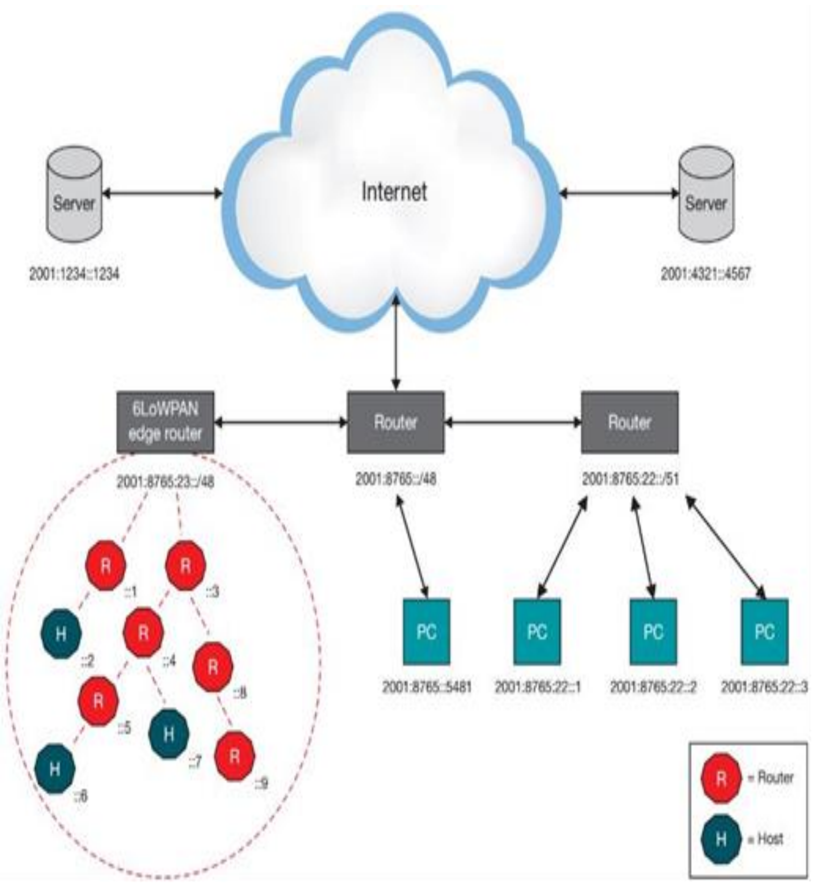

Figure 9: Visual representation of how an IPv6 network including a 6LoWPAN mesh network can look

The insides of a 6LoWPAN network usually include a router and a host [34]. Routers will send packets to its destination in the 6LoWPAN network while hosts, or end devices, do not have the routing possibility. End devices, like the host, may be sleeping and periodically waking up to check routers for data, thus enabling saving of power.

There are two categories of routing in a 6LoWPAN:

- Mesh-under, utilizes the data link layer addresses (IEEE802.15.4 MAC) in order to forward packets. The routing of data is transparent and mesh-under networks are therefore considered an IP subnet. The edge router is the only IP router in the system. These networks are best suited in local and smaller networks.

- Route-over, utilizes network layer addresses (IP addresses) in order to forward packets thus each hop represents one IP router. The foundation to a larger, more powerful and scalable network is provided with this IP routing. The most common protocol for routing over a 6LoWPAN is RPL, thoroughly explained in later chapter.

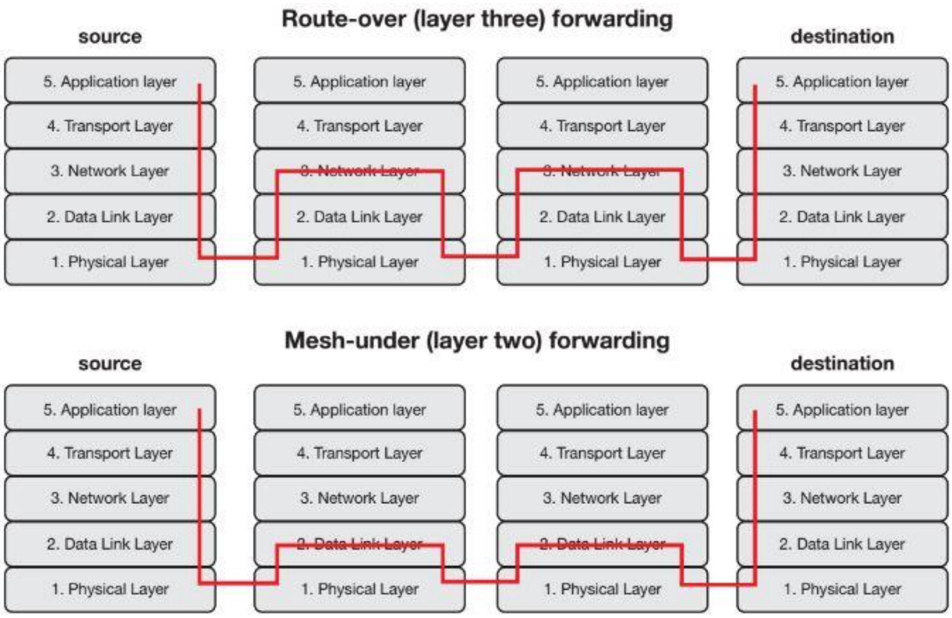

Figure 10: Route-over and mesh under packet forwarding [34]

Many protocols used on a standard TCP/IP stack can, with the advantages of route-over, be implemented and used as is. A visual representation is illustrated in figure ten.

The features of 6LoWPAN make the technology optimal for markets like home automation, streetlight control and Internet of Things applications with Internet connected devices.

3.2 Routing

Routing is a method of discovering paths where it is possible to send packets from an originating host (source) to a destination [4, 35]. When the originator is deciding where to send a packet it uses a simple routing logic, often called host routing. If the host and the destination are within the same subnet (a small group of IP addresses) the packet is sent directly to the destination. If the host and destination are not in the same subnet the host will have to send the packet to its default gateway, a router, and this router has to decide where to send the packet. The routers in a network have on startup, through routing protocols gained knowledge of the networks address space. In order to avoid running an IP lookup every time a packet is received the router stores information necessary for forwarding in its routing table. For best possible efficiency in the forwarding process this table must be accurate and up-to-date.

A routing protocols task is to add and maintain valid, loop free routes to the routing table [35]. A routing protocol will in general (i) dynamically learn the routes to the other subnets in the network and add these to the routing table. (ii) Favor the best route to a destination in the case of several possible paths. (iii) Discard no longer available paths. (iv) Add/replace routes as quickly as possible, lowest possible convergence time. (v) Prevent loops. Although this is a general description of a routing protocol, the way they operate can be significantly different and we have many to choose from in order to fulfill our current network demands.

The characteristics and challenging factors of a WSN is often mentioned as energy consumption, limited coverage, scalability and quality of service (QoS) and environmental. Because of these somewhat restricting characteristics the routing protocols applied in a WSN pay a significant role in the networks lifetime.

3.2.1 Routing in relation to WSN

Energy consumptions are required by a node to sense, process, receive and transmit information, the most energy consuming task is data transmission. A mobile node will no longer work if its energy source is depleted and that will in turn result in topology and network changes. The alteration of a network topology will cause a reorganization of the network and new routes must be found, this will contribute to the depletion of other mobile nodes energy source. If two parts of a WSN is connected through a single node and the node stops working you end up with two separate partitions and the network may not perform as required. Therefore the design/choice of a routing protocol is important. Some of the design issues are:

Coverage, the sensors given view of the environment, in a WSN is a design issue because the view is narrowed in range and accuracy. In the case where a WSN is deployed outside, a hill or vegetation will decrease the coverage.

The number of nodes which is deployed may vary. Each node in it selves cannot hold global knowledge of the network topology when the number of nodes is extensive.

The information obtained from nodes in a WSN is in many cases used by applications. An example of an application is target/movement detection. Applications deployed in crucial environment need some form of reinsurance to ensure system operation as required and as the vendor advertised. The name for this is Quality of service (QoS) requirements and some of its parameters are bandwidth, delivery delay, throughput, jitter etc. Target/motion detection, as an example, requires low transmission delay for time sensitive data and in the case of multimedia network the requirements are high throughput.

Large WSN have a lot of nodes, usually many cannot reach the access point directly. A node outside the access points range relies on intermediate nodes to forward its packets. By implementing a routing protocol we gain control of the resources. The choice of protocols falls upon the one offering the best possible solution for the requirements.

3.3 Routing protocol specified

By installing a wireless solution compared to a wired solution one can avoid the potential cost and hardship of installation. A wired solution requires cables, which can be costly in large amounts, and installation which also can be costly and more difficult than previously anticipated. A wireless settlement on the other hand is susceptible for interference from objects and personnel, and can become quite a challenge in an industrial environment over the course of time. As mentioned previously for nodes to communicate over the wireless medium, a routing protocol made for the task of transporting information is applied. You have different protocol options when installing a WSN, but the two mentioned in this thesis are WirelessHart and RPL. These protocols, as general routing protocols, have as mentioned in chapter 3.2 a task of discovering paths and creating a topology in order to ensure routing of packets.

3.3.1 WirelessHart

WirelessHart aims to resolve these issues by applying IEEE 802.15.4 to the physical layer, its own time-synchronized MAC layer and a network layer supporting techniques ensuring self-organizing and self-healing in a mesh network [2]. By implementing these layers as described one is left with the possibility to reroute traffic around obstacles and interference. Other core modules in WirelessHart are time management, security and network management.

WirelessHart is a TDMA (time division multiple access) based wireless mesh networking technology operating in the 2.4GHz radio band and is a set of rules applied to a WSN in order to make the units transmit as desired [2, 41]. WirelessHart have similarities to Bluetooth, and ZigBee but WirelessHart separate itself from these other public protocols by providing a managed up-to-date communication schedule to the network via a central network manager, thus providing improved network performance. Although WirelessHart have many similarities to ZigBee and Bluetooth, it differs (1) in its deployment. WirelessHart is not deployed randomly but attached to field devices meant for environmental information collection, thus limiting redundancy. (2) In the sensors tasks. The generic WSN deploy many nodes with the same task in a relative small area, while WirelessHart utilizes the sensors to only one task. For example pressure on one point of a gas pipe. Data readings can therefore not be replaced by a nearby node. (3) Another difference between a generic WSN and WirelessHart is that the generic network have no timing requirements and lack communication reliability which, in an industrial environment, will be the cause of many lost packets and extensive energy usage on resending of these packages. (4) Bluetooth target a Personal Area Network (PAN) with the usual range of 10 meters, only star type topology and one master seven slaves. WirelessHart have the topology option to choose star, cluster or mesh and in that way deliver more scalability. (5) Both ZigBee and WirelessHart apply IEEE802.15.4 on the physical layer, but where ZigBee utilizes IEEE 802.15.4 MAC layer

WirelessHart define one for itself where channel blacklisting and channel hopping is introduced. (6) In the case of a persistent interference, not unusual in an industrial environment, ZigBee make use of Direct Sequence Spread Spectrum (DSSS) provided by IEEE 802.15.4 which can result in a severe downgrade in network performance. WirelessHart reduces these damages to a minimum by pseudo randomly adjusting the communication channel. For WirelessHart's network manager, the two most severe objectives are to generate routes and communication schedules. WirelessHart has strict objectives for the network manager but leaves room for alterations such as where to put the focus, on for example load balance or minimizing average network latency and depending on which metric the focus falls on the final routes can differ.

3.3.1.1 WirelessHart Architecture

In reference of the OSI 7-layer communication model WirelessHart has a five layer stack including: application, transport, network, data link and physical layer [2]. This model will be further utilized in the description of WirelessHart and its components and can be seen in figure 11. Additional to the five layer stack a central network manager is introduced in order to manage routing and communication schedule.

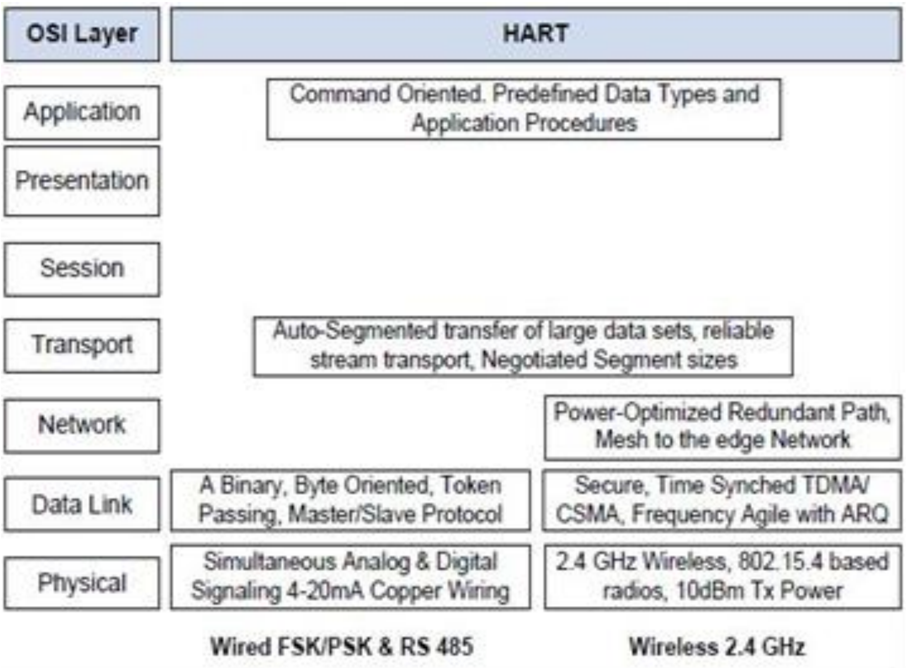

Figure 11: HART protocol architecture [2]

Examples on elements in a generic WirelessHart network is: (1) Field devices which is responsible for communicating the sensor data, (2) Handheld that works as a wireless computer with WirelessHart enabled and is utilized to run diagnostic, configure devices and perform calibrations, (3) The gateway tasked with the responsibility to connect host applications with field devices, and (4) the manager in charge of network configuration, scheduling and have the responsibility of communication between WirelessHart devices [2, 41].

WirelessHart application Layer

In the WirelessHart five stack model the layer on top is called the application layer and is responsible for definition of differing device commands, responses, data types and status reporting. Commands and responses are the basis of communication between gateway and devices, in WirelessHart, and the responsibility for generating responses, extracting the command number and parsing the message content falls on the application layer.

Transport layer and network layer

In order to deliver reliable and secure end-to-end communication for network devices the transport layer and the network layer work together. WirelessHart devices are required to forward packets in order to be a mesh network. Two routing mechanisms are defined in WirelessHart, graph routing and source routing. The network layer got a transport table, session table and a route table. WirelessHart is built around the thoughts of secure session, the session table is therefore in focus when it comes to design and end-to-end communication. The transport table is utilized in order to provide end-to-end acknowledged transactions with automatic retries.

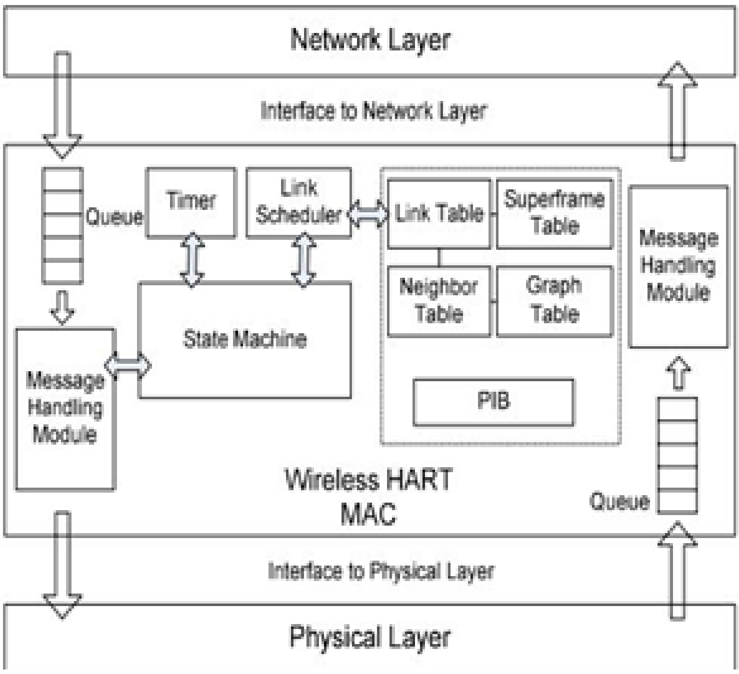

Figure 12: Data link layer architecture of WirelessHart [2]

Data Link Layer

WirelessHart make use of a technology called Time Division Multiple Access (TDMA) and utilizes this with its own strict 10ms time slot in order to provide as few packet losses as possible. The reduction of packet loss in WirelessHart is also countered with a technique called “channel blacklisting”. The feature required by a channel to be blacklisted is persistent interference. If a channel is blacklisted the administrator can choose to disable WirelessHart from using these channels. Each device in a WirelessHart network has an active channel table for channel hopping. If a channel is registered with significant interference and packet loss, the device will change channel and try again, in that way ensuring further network uptime.

Figure 12 is a visual illustration on the WirelessHart datalink layer and provides a simple graphical explanation on how it works.

Timer:

The timer module is important in WirelessHart due to its provision of accurate timing this to ensure that system operation is correct. This puts a strict timing demand on each network devices.

Communication tables:

Devices in the WirelessHart network each have a set of tables in the MAC layer. These are maintained be the device itself.

- Link and superframe table: The network manager generated communication configurations is stored in the link and superframe table.

- Neighbor table: This table list directly connected devices, no hops needed in order to reach, or neighbor devices. Devices in this table can be reached directly.

- Graph table: Records routing information and work with the network layer

Link scheduler:

Decides next slot to be serviced according to the communication schedule in the link and superframe table.

Message handling module:
Packets from the network and physical layer are put in que, buffered, separately in the message handling module.

State machine:
The state machine module contains three components; (1) TDMA state machine, (2) RECV engines and (3) XMIT engine. Execution of transactions in a slot and adjustments of the timer clock is the responsibilities of the TDMA state machine. The responsibility for sending and receiving packets falls on the hardware, and the XMIT and RECV is in turn responsible for the hardware. Three steps are called upon each time the state machine run;

- Contact link scheduler to decide next slot to be served.
- Obtain the time slot start event from the timer.
- Execute chosen transaction when it is time to serve given time slot.

Physical Layer
Radio characteristic such as signal strength, device sensitivity and signaling method is defined in the physical layer. WirelessHart utilizes a lot of the IEEE 802.15.4 2.4GHz DSSS physical layer, operation in the 2.4-2.4835GHz license free ISM band with data rate up to 250 kbit/s and numbered channels ranging from 11 to 26 are some of the borrowed features from 802.15.4.

3.3.1.2 In progress

With the utilization of communication tables, graph routing protocol and source routing protocol, WirelessHart supports trustworthy end-to-end communication and gives the option to choose from various network topologies [2].

The network manager must construct an overall network topology before optimized transmission can begin. The manager does this by using link information delivered by each node and ensuing six rules in this order;

- Decrease hop count

- Send traffic through power connected units, if available
- Detect signal strength of neighbors in order to allocate path with least loss
- Utilize several signal strengths to choose between alternative paths
- Lessen neighbor count to 4 or less

When the overall network topology is generated three more topologies will be created; a topology explaining routes from each network unit to the gateway, a broadcast topology from the gateway to each unit and topologies from the gateway to each unit.

After generating the topologies the network manager assign time slots to each unit based on these topologies.

3.3.2 IPv6 Routing Protocol for Low Power and Lossy Networks (RPL)

IPv6 routing protocol for low power and lossy network or shortened RPL have experienced increased popularity in the community and its field of expertise [12].

RPL is standardized by Internet engineering task force (IEFT) for a WSN and its main focus is keeping the cost between the access point and any other sensor to a minimum, therefore contributing to the operating scenario of obtaining a very high flexibility [7]. RPL is a distance-vector (DV) protocol [12], which means a node about to send a packet knows only in which direction to send and the distance [13]. A unique feature in RPL is the specific routing solution for low power and lossy networks (LLN), one can look at LLNs as networks with limited resources in form of energy, computational power and bandwidth [12].

RPL organize the WSN as a Direct Acyclic Graph (DAG) rooted at the access point and is also a gradient routing technique. According to the results presented in the article by Accettura et al ([7]) we can conclude that RPL is an effective routing algorithm because it grants a fast network set up and restricted delay. This DAG is often destination oriented towards the access point, therefore making it a destination oriented direct acyclic graph (DODAG) [12].

As illustrated in Figure 13 nodes in a DODAG have numbers, these numbers is referred to as rank and the nodes with the highest number have the lowest rank. As they mention in [12] nodes self-organize as one or several DODAGs, based on parent-to-child relationship. If we take left DODAG in figure 4 as an example; the node with rank three will be child to nodes with rank two, and be parents to nodes with rank four. So the parent rank is higher (lower number) than its child. In the left DODAG in Figure 13 you have two rank four nodes, these see each other as siblings. The access point have rank one, and the node with a direct link to the access point get rank two [12].

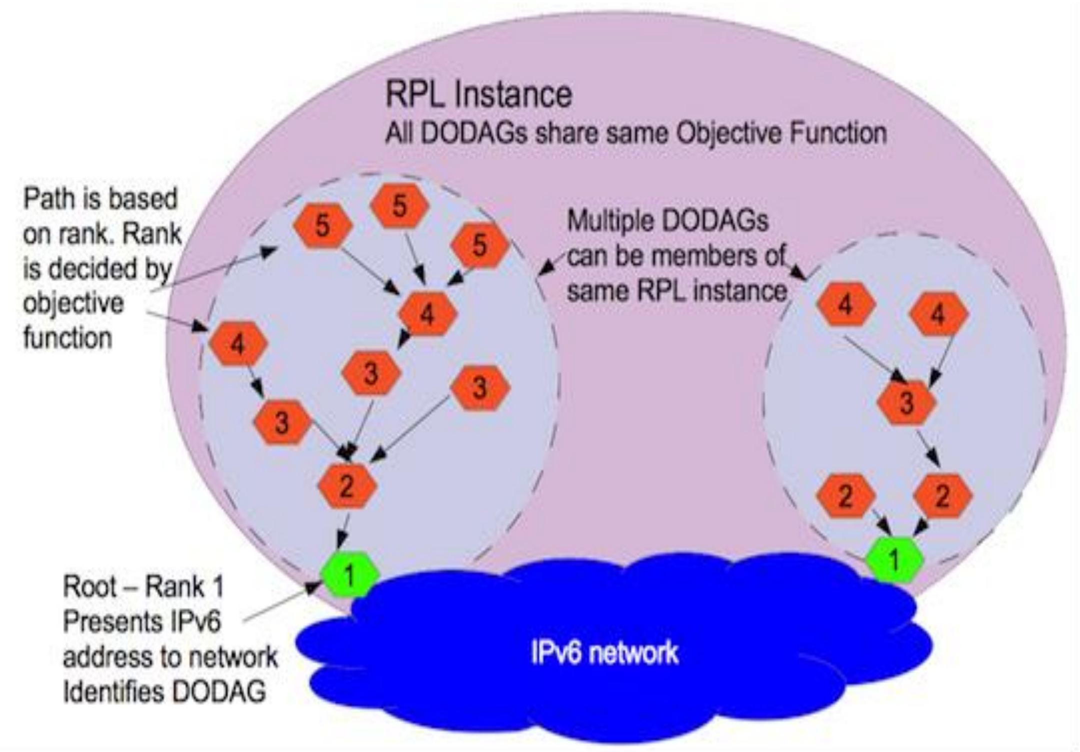

Figure 13: Visual representation of RPL instance with two DODAGs

Information in a DODAG can flow from top to bottom (five to one), or bottom to top (one to five). In this paper; (i) upward information flow is defined as information flowing from root (green one) up to the node with the number two, and then further up (to number three) as the illustration shows in figure four. (ii) Downward information flow is defined as information flowing in the roots direction, the same way as the arrows illustrate in figure four (from five to four to three to two and then to one).

It is defined three types of nodes in a RPL network [12]:

- Low power and lossy boarder routers (LBRs): Refers to the root of a DODAG, the green rank one node illustrated in figure four. These LBR nodes acts as the gateway between the Internet and the low power lossy network (LLN) and also have the option to construct a DAG.

- Router: A node device capable of generating and forwarding of traffic. Associated to one or more existing DAGs, but is incapable of creating a new on.

- Host: A typical end-device. This node cannot forward traffic from other nodes, only generate data traffic.

RPLs approaches in case of faults are reactive. To be reactive means it will react after a fault is detected rather than the proactive approach, which is to run fail checks regularly to try to prevent a fail before it happens [12, 15]. RPL favors the reactive solutions because it is more energy-efficient. “In a general fashion, a detection mechanism that is reactive to traffic is favored in order to minimize the cost of monitoring links that are not being used.” [15]. However when it comes to topology construction RPL acts proactively thus discards the need to broadcast route request (RREQ) messages [12].

A unique feature with RPL is that it combines both mesh and hierarchical topologies. RPL-based networks forces underlying nodes to self-organize as one or several DODAGs and because of this RPLs topology is part hierarchical [12]. RPL also allows routing through siblings (nodes with same rank/number, figure four) if it is more efficient that routing through parents and children. If a link between a child and parent goes down, this sibling routing may be the only option to deliver information. The routing through sibling just described is RPLs mesh topology elements. The combination of mesh and hierarchical ensure flexibility for routing and topology management.

A RPL message is composed of an ICMPv6 header and a message body consisting of a message base and a number of options [12]. The header have three fields; Type, Code and Checksum. The RPL control message type is identified by the Code field, these four codes are defined:

- DODAG information object (DIO): This message consist of relevant network information that allows a node to find a RPL instance, learn its configuration parameters, select a DODAG parent set and maintain the DODAG. A DIO message can be issued by a DODAG root to construct a new DAG.

- DODAG information solicitation (DIS): This message is used to request a DODAG information object (DIO) from a RPL node.

- Destination advertisement object (DAO): This message is as they explained in [12] "The DAO message … is used to propagate reverse route information to record the nodes visited along the upward path."

- Destination advertisement object acknowledge (DAO-ACK): This message is sent by a DAO receiver and contains DAOsequence and status.

The maintenance of a DODAG is managed by each node periodically generating DIO messages, triggered by a trickle timer [12].

Feature	Description
Target network	LLN; IPv6/6LowPAN networks
Routing type	Source-routing, Distance-vector
Topology	Mesh/hierarchical based on DAGs
Traffic flows	MP2P, P2MP and P2P
Message update	Trickle timer
Control messages	DIO, DAO, DIS
Neighbor discovery	Like IPv6 ND mechanisms
Transmission	Unicast and multicast
Metric and constraints	Dynamic, based on OF and rank
Modes	Storing and non-storing

Table 5: RPL routing protocol main features

RPL have the possibility to transfer information upwards, from the root and outward. Here we can choose between to modes of operation in order to maintain upward routes in a RPL instance:

- Storing mode: In this mode a DAO message is received by a parent, from its child, which is able to store DAO messages. The parent then aggregate reachability information to its parents.

- Non-storing mode: In this mode the DAO message is sent to the DODAG root so the intermediate parents do not store the DAO messages. The parents only insert their own addresses to the reverse route stack in the received DAO message then forward it to its parents

In relation to power usages in nodes it is important to mention the “trickle” algorithm or the trickle timer. The trickle timer ensures that the number of packets is reduced and loops are detected, in other words it is used to avoid redundancies [7]. A node is only allowed to send control messages within a certain time window and if the number of control messages has not exceeded the redundancy constant. The redundancy constant is typically set to 1-5, because these numbers serve a balance between low cost and redundancy [40]. Table 5 provides information on RPL routing main features.

4 Influence of routing protocols

The most significant influence protocols for a WSN is the header field in routing packets and the size of this header field. In some cases you only want the smallest of headers in order to minimize the power consumption, but in other cases a certain feature is desired more than the conservation of energy.

Both WirelessHart and RPL are set up with a time slotted solution in this thesis so the main focus can be on the protocol header. The larger the header, the bigger the energy consumption because a bigger/longer header means that the node have to stay in transmission for a longer period of time which in turn means more energy consumed all together.

Based on the node power supply sheet we can assume that in order to save the most power, and network lifetime, the nodes have to be put in sleep as fast and as long as possible. Based on this sleeping factor it is assumed that the protocol putting the most sensors most often into sleep will be the protocol managing to support network lifetime the longest.

Also more packets maybe mean more relaying of packets. Some nodes will maybe become only router/relaying nodes in some cases.

4.1 Time slotted Channel Hopping (TSCH)

Time slotted channel hopping (TSCH) is a medium access control technology in IEEE802.15.4 [50]. WirelessHart as mentioned have a strict 10ms time interval for its node to send its packets, before the next node get its 10ms. This frame or slot containing all the smaller timeslots is often referred to as a superframe or a slotframe. With a network update or new send interval approximately every four second the network initiate a new slotframe.

The sensor node (CC2650) utilized for this paper is described in chapter five but for this chapter we need to mention some of the specifications in order to deliver explanatory calculations. With this node you have the option of choosing two signaling strengths, 0dBm and +5dBm. The difference with a transmission on +5dBm compared to a transmission on 0dBm is that you will reach further out in the network during the +5dBm transmission, however the node require a higher energy output thus draining the power source faster. To simplify one can say that the node “hears” you better with the +5dBm.

Because of the difference between +5dBm and 0dBm the author chooses to use only 0dBm as the source for the calculations, since this transmission strength requires less energy. This will be further discussed in chapter 6. Since receive and transmit power (with 0dbm) is so similar (difference is 0.2mA) [46] this paper will use the average between RX and TX in a 0dBm transmission as only one energy output, 6.0mA ((RX+TX)/2 = (5.9+6.1)/2).

Furthermore, it is assumed that the superframe or slotframe interval is four seconds and that a node during this time period is in transmission state twice, receive and transmit (RX and TX). Since it is fair to assume that a node will during a superframe receive information and have something to transmit one can assume that the node will be initiated in two transmissions, RX and TX. Therefore the nodes stay in the state transmission in a total of 20ms (2*10ms) in every four second. The rest of the four second (3980ms) the nodes stay in standby (1microA [46]) to save power. This may not always be the case, that two nodes transmit and receive in approximately 5ms each, but simplifies calculations. It is also important to mention that a transmission with the AP only will influence one node and the AP is connected to an undisrupted power source.

From [47] we get the formula:
C=xT -> Ah = A*h, where
C equals the capacity in amp hours,
x equals the current that is drawn in amps and
T equals the time in hours.

As discussed above, the current drawn was equal to 6mA, so x equals 0.006.
The time for one transmission is 10ms and to get from millisecond to hour we multiply with $2.78 * 10^{-7}$.

$C = x * T$
$C = 0.006 * (10 * 2.78 * 10^{-7})$
$C = 0,006 * 0,00000278 = 0,00000001668Ah$
$C = 16,7nAh$

One transmission cost the node a total of 16.7nAh (nano ampere hour). The remaining 3990ms is spent in sleep/standby. The current drawn by the node in standby is 1microA.

C = 0,000001 * (3990 * 2.78 * 10^-7)
C = 0,000001 * 0,00110922
C = 0.00000000110922 = 1.1nAh

10ms of standby:
C = 0,000001 * (10 * 2.78 * 10^-7)
C = 0,000001 * 0,00000278
C = 0,00000000000278 = 0,00278nAh = 2.78pAh

So in four seconds, one superframe, with one transmission, the total energy consumption from one node is 0.00000000110922 + 0.00000001668
= 0,00000001778922Ah = 17.8nAh

Since each node gets one slot to send information it is reasonable to assume that each node will be in transmission 20ms (ten ms in Rx and ten ms in Tx). For example if node A transmit to node B and node B want to transmit to node C, B will first be in Rx in 10ms and then Tx towards C in 10ms.

Previously in this chapter we mentioned that the current drawn from the node in RX and TX is the same (6mA) since RX and TX with 0dBm energy consumption is so similar we take the average between them ((5.9+6.1)/2).
One nodes energy consumption in one superframe is therefore equal to
0.00000001668 + 0.00000001668 + (0.00000000110922 – 0.00000000000278)
Rx + Tx + (3990ms of sleep – 10ms of sleep)
= 0,00000003446644 = 34.5nAh

34.5nAh per node per superframe. / per 4 second * 15 * 60
31050nAh = 31.1uAh

As mentioned in chapter 2.1 the source of energy in nodes is usually a coin cell battery, therefore will our energy consummation calculation be done with in mind that this battery is powering the node. The coin cell battery in use has a capacity of 225mAh.

A quick calculation to see how long a node will survive with the current settings.

225000uAh/31.05uAh = 7246.38

7246.38/24 = 301.93 days

Node lifetime is with the current settings less than a year.

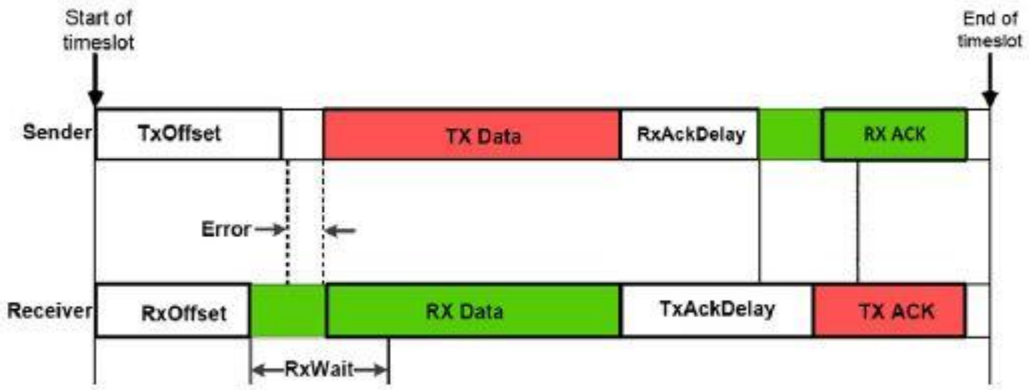

Figure 14: Dedicated time slot, internal structure [41]

The calculations done above are made with a thought that the whole transmitter and receiver field in the above figure is filled with packets/data, but as you can see figure 14, it is approximately half. In a table in [41] they write the time for TxOffset, RxAckDelay, RxOffsett, RxWait and TxAckDelay. They also mention that the maximum frame length is 4.256ms, Ack is 0.832ms and on the receiver end Rxwait is 2.2ms. The maximum amount of ms the receiving end is in transmission is 7,288ms.

RxWait + Rx frame + TxAck = 2.2 + 4.3 + 0.8 = 7.3ms.

So maximum Tx/Rx will be approximately ¾ of previously calculated.

Previous assumed energy usage multiplied with (3/4):

16.7nAh * ¾ = 12.53nAh

We multiply with two because of two transmissions, RX and TX and adds 3980ms of standby mode:

12.53nAh*2 + (0.00000000110922 – 0.00000000000278) = 26.17nAh per superframe

Multiply it so we get energy consumption for one hour:
26.17 *15 *60 = 23.55uAh

225000uAh/23.55uAh = 9554.14
9554.14 / 24 = 398.1 days = 1.1year

By fine tuning the energy consumption calculation we get over 90 more days. As you can see small deviations or adjustments can cost, or save, many days' worth of energy. But desired node lifetime is still five to ten years.

The node lifetime and duty cycle is further discussed in chapter 6.

It is not only WirelessHart that can be set up with a time slotted solution mentioned above, because of RPLs flexibility we are setting it up with slotted time interval as well. By doing this we make the two WSN scenarios as similar as possible and can put the focus on headers and direct energy consumption calculations.

All the following calculations are done without optional headers for simplifications and to avoid uncertainties.

4.1.1 WirelessHart Header and time

It was challenging to find information about the WirelessHart header and detailed information, largely because it is not open source. To get access you have to purchase a license. The technical details found are in a US patent [44].

The WirelessHart MAC header is 88bit, and this is without the WirelessHart MAC payload. The WirelessHart DLL header is 40bit and the WirelessHart network header is 112bit.

In all these headers we have an optional or variable field called the payload, but since the payload is either optional or variable it will not be included in further calculations.

Added together these headers are 240bit.

It is worth to mention that the WirelessHart network header consist of three additional optional fields not included in the above calculations.

250kbp/s

250'000bp/s

250bp/ms

2.5kbp/10ms

240/250 = 0.96ms for WirelessHart header

With a time slotted solution you had as mentioned in chapter 4.1 a max frame time on 4.2ms and the time WirelessHart needs is only 0.96ms. This roughly is one fourth of the maximum frame time.

4.1.2 PRL header and time

When calculating the impact RPL have on the network based on the header it is important to include the headers from the MAC, in this case 6LoWPAN, IPv6 and RPL itself. From [34] we get the information that 6LoWPAN compresses the IPv6 header.

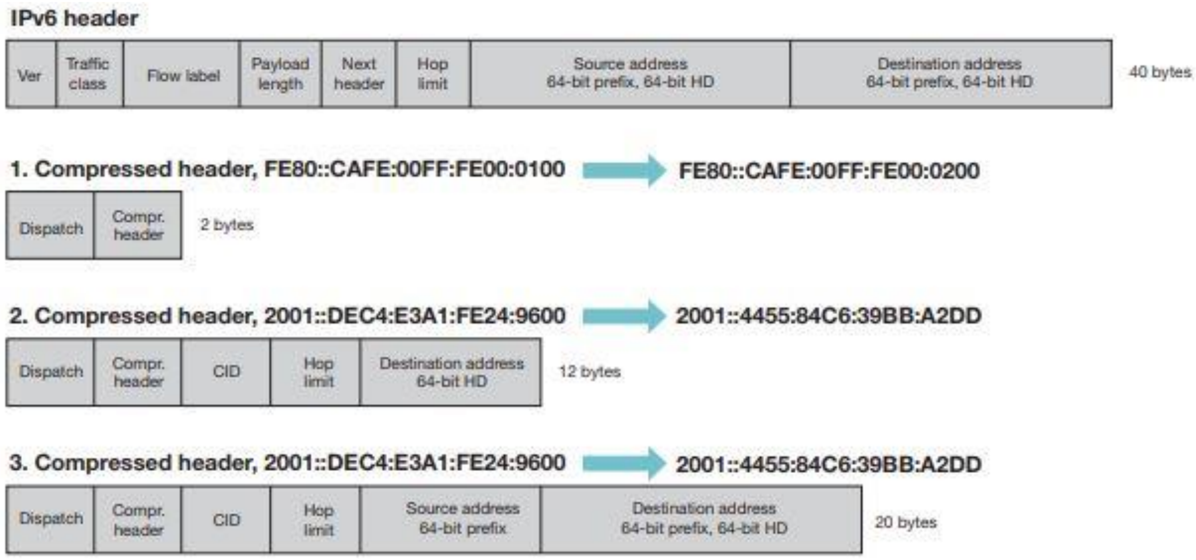

Figure 15: Three examples on 6LoWPAN IPv6 header compression [34]

In figure 15 you get a visual representation of the compressions on IPv6 by 6LoWPAN [34]. The first compression will is relevant in communication between two devices inside the same 6LoWPAN network and is 2 bytes or 16bit. The second compression is used when destination is outside of the 6LoWPAN network and the prefix for the external network is familiar, the header size is here 12bytes or 96bit. The third compression is when destination is outside of the 6LoWPAN network and the prefix of the external device is not known, here compressed down to 20bytes or 160bit. The writes choice is the second compression due to its suitability to the thesis scenario.

The RPL header is 44 bit [42],
6LoWPAN IPv6 header with compression is 12 bytes which is 96bit
the MAC header is 50 byte = 400 bit [43]

The total header size of a RPL packet is 540 bit.

540/250 = 2.16ms for RPL frame

4.2 Discussion WirelessHART vs RPL header

From calculations done in chapter 4.1, 4.1.1 and 4.1.2 the information on header sizes are obtained. We found that the WirelessHart headers are 240bit and that the RPL headers are 540bit, a difference of 300bit.

That difference will in turn be the reason for higher energy consumption. The protocol with the highest header size will have the nodes stay in transmission mode for a slight longer period of time in each timeslot. This will in the long run ensure that the WSN running the protocol with the largest headers get the smallest node lifetime.

Divided with each other (540/240) we get that RPL is 2.25 times larger than WirelessHart and by that WirelessHart have roughly a node lifespan of 2.25 time that of RPL. The author uses the term roughly because the network draws power in standby mode while being alive. To simplify with an example; the 2.25 times extra that RPL have to be in transmission the nodes in WirelessHart stays in the mode standby and thus draws energy from the nodes energy reserve but not as much as in transmission.

From chapter 4.1.1 and 4.1.2 the time it takes for the headers to be transmitted is calculated and the result was:
WirelessHart headers: 0.96ms

RPL headers: 2.16ms
Difference (2.16 – 0.96): 1.2ms

So RPL is in transmission state 1.2ms longer than WirelessHart every timeslot. From chapter 4.1 we found that 10ms of transmission drains 16.7nAh and divided by ten one ms equals 1.67nAh. Multiplied with the difference in time (1.2ms) we find that the difference in power usages during one transmission is 2nAh. Since it is two transmissions in one timeslot the energy consumption difference is 4nAh.

4nAh is roughly, it means it is not entirely true, because when a WirelessHart node is finished its energy consumption is not zero. The nodes energy consumption when it is not in transmission is the standby mode. So to make the calculation right we have to subtract 1.2ms of standby from the difference in energy consumption.

10ms of standby equals 2.78pAh, from chapter 4.1, divided by ten and multiplied with 1.2 is 0.3pAh which equals 0.0003nAh.

Transmission calculations:
10ms of transmission: 16.68nAh
10ms of transmission divided by ten multiplied with 1.2: 2.0016nAh

1ms of transmission multiplied with 2.16 subtracted with 0.0003nAh: 2.0013nAh

More precisely the difference in energy consumption during one transmission is 2.0013nAh, multiplied by two because of two transmissions during each timeslot equals 4.0016nAh.

Every timeslot the RPL protocol use 4.0016nAh more energy than WirelessHart. This may not seem as much, but in long term it makes a difference.

4.0016nAh * 15 * 60 * 24 * 365 = 31548614.4nAh = 31.55mAh

By those calculations RPL utilizes 31.55mAh more energy each year than WirelessHart, excluding Ack messages and wait time meaning only transmitting the headers and that’s that with a timeslot every four seconds.

The 31.55mAh conclusion above does not include any calculation on used standby power while the node is in standby mode nor does it include any numbers or calculations from possible retransmission. It only demonstrates the difference in energy consumption consumed only by the headers by the two protocols WirelessHart and RPL.

5 Wireless sensor node

The choice of sensor node was made at the beginning of this master project, and chosen because at the time believed to be the best choice.

The tool theoretical used for this project is; the Texas Instrument (TI) SimpLelink CC2650 Wireless MCU Launchpad kit, shortened LAUNCHXL-CC2650. The Launchpad is illustrated in figure 16 [16].

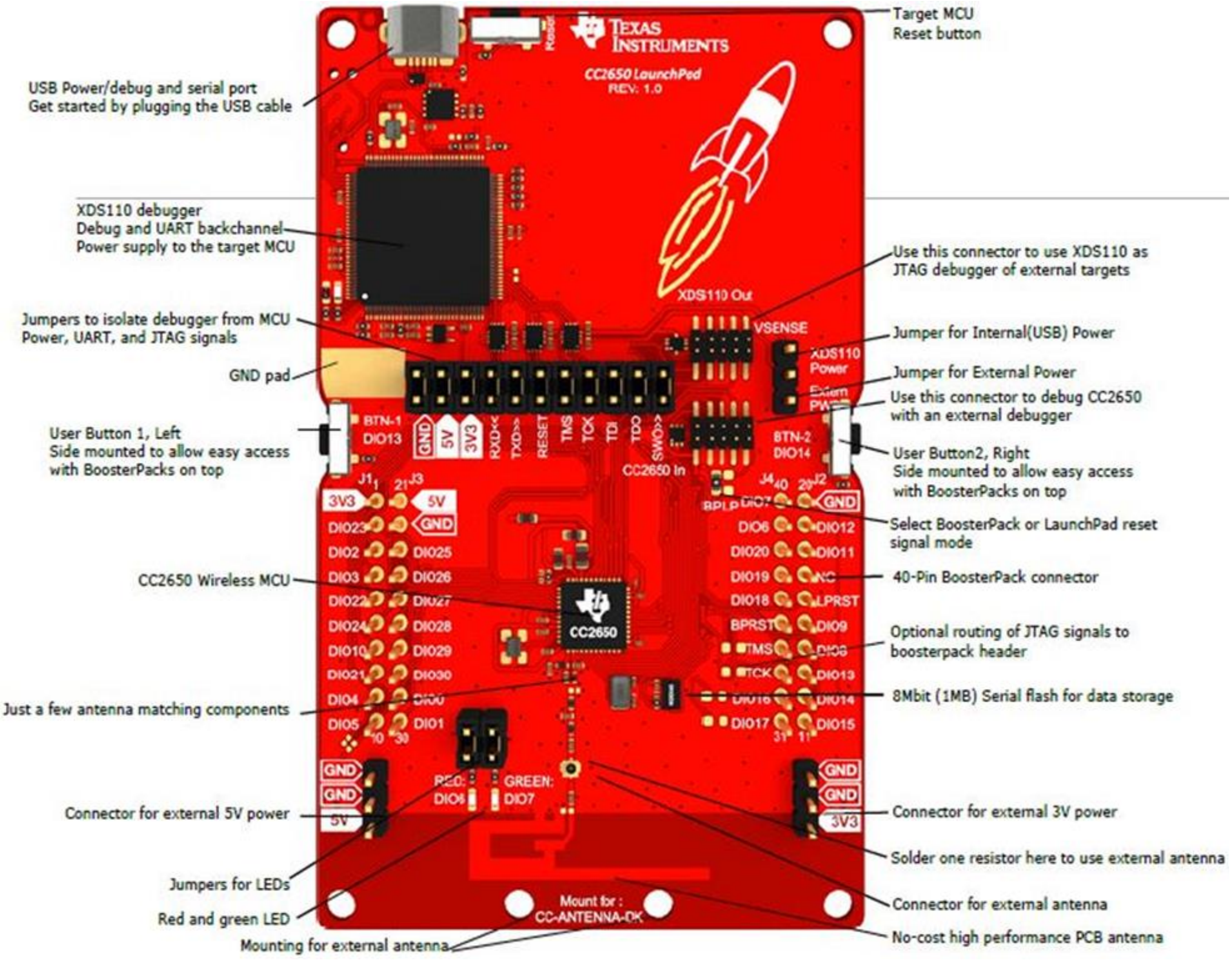

Figure 16: Texas Instrument (TI) SimpleLink CC2650 Wireless MCU Launchpad kit [16]

The Launchpad kit has several features and possibilities, the ones most important to mention:

- USB power/debug and serial port
- XDS110 debugger, which contains

- Debug and UART backchannel
- Power supply to the target MCU

- CC2650 wireless MCU, the node
- No-cost high performance PCB antenna
- Serial flash for data storage, 8Mbit (1MB)

The connection between a computer and the Launchpad board is through a micro-USB cable. The debugger can be used to compile self-made code and transfer the code to the node. The node uses the code as a runnable program, and the antenna will send and receive data packets.

In order to transfer the self-made code from the computer to the board we have to use a program from Texas Instrument called "Smart RF Flash Programmer 2". The process of transferring from the computer to the board with this program is called flashing. The flashing procedure is complete after three steps:

- Erase: The Smart RF Flash programmer 2 erases all other information on the board, including received packets which are not transferred.

- Program: The Smart RF Flash Programmer 2 gives the program/code to the debugger and the debugger adds it to the node

- Verify: The Smart RF Flash Programmer 2 verifies that everything is working properly.

We assume a lower power consumption by using the 0dBm on shorter distances rather than +5dBm on greater distances. The difference is further discussed in chapter 6.6.3.

6 Sensitivity analysis and evaluation

In this chapter the author will use the information gathered in previous chapters, do calculations based on different factors and discuss energy consumption outcomes.

Some assumptions we do for later calculations is that application data or payload data sent is 10bit. We assume the 10bit because it is only notification data when the measuring value drops below a boundary limit, so it does not have to be large. This payload is only the data that is supposed to tell the access point information regarding the application. The house described in chapter 2.2 uses radiators for a source of warmth and it is on a certain boarder temperature that the sensor nodes will transmit application data, notifying the access point that the room temperature is now under the set boarder temperature.

Another assumption made in this chapter is that the network is fully converged, and that it has been running for a long time. This way it is simpler to calculate the energy consumed since we can decide that in a converged network there will only be sent routing information in two minutes every thirty minutes the network is active. The reasoning for assuming a two minute window within the thirty minutes is that we want to assure that all the nodes can send the routing information needed and to provide a scenario where we can present the theoretically most reliable energy consumption calculations.

Further down in chapter 6.4 the subject of duty cycle is brought up and discussed. After discussing and mentioning different aspect of households' habits it is concluded that the network is active ten hours during a day (24h). During these ten hours there will be sent one application packet each hour, so one node will transmit two application data packet during the ten hours. The access point or software receiving the application data will tell the radiator in the current room to heat for 20 to 30 minutes so our nodes don't have to look for an upper boarder temperature, this way reducing the necessary application packet transmissions.

6.1 Simple power calculation

Utilizing the node mentioned in chapter five [46], we can do some simple calculations to get a general idea on how long the lifetime of a node will be. The node is powered by a coin cell battery with 225mAh capacity. From [16, 46] we get power usage from the node in standby, transmit (TX) and receive (RX).

Explanation	Energy numbers
Wide supply voltage range, Normal operation	1.8 – 3.8V
Active-Mode RX	5.9mA
Active-Mode TX, 0dBm	6.1mA
Active-Mode TX, 5dBm	9.1mA
Standby	1 microA
Shutdown	100nA

Table 6: LAUNCHXL-CC2650 energy statistic

Table 6 provides a short summary of the utilized technicalities from [46].

In shutdown:
100nA = 0.0001mAh
225/0.0001 = 2250000 hours in shutdown
(2250000/24) / 365 = 256.8 years in shutdown

In standby only:
Use 1microA = 1microAh = 0.001mAh
225/0.001 = 225000, hours in standby
(225000/24) / 365 = 25.7 years of sleep

In receive (RX) only: 5.9mAh, 225/5.9 = 38.1h

In transmission (TX) only: 6.1mAh. 225/6.1 = 36.9h

The longer a node stays in the shutdown or standby state the longer its lifetime will be, observed from the calculations. So in order to prolong the lifetime of your network you have to put your nodes in shutdown or standby state as often as possible.

A long node/network lifetime may not be your only option. If some nodes are connected to uninterrupted power supplies the choice of reliability may become more desirable.

As mentioned in the introduction in chapter six and brought up in the duty cycle chapter (6.5) the network is active for ten hours during the day. Ten hours is found in chapter 6.5 to be the time where the inhabitants of the house are home and in need of the network. During that time period the network transmits router header packets for two minutes every thirty minutes, four minutes with router packets in an hour. The application data is 10bit and is sent from one node two times during that ten hour window.

If we first look at the four minutes of router headers sent we know from chapter four that a node is in transmission two times during a superframe, and a superframe happens every 4 second. The four second used here and in earlier chapters is just an example meant to show that if you transmit too often you will see higher energy consumption and provides us with another aspect to discuss when writing about the energy consumption in nodes.

6.1.1 Energy consumption model for WirelessHart

What we discovered from chapter four is that the 240bit WirelessHart header must use 0,96ms to be transmitted with a transmission rate on 250kbps. However the acknowledged packet and wait time is not considered in the previous calculation. Found in chapter four is the time it takes to transmit the acknowledge packet and how long the node is in RX wait. The RX wait, 2.2ms, is used as a reassurance time incase the clocks in the nodes are desynchronized and will provide a higher probability for a successful transmission. Including the Ack, 0.832ms, and wait the total transmission time with WirelessHart is 3.99ms (0.96+0.832+2.2) and with a transmission rate of 250kbps that gives us 6.66nAh. It is possible to find this number because chapter four gave us that one millisecond of transmission equal 1.67nAh, and we simply multiply the number 1.67 with the time 3.99ms and got 6.66nAh.

6.66nAh is the energy consumed by the node during one transmission running WirelessHart. As mentioned a node is counted on having two active states during a superframe, RX and TX. So the total energy consumed during one superframe in an active state is 13.32nAh, based on the assumptions and calculations done in chapter four.

In a superframe the largest time interval will be spent in the standby state and we therefore calculate the standby mode energy consumption to add to the active mode energy usage in order to get the energy consumed by a superframe.

Standby mode energy consumption:
1109.22pAh was found in chapter 4.1 to be the energy consumption for a node being in the standby for 3990 milliseconds.

If we divide this energy consumption with the time we get the energy consumption for one millisecond.
1109.22 / 3990 = 0.278pAh for energy usage in one millisecond in standby mode.
We multiply the energy usage with two in order to get the energy consumption for two milliseconds which equals to 0.556pAh. This added with the 3990 milliseconds of energy consumed will give us the energy consumed in 3992 milliseconds of standby mode. 3992ms is further described in the nest paragraph.
1109.22 + 0.556 = 1109.776pAh = 1.11nAh

The energy consumed in the remaining standby mode is 1.11nAh. If you look at the calculation done above you will notice that the standby time is 3992ms. This is because transmission time is two times 3.99ms (one TX and one RX) which equals approximately 8ms, and the remaining time is (4000-8) 3992ms. So in one superframe the WirelessHart node consume 14.43nAh (13.32+1.11).

So now that we have the WirelessHart energy consumption we add the application data from the sensors. As mentioned we set this application data as 10bit, and in order to transmit this application data we have to put all the headers in the packet. One application packet contains all the headers including the application data. That means to add 10bit of transmission and subtract the coherent time in standby mode.

With a transmission rate of 250kbps or 0,250bp/µs ten bit takes forty microseconds to transmit and with the 1.67nAh consumption for one millisecond that equals to 0.0668nAh or 66.8pAh. 14430pAh + 66.8pAh equals 14496.8pAh or 14.49nAh . We do not subtract 40µs of standby energy due to its insignificant energy usage.

As mentioned in the beginning of chapter six the superframe has an interval of four seconds and every 30 minutes the network will have two minutes to send network information, this equals four minutes per hour. In these four minutes the superframe occurs fifteen times during one minute, thereby resulting in sixty times per hour.

The energy consumption for a node in one hour running WirelessHart will therefore equal to:
14.43nAh * 60 = 865.8nAh

In the beginning of chapter six and in chapter 6.4 it is mentioned that the network only will be active in ten hours during the day and one node will during these ten hours transmit two application packets. In the introduction to chapter six we assume that there will be an application packet per hour, and since it is ten hours it is approximately two packets per node per day. In order to get the most accurate packet sending interval further study on temperature decline in a home have to be researched and is assumed beyond the scope of this thesis.

One day of protocol headers:
865.8nAh * 10 = 8658nAh
Adding the two application packets:
8658 + (14.49*2) = 8686.98nAh = 8.69µAh,

During one day a node consumes 8.69µAh in the active mode (TX, RX and standby). The rest of the day will be spent in shutdown mode. The power drawn by the node in shutdown is 100nA, and utilizing the formula in chapter 4.1 [47] (C=xT) the remaining fourteen hours cost the node 1400nAh or 1.4µAh. During 24 hours with WirelessHart the node consumes 10.09µAh.

Node lifetime:
225000/10.09 = 22’299.3 days = 61 years
Yearly consumption:
10.09µAh * 365 = 3682.85µAh = 3.7mAh

With the coin cell battery utilized in our scenario with the 225mAh capacity with WirelessHart and the daily consumption of 10.09µAh the node will have a lifetime of approximately 61 years.

6.1.2 Energy consumption model for RPL

To calculate the same for RPL, we have the header size which is 540bit and will use 2.16ms with the transmission rate of 250kbps. Added with the ack and wait the total time is 5.19ms. The waiting time mentioned here is assumed the same as the waiting time in RX since no other variables where found. The waiting in the TX sequence happens before the acknowledge packet is sent and work as a time buffer in order to increase transmission success rate, a visual representation is illustrated in figure 14. The time multiplied with the energy consumption for one millisecond (1.67nAh) equals 8.67nAh.

8.67nAh is the energy consumed by the node during one transmission running the protocol RPL. As mentioned a node is counted on having two transmissions during a superframe, RX and TX. So the total energy consumed during on superframe only in transmission is 17.34nAh.

Standby mode energy consumption is 1109.22pAh for standby in 3990ms. The energy consumed in the remaining standby mode is 1.11nAh. The total time in transmission is 10.36ms, approximately 10ms which means we have 3990ms left. The author chooses to ignore the 0.36ms of standby energy due to its insignificant energy usage.

0.278pAh for one millisecond equals 0.1pAh for 0.36ms.

So in one superframe the RPL node consume 18.45nAh (17.34+1.11).

So now we have the RPL energy consumption we add the application data from the sensors. As mentioned we set this application data as 10bit, and in order to transmit this application data we have to put all the headers in the packet. One application packet contains all the headers including the application data. That means to add 10bit of transmission and subtract the coherent time in standby mode.

As mentioned in chapter 6.1.1, with a transmission rate of 250kbps or 2,50bp/µs ten bit takes four microseconds to transmit and with the 1.67nAh consumption for one millisecond that equals to 0.0668nAh or 66.8pAh. 18450pAh + 66.8pAh equals 18516.8pAh or 18.51nAh . We do not subtract 4µs of standby energy since it is so little.

The energy consumption for a node in one hour running RPL will equal to:
18.45nAh * 60 = 1107nAh

One day of protocol headers:
1107nAh * 10 = 11070nAh
Adding the two application packets:
11070 + (18.51*2) = 11107.02nAh = 11.11µAh,

During one day a node consumes 11.11µAh in the active mode (TX, RX and standby). The rest of the day will be spent in shutdown mode. The power drawn by the node in shutdown is 100nA, and utilizing the formula in chapter 4.1 [47] (C=xT) the remaining fourteen hours cost the node 1400nAh or 1.4µAh. During 24 hours with RPL the node consumes 12.51µAh.

Node lifetime:
225000/12.51 = 17985.6 days = 49 years
Yearly consumption:
12.51µAh * 365 = 4566.15µAh = 4.6mAh

With the coin cell battery utilized in our scenario with the 225mAh capacity with RPL and a daily consumption of 12.51µAh the node will have a lifetime of approximately 49 years.

6.1.3 Variation in energy consumption model

The two previous subchapters calculated the energy consumption by nodes with running different protocols, WirelessHart and RPL.

One node running wirelessHart daily usage: 10.09µAh
One node running RPL daily usage: 12.51µAh
Difference: 2.42µAh

One node running WirelessHart yearly usage: 3.7mAh
One node running RPL yearly usage: 4.6mAh
Difference: 0.9mAh

One node running WirelessHart lifetime: 61 years
One node running RPL lifetime: 49 years
Difference: 12years

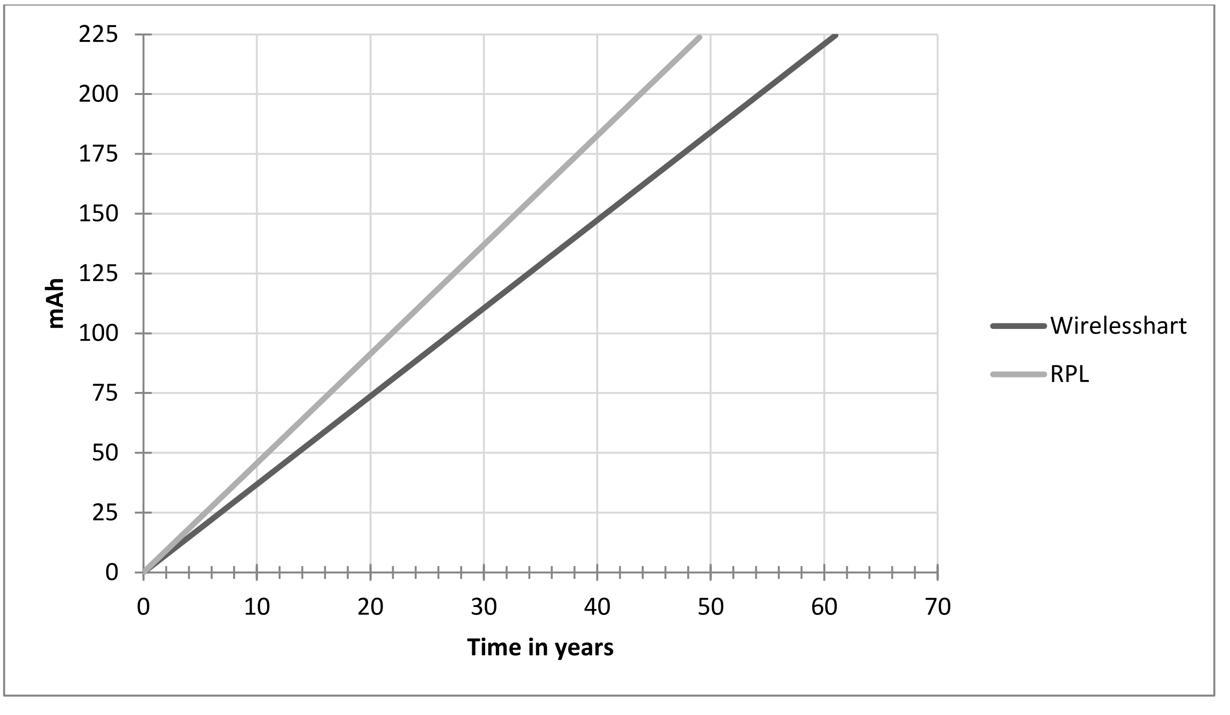

Figure 17: WirelessHart and RPL energy consumption model

Figure 17 provides a visual representation of the current linear energy consumption by the two protocols WirelessHart and RPL in a node.

6.2 Indoor propagation model

Our first step in calculating the necessities for retransmission is discovering the path loss in a residential area, so we utilize the indoor propagation model. From [48] we get the equation to calculate the indoor propagation model that shows us the path loss.

The indoor propagation model is:

$$L = 20 \log_{10} f + N \log_{10} d + P_f(n) - 28$$

Where:

L = the total path loss. Unit: decibel (dB).

f = Frequency of transmission. Unit: megahertz(MHz).

d = Distance. Unit: meter (m).

N = The distance power loss coefficient.

n = Number of floors between the transmitter and receiver.

Pf(n) = the floor loss penetration factor = 4n in our scenario according to table in [48].

The f is 2400 MHz (2.4GHz), all the distances is 5 meters (d = 5), from table 7 in [48] we choose an N equals 28 based on the closest match to our frequency band and that this is in a residential area.

Band	Residential area	Office area	Commercial area
900 MHz	N/A	33	20
1.2–1.3 GHz	N/A	32	22
1.8–2.0 GHz	28	30	22
4 GHz	N/A	28	22
5.2 GHz	30 (apartment), 28 (house)	31	N/A
5.8 GHz	N/A	24	N/A
60 GHz	N/A	22	17

Table 7: Power loss coefficient, N in [48]

The choice for Pf(n) is based on table 8 from [48].

Band	Floors	Residential area	Office area	Commercial area
900 MHz	1	N/A	9	N/A
900 MHz	2	N/A	19	N/A
900 MHz	3	N/A	24	N/A
1.8–2.0 GHz	n	4n	15+4(*n*-1)	6 + 3(*n*-1)
5.2 GHz	1	N/A	16	N/A
5.8 GHz	1	N/A	22 (1 floor), 28 (2 floors)	N/A

Table 8: Penetration loss factor Pf(n) from [48]

In a residential area the Pf(n) equals 4n based on the closest match to our frequency band and that this is in a residential area, n varies from zero to one so 4n varies from 0 to four.

L, path loss between two nodes on same floor:
20 log 2400 + 28 log 5 + 0 - 28 = 67.6 + 19.57 – 28 = 59.17 dB

L, path loss between two nodes on different floors:
20 log 2400 + 28 log 5 + 4 – 28 = 67.6 + 19.57 + 4 – 28 = 63.17 dB

By applying the indoor propagation model and other formulas in the next chapter we are able to calculate the loss of signal in the air and that can show us if we have to calculate any retransmissions.

6.3 dB calculations

A sensitivity analysis or calculation is applied in order to see if the nodes are able to communicate. In order for there to be communication the receiving node have to be able to receive the transmission. We calculate the received signal strength based on the loss found in 6.2, the gain from Tx antenna, the gain from Rx antenna and transmission rate.

$P_{Rx} = P_{Tx} + g_{tx} + g_{rx} - L_{tap}$

Where:
P_{Rx} is the signal strength received
P_{Tx} is the transmitting signal strength
g_{tx} is antenna gain from the transmitting side
g_{rx} is antenna gain from the receiving side
L_{tap} is the path loss between the nodes, calculated in 6.2

The variables g_{tx} and g_{rx} is zero because the antennas are integrated and therefor provide no direct gain. Previously mentioned is the P_{Tx} 0dBm. So P_{Rx} equals $-L_{tap}$ and L_{tap} is the path loss calculated in chapter 6.2, indoor propagation model, and differs depending on if the two nodes in transmission is on the same floor or between floors.

L_tap on same floor = 59.17dB

L_tap between floors = 63.17dB

P_Rx on same floor then equals -59.17dB

P_Rx on different floor then equals -63.17dB

Now that have signal strength the node receives we have to see if the signal is strong enough for the node to interpret. For the node to be able to receive and understand the signal the received signal must be greater than the nodes receiver sensitivity added with the fading margin.

P_Rx > P_Sens + F_margin

From [16] we get that the receiver sensitivity (P_Sens) equals to -100dBm and we continue with a fading margin of 20dB.

Same floor: P_Rx > P_Sens + F_margin = -59.17 > -100 +20 = -59.17 > -80

Different floor: P_Rx > P_Sens + F_margin = -63.17 > -100 +20 = -63.17 > -80

We see that in both cases the signal strength in strong enough to be received. In order to eliminate retransmission or calculate how many retransmissions necessary, bit error rate (BER) is used with signal to noise ratio (SNR).

We use a simplified bit error rate BER = 10^{-6} when SNR > 20dB. When the signal to noise ratio is bigger than 20dBm we assume the conditions so optimal that no retransmissions are necessary

SNR > 20dBm – No retransmission, so good that retransmission calculation is not necessary.

10 < SNR < 20dBm = 10^{-5} bit error, approximately every hundred thousand bit is wrong and the packet sending the 100’000 bit have to do a retransmission.

0 < SNR < 10dBm = 10^{-3} bit error, approximately every thousand bit is wrong and the packet sending the 1’000 bit have to do a retransmission.

SNR < 0 -> No communication

To calculate SNR we use the formula from [49]:

SNR = P_Rx - P_sens - F_margin

SNR on same floor: SNR = -59.17 – (-100) – 20 = 20.83dBm

SNR on differen floor: SNR = -63.17 – (-100) – 20 = 16.83dBm

With a SNR equal to 20.83dBm we don't have to consider any retransmission between nodes on the same floor. This means there won't be any additional energy consumptions to take into account when looking at nodes transmitting on the same floor.
On the other hand when looking at transmissions across floors one can notice that signal to noise ratio is between 10 and 20 dBm which means that every 10^5 bit will fail. After calculations in chapter 4.1.1 and 4.1.2 we know that a RPL header packet is 540 bit and WirelessHart packet is 240bit. But that will not be the total bit sent in one transmission, in the transmission is also an acknowledge packet that has the size of 208bit [41]. This acknowledge packet has to be included since we will be calculating in bit per transmission.

6.4 Retransmissions

An important aspect of a wireless sensor network is the retransmission of packets. The transmission of a packet happens over air and will be influenced by many factors, as walls, floors, noise or moving obstacles. This chapter will mainly focus on retransmissions and how often a node have to retransmit a packet. Two scenarios are represented, when the node have to retransmit every hundred thousand bit and when a node have to retransmit every thousand bit. The discoveries will also be tied to the energy consumption model calculated in chapter 6.1.3.

As discussed in the chapter above we have two signal to noise ratio boundaries we associate with:
10 < SNR < 20dBm and
0 < SNR < 10dBm

If a signal is below 20dBm but above 10dBm there will be a retransmission on every hundred thousand bit, and if the signal is below 10dBm but above 0dBm there will be a retransmission every thousand bit.

The calculations done below are done on node A and C according to Figure 5. The calculations on node A will be the same as on node B and E, while the numbers associated with node C will be the same as node D.

The calculations done are made with the assumption that each node communicates an equivalent number of times with each neighboring node.

Previous we found that the RPL headers are 540bit and WirelessHart headers are 240bit but we cannot use only these because in a transmission it is also an acknowledgment packet that has the size of 208bit [41]. We assume that the bit error will be “reset” after each day, at nighttime.

6.4.1 Error every 10^5 bit

WirelessHart:
The size in bits of a WirelessHart packet including the WirelessHart headers and the acknowledge field is 448bit.

If we divide the limit of 100 000bit on the size of a WirelessHart packet we get the number of packets necessary to transmit in order to reach the retransmission boundary.

100’000/448 = 223.21 -> 224

224 transmissions is necessary in order reach the retransmission boundary in WirelessHart, if the node transfers this amount of data in the direction where bit error rate is every 10^5 the node has to retransmit one packet in that direction.

For node A, B and E this means every 448 packet, because we assume that a node communicate an equivalent time with each neighbor. So if we take node A as an example, node A will have to transmit 224 packets to node B and 224 packets to node C before a retransmission occur. If we multiply the number of transmissions necessary to reach the retransmission boundary with the time of a superfram, because a node can only transmit during a timeslot and have only one Tx each timeslot, we get the time when a node has to perform a retransmission.

In this case: 448 * 4 = 1792s = 29.86 minutes.
As we know, the total time during one day is 40 minutes, four minutes every hour for ten hours so there will be one retransmission during the day.

For node C and D this means retransmissions every 672 packet.
In that case: 672 * 4 = 2688s = 44.8 minutes.
This time interval will not occur during the day and will therefore be no retransmissions.

RPL:
The size in bits of a RPL packet including the RPL headers and the acknowledge packet is 748bit.

If we divide the limit of 100 000bit on the size of a RPL packet we get the number of packets necessary to transmit in order to reach the retransmission boundary.

100’000/748 = 133.69 -> 134

134 transmissions is necessary in order reach the retransmission boundary in RPL, if the node transfers this amount of data the node has to retransmit one packet.

For node A, B and E this means every 264 packet, because we assume that a node communicate an equivalent time with each neighbor.

In this case: 264 * 4 = 1056s = 17.6 minutes.
This time interval will occur twice during the day and will therefore require two retransmissions.

For node C and D this means retransmissions every 402 packet.
In that case: 402 * 4 = 1608s = 26.8 minutes.
This time interval will occur once during the day and will therefore require one retransmission.

6.4.2 Error every 10^3 bit

WirelessHart:
If we divide the limit of 1000bit on the size of a WirelessHart packet we get the number of packets necessary to transmit in order to reach the retransmission boundary.

1000/448 = 22.3 -> 3

3 transmissions is necessary in order reach the retransmission boundary in WirelessHart, if the node transfers this amount of data the node has to retransmit one packet.

For node A, B and E this means every 6 packet, because we assume that a node communicate an equivalent time with each neighbor.

In this case: 6 * 4 = 24s = 0.4 minutes.
This time interval will occur 100 times during the day and will therefore require one hundred retransmissions.

For node C and D this means retransmissions every 402 packet.
In that case: 9 * 4 = 36s = 0.6 minutes.
This time interval will occur 66 times during the day and will therefore require 66 retransmissions.

RPL:
If we divide the limit of 100bit on the size of a RPL packet we get the number of packets necessary to transmit in order to reach the retransmission boundary.

1000/748 = 1.3 -> 2

Every second will fail and two transmissions is necessary in order reach the retransmission boundary in RPL, if the node transfers this amount of data the node has to retransmit one packet.

For node A, B and E this means every 2 packet.

In this case: 2 * 4 = 8s = 0.133 minutes.
This time interval will occur 300 times during the day and will therefore require 300 retransmissions.

For node C and D this means retransmissions every 6 packet.
In that case: 6 * 4 = 24s = 0.4 minutes.
This time interval will occur 100 times during the day and will therefore require one hundred retransmissions.

Table 9 provides a visual representation of the above calculations and summarizes the two subsections.

Bit error	**Protocol**	**Node**				
		A	**B**	**C**	**D**	**E**
10^5	WirelessHart	1	1	0	0	1
	RPL	2	2	1	1	2
10^3	WirelessHart	100	100	66	66	100
	RPL	300	300	100	100	300

Table 9: General daily node retransmissions based on different Bit Error Rate and protocol

6.4.3 Retransmissions necessary in current energy consumption model

The result of the signal to noise ratio calculations done in chapter 6.3 showed us that nodes transmitting between floors experience the most signal path loss and that approximately every hundred thousand bit fails. The signal to noise ratio between nodes on the same floor is so good that we do not have to calculate any retransmissions. The calculation in this section will not contain the application data since the effect of application data will be further discussed in chapter 6.6 (application data).

Each node will communicate with its neighboring node the same, based on the author's assumptions, but in real life there would be a difference in the communication load between the neighboring nodes.

The access point is assumed connected to an uninterrupted power source, so we do not have to calculate any energy consummation for the access point. In case it is of interest the access point would have approximately the same energy consumption model as node A, B and E.

WirelessHart:
Using the consumption model from chapter 6.3 with WirelessHart the nodes has to do one retransmission on every 224 transmission to the neighboring node on a different floor.

For node A, B and E this means that every 448 transmission have to be retransmitted, since every node assumable communicate an equivalent number of times with its neighbors. We multiply the number of transmission with the time of a superframe to find the time interval between the errors.

448 * 4 = 1792s = 29.86 minutes
Total transmission time per day equals 40 minutes (4 minutes per hour ten time's day), the time between each retransmission is approximately 30 minutes. Since this is only once during the day, and that bit error rate is "reset" during the nighttime we say that node A,B and E has to do a retransmission once a day with neighboring nodes on different floors with the running protocol WirelessHart.

For node C and D however that means every 672 (224*3) transmission the node may has to perform two retransmissions. This is because two out of the three neighboring nodes is on a different floor.

672 * 4 = 2688s = 44.8minutes
The total transmission time per day is 40 minutes (4 minutes ten times during one day), the time between each retransmission is approximately 45 minutes. Since each day is 40 minutes but it takes 45 minutes before a retransmission there will not be any retransmissions from node C and D running WirelessHart.

The result of these retransmissions is that all the nodes experience increased energy consumption:
Node A: Transmits a retransmission to node C – One Tx, energy consumption increase with 6.66nAh.
Node B: Transmits a retransmission to node D – One Tx, energy consumption increase with 6.66nAh.

Node E: Transmits a retransmission to node D – One Tx, energy consumption increase with 6.66nAh.
Node C: Receive two retransmission, one from the access point and one from node A – 2*Rx, energy consumption increase with 13.32nAh.
Node D: Receive two retransmissions, one from node B and one from node E – 2*Rx, energy consumption increase with 13.32nAh.

Daily energy consumption by a node running WirelessHart was previously set to 10.09µAh, if we add the additional energy consumed by our retransmissions we get:
Node A, B and E: 10.09µAh + 6.66nAh = 10090 + 6.66 = 10096.6 -> 10.10µAh
Node C and D: 10.09µAh + 13.32nAh = 10090 + 13.32 = 10103.32 -> 10.10µAh

Battery capacity divided with the new daily consumption:
225000µAh/10.10µAh = 22277 days. The difference from previous model is 22 days.

So with the retransmission added in our WirelessHart running wireless sensor network the nodes lifetime suffer a 22 day decrease.

RPL:
Using the consumption model from chapter 6.3 with RPL the nodes has to do one retransmission on every 134 transmission to the neighboring node on a different floor.

For node A, B and E this means that every 264 transmission have to be retransmitted, since every node assumable communicate an equivalent number of times with its neighbors. We multiply the number of transmission with the time of a superframe to find the time interval between the errors.

264 * 4 = 1056s = 17.6 minutes
The total transmission time per day is 40 minutes (4 minutes ten times during one day), the time between each retransmission is approximately 18 minutes. This time will happen twice during the day, and then that bit error rate is “reset” during the nighttime, we say that node A,B and E has to do retransmissions twice a day with neighboring nodes on different floors with the running protocol RPL.

For node C and D however that means every 402 (134*3) transmission the node may has to perform two retransmissions. This is because two out of the three neighboring nodes is on a different floor.

402 * 4 = 1608s = 26.8minutes

The total transmission time per day is 40 minutes (4 minutes ten times during one day), the time between each retransmission is approximately 27 minutes. Since each day is 40 minutes but it takes 27 minutes before a retransmission there will be one retransmissions from node C and D running RPL in both directions, so two retransmissions during the day.

So in our current model the network running the protocol WirelessHart has to perform three retransmissions during a day, node A, B and E. While RPL has to perform ten retransmissions during a day, two times on A, B, E and one time each direction for node C and D.

The result of these retransmissions is that all the nodes experience increased energy consumption:

Node A: Transmits two retransmission to node C and receive one retransmission from the same node – (2*Tx + Rx), energy consumption increase with 26.01nAh.

Node B: Transmits two retransmission to node D and receive one retransmission from the same node – (2*Tx + Rx), energy consumption increase with 26.01nAh.

Node E: Transmits two retransmission to node D and receive one retransmission from the same node – (2*Tx + Rx), energy consumption increase with 26.01nAh

Node C: Transmits two retransmissions one to the access point and one to node A. Receive four retransmission two from the access point and two from node A – (4*Rx + 2*Tx), energy consumption increase with 52.02nAh.

Node D: Transmits two retransmissions one to node E and one to node A. Receive four retransmission two from node E and two from node A – (4*Rx + 2*Tx), energy consumption increase with 52.02nAh.

Daily energy consumption by a node running RPL was previously set to 12.51µAh, if we add the additional energy consumed by our retransmissions we get:

Node A, B and E: 12.51µAh + 26.01nAh = 12510 + 26.01 = 12536 -> 12.54µAh

Node C and D: 12.51µAh + 52.02nAh = 12510 + 52.02 = 12562 -> 12.56µAh

Battery capacity divided with the new daily consumption:

Node A, B, E: 225000µAh/12.54µAh = 17942 days. The difference from previous model is 43 days.

Node C, D: 225000µAh/12.54µAh = 17914 days. The difference from previous model is 71 days.

With the retransmission added in our RPL running wireless sensor network the node A, B and E lifetime suffers a 43 day decrease. Node C and D lifetime suffers a 71 day decrease.

Bit error	**Protocol**	**Node**				
		A	**B**	**C**	**D**	**E**
10^5	WirelessHart	6.66nAh	6.66nAh	13.32nAh	13.32nAh	6.66nAh
	RPL	26.01nAh	26.01nAh	52.02nAh	52.02nAh	26.01nAh

Table 10: Current energy model excess energy consumption due to retransmissions

Bit error	**Protocol**	**Node**				
		A	**B**	**C**	**D**	**E**
10^5	WirelessHart	22	22	22	22	22
	RPL	43	43	71	71	43

Table 11: Node lifetime decrease in days

Table 10 and 11 provides a simplified overview on the results from this subsection.

6.5 Duty Cycle

The duty cycle in a WSN is important to mention, especially when talking about energy consumption. The duty cycle can be seen as the cycle in which the node performs its desired duty. An example is the calculations done in chapter four, made with a duty cycle of two transmissions every four second.

Calculations in chapter four is with the time interval of four second. So that means every node is in transmission two times (TX and RX), and the lifetime of one node is then less than a year.

This is the energy consumption based on maximum packet size and two transmissions every four seconds. However, as calculated and discussed in chapter 6.1 the protocol headers do not utilize the whole space and the node is mostly in standby or shutdown.

It is in the authors mind that the sensor nodes in this network is connected to radiators and thermometers and have a task of upholding the temperatures decided by the house holding. This is not essential for the project but assist us when discussing duty cycle.

To increase the nodes lifetime, decrease the battery output, the nodes time interval can be increased to eight seconds instead of four and in theory doubling the node lifetime. Not only that, but we can assume that in a regular house holding all the inhabitants are asleep or confined to their representative rooms at nighttime. It is fair to assume that nighttime is between 00:00 - 06:00 and that between this time interval there will not be made any changes to the layout of the residential area. Since it is little reason to send application data during this period the nodes can stay in standby, or put in shutdown for an even greater energy save. Another step one can do to save energy is to have the nodes in shutdown between 08:00 - 16:00 from Monday to Friday as these hours are the most common work hours (in Norway). Thus we can assume the same conditions during the working hours as in nighttime and (combined with nighttime) we now have fourteen hours where the network activity is not needed and can be in the shutdown mode.

In further chapters the different aspects influencing energy consumption will be discussed

6.6 Variables affecting energy consumption

Previously in this paper certain variables affecting the energy consumption in a node have been discussed, many of these are the reason for the difficult in explaining how long a node will survive in a network. The variables will be briefly discussed and mention the impact on energy consumption they make.

6.6.1 Retransmission

In chapter 6.2 – 6.4 the main focus is discovering the signal strength and look at the retransmission necessities. A retransmission can happened often in a WSN, there could be an obstacle blocking the way for the communicating nodes or a bit error. These are often difficult to count on or calculate which is why we utilize the calculation and formulas in these chapters (6.2-6.4) in order to have an estimate to work from.

In chapter 6.1.1 and 6.1.2 we found that a node running WirelessHart consumed 6.66nAh during one transmission and that a node running RPL consumed 8.67nAh. Simply that means when a node is required to do a retransmission one can simply add the power consumption of one transmission to the total energy consumed. If we were just looking at exactly this single node this would be the case, but when a node transmit its receiving neighbor will have to enter the receiving state instead of staying in standby or shutdown. So if we were to think further a retransmission (Tx) causes a re-receiving (Rx). If it is one Tx and one Rx caused by a retransmission one may believe that you can add the power of a superframe as the additional energy consumption, but this is not the case as it's a Tx from one node and a Rx from another. These guidelines have been included in the calculations done in the next chapter.

As discussed in chapter 4.1 a Tx and a Rx cost the same. That means if node A utilizes 6.66nAh to retransmit to node B, node B will use 6.66nAh in order to receive the data.

A retransmission model for our current energy consumption model is discussed in chapter 6.4.3, and combined with the knowledge from 6.4.1 and 6.4.2 we get a picture of the difference between signal to noise ratio limits. It seems that the importance lays not directly in the size of the packet transmitted but rather how many extra packets that must be transmitted. From 6.4.3 we see that exceeding the first limit ($10 < SNR < 20$) with only nodes communicating through floors does not make a big difference, with the largest difference being 71 days (approximately 2.5 months). This may seem as a lot, but compared with 49 years it seems insignificant.

6.6.2 Node distance

The distances between nodes are discussed in chapter 6.2 when talking about indoor propagation model.

$$L = 20 \log_{10} f + N \log_{10} d + P_f(n) - 28$$

As mentioned in chapter 6.2 the variable “d” in the above formula represents the distance between the two nodes when you calculate the loss between them. If you increase the distance between the nodes, the loss between them will be increased as well.

With a “d” equal to 5 on same floor:
L = 59.17 dB

With a “d” equal to 10 on same floor:
L = 67.60 dB

Continuing with chapter 6.3 and signal to noise ratio we get that;
SNR on same floor with distance 5: SNR = -59.17 – (-100) – 20 = 20.83dBm
SNR on same floor with distance 10: SNR = -67.60 – (-100) – 20 = 12.4dBm

According to this information from chapter 6.3 we now have one retransmission every hundred thousand bit that we previously didn’t have when transmitting between two nodes on the same floor.

Differentiating the distance between nodes on different floors may be difficult, but in case one manages to do it:

With a “d” equal to 5 on different floor:
L = 63.17dB
With a “d” equal to 10 on different floor:
L = 71.6dB

Continuing with chapter signal to noise ratio we get that;
SNR on different floor with distance 5: SNR = -63.17 – (-100) – 20 = 16.83dBm
SNR on different floor with distance 10: SNR = -71.6 – (-100) – 20 = 8.4dBm

Between two floors with the distance of ten meters contra five meters we now have a retransmission every thousand bit.

We do now have four scenarios:

1. Distance between nodes on same floor is 5m, and distance between nodes on different floors is 5m. Original model.

2. Distance between nodes on same floor is 10m, and distance between nodes on different floors is 5m.

3. Distance between nodes on same floor is 5m, and distance between nodes on different floors is 10m.

4. Distance between nodes on same floor is 10m, and distance between nodes on different floors is 10m.

6.6.2.1 Distance 5m, 5m scenario one

The distance between nodes on same floor is five meters and the distance between nodes on different floors is five meters.

Discussed in chapter 6.4.3 and concluded that WirelessHart has to perform three retransmissions during a day, node A, B and E. While RPL has to perform ten retransmissions during a day, two times on A, B, E and one time each direction for node C and D. These calculations contain information regarding energy consumption when retransmitting is done between nodes on different floors. Communication between nodes on same floor with the distance of five meters have such a great signal to noise ratio that no additional transmissions have to be considered.

WirelessHart:
Node A, B and E: 10.09µAh + 6.66nAh = 10090 + 6.66 = 10096.6 -> 10.10µAh
Node C and D: 10.09µAh + 13.32nAh = 10090 + 13.32 = 10103.32 -> 10.10µAh

Battery capacity divided with the new daily consumption:
225000µAh/10.10µAh = 22277 days. The difference from previous model is 22 days.

So with the retransmission added in our WirelessHart running wireless sensor network the nodes lifetime suffer a 22 day decrease.

RPL:
Node A, B and E: 12.51µAh + 26.01nAh = 12510 + 26.01 = 12536 -> 12.54µAh
Node C and D: 12.51µAh + 13.32nAh = 12510 + 52.02 = 12562 -> 12.56µAh

Battery capacity divided with the new daily consumption:
Node A, B, E: 225000µAh/12.54µAh = 17942 days. The difference from previous model is 43 days.
Node C, D: 225000µAh/12.54µAh = 17914 days. The difference from previous model is 71 days.

So with the retransmission added in our RPL running wireless sensor network the node A, B and E lifetime suffers a 43 day decrease. Node C and D lifetime suffers a 71 day decrease.

6.6.2.2 Distance 10m, 5m Scenario two

The distance between nodes on same floor is ten meters and the distance between nodes on different floors is five meters.

Discussed in chapter 6.3 and 6.4 and concluded that WirelessHart has to perform three retransmissions during a day, node A, B and E. While RPL has to perform ten retransmissions during a day, two times on A, B, E and one time each direction for node C and D. When there were no retransmissions between nodes on the same floor. From calculation previously in this chapter we get the following information:

SNR on same floor with distance 10: SNR = -67.60 – (-100) – 20 = 12.4dBm
SNR on different floor with distance 5: SNR = -63.17 – (-100) – 20 = 16.83dBm

Both is between the SNR boundary of 10 < SNR < 20 and will therefore have one retransmission every 100’000 bit.

The energy impact with “SNR on different floor with distance 5” was calculated in previous chapter (6.6.2.1), we now only have to calculate and add the energy consummation impact of the “SNR on same floor with distance 10”. From the boundaries we see that 12.4dBm falls within the 10 < SNR < 20 interval and therefore have a retransmission ever hundred thousand bit.

WirelessHart:

Node A: Transmits a retransmissions to node B and receive one retransmissions from the same node – (Tx + Rx), energy consumption increase with 13.32nAh.

Node B: Transmits a retransmissions to node A and receive one retransmissions from the same node – (Tx + Rx), energy consumption increase with 13.32nAh.

Node E: Transmits a retransmission to the access point and receive one retransmissions in return – (Tx + Rx), energy consumption increase with 13.32nAh

Node C: Does not have enough transmission to hit the 100 000 bit limit so zero energy consumption increase.

Node D: Does not have enough transmission to hit the 100 000 bit limit so zero energy consumption increase.

PRL:

Node A: Transmits two retransmissions to node B and receive two retransmissions from the same node – (2*Tx + 2*Rx), energy consumption increase with 34.68nAh.

Node B: Transmits two retransmissions to node A and receive two retransmissions from the same node – (2*Tx + 2*Rx), energy consumption increase with 34.68nAh.

Node E: Transmits two retransmissions to the access point and receive two retransmissions in return – (2*Tx + 2*Rx), energy consumption increase with 34.68nAh

Node C: Transmits a retransmissions to node D and receive one retransmissions from the same node – (Tx + Rx), energy consumption increase with 17.34nAh.

Node D: Transmits a retransmissions to node C and receive one retransmissions from the same node – (Tx + Rx), energy consumption increase with 17.34nAh.

Nodes on same floor, distance between them equals 10 meters:

In WirelessHart nodes A,B and E daily energy consumption increase from 10.09µAh to 10.10µAh, while node C and D have unchanged energy consumption In RPL node A,B and E have a daily energy consumption increase from 12.51µAh to 12.54µAh, while node C and D have an increase from 12.51µAh to 12.52µAh

Nodes on different floor, distance between them equals 5 meters:
In WirelessHart all the nodes daily energy consumption increase from 10.09µAh to 10.10µAh. In RPL node A,B and E have a daily energy consumption increase from 12.51µAh to 12.54µAh, while node C and D have an increase from 12.51µAh to 12.56µAh

Total daily energy consummation in nodes running WirelessHart in current scenario:
Node A, B and E: 10090nAh + 13.32nAh + 6.66nAh = 10109,98 = 10.11µAh, an increase of 19.98nAh and a node lifetime decrease of 44 days.
Node C and D: 10090nAh + 0 + 13.32nAh = 10103.32 = 10.10µAh, an increase of 13.32nAh and a node lifetime decrease of 22 days.

Total daily energy consummation in nodes running RPL in current scenario:
Node A, B and E: 12510nAh + 34.68nAh + 26.01nAh = 12570.69 = 12.57µAh, an increase of 60.69nAh and a node lifetime decrease of 86 days.
Node C and D: 12510nAh + 17.34 + 52.02nAh = 12579.36 = 12.58µAh, an increase of 69.36nAh and a node lifetime decrease of 100 days.

By applying the current scenario the most suffering protocol is RPL with the highest decrease in node lifetime being one hundred days.

6.6.2.3 Distance 5m, 10m Scenario three

The distance between nodes on the same floor is five meters and the distance between nodes on different floors is ten meters.

SNR on same floor with distance 5: SNR = -59.17 – (-100) – 20 = 20.83dBm
SNR on different floor with distance 10: SNR = -71.6 – (-100) – 20 = 8.4dBm

According to the signal to noise ratio and as previously mentioned with a distance of five meters between the nodes on the same floor we experience such a low signal to noise ratio that we are not required to calculate or add any retransmissions.

The “SNR on different floor with distance 10” however falls under the SNR boundary of $0 < SNR < 10$ and will have to retransmit on every thousand bit.

WirelessHart:
Node A: Transmits 100 retransmissions to node C and receive 62 retransmissions from the

same node – (100*Tx + 62*Rx), energy consumption increase with 1078.92nAh.
Node B: Transmits 100 retransmissions to node D and receive 62 retransmissions from the same node – (100*Tx + 62*Rx), energy consumption increase with 1078.92nAh.
Node E: Transmits 100 retransmissions to node D and receive 62 retransmissions from the same node – (100*Tx + 62*Rx), energy consumption increase with 1078.92nAh.
Node C: Transmits 62 retransmissions to node A and 62 retransmissions to the access point, receive 100 retransmissions from the node A and 100 retransmissions from the access point – (132*Tx + 200*Rx), energy consumption increase with 2211.12nAh.
Node D: Transmits 62 retransmissions to node B and 62 retransmissions to node E, receive 100 retransmissions from the node B and 100 retransmissions from node E – (132*Tx + 200*Rx), energy consumption increase with 2211.12nAh.

PRL:
Node A: Transmits 300 retransmissions to node C and receive 100 retransmissions from the same node – (300*Tx + 100*Rx), energy consumption increase with 3468.nAh.
Node B: Transmits 300 retransmissions to node D and receive 100 retransmissions from the same node – (300*Tx + 100*Rx), energy consumption increase with 3468.nAh.
Node E: Transmits 300 retransmissions to node D and receive 100 retransmissions from the same node – (300*Tx + 100*Rx), energy consumption increase with 3468.nAh.
Node C: Transmits 100 retransmissions to node A and 100 retransmissions to the access point, receive 300 retransmissions from the node A and 300 retransmissions from the access point – (200*Tx + 600*Rx), energy consumption increase with 6936nAh.
Node D: Transmits 100 retransmissions to node B and 100 retransmissions to node E, receive 300 retransmissions from the node B and 300 retransmissions from node E – (200*Tx + 600*Rx), energy consumption increase with 6936nAh.

Nodes on same floor, distance between them equals 5 meters:
According to the signal to noise ratio and as previously mentioned with a distance of five meters between the nodes on the same floor we experience such a low signal to noise ratio that we are not required to calculate or add any retransmissions.

Nodes on different floor, distance between them equals 10 meters:
In WirelessHart node A,B and E have a daily energy consumption increase from 10.09µAh to 11.17µAh, while node C and D have an increase from 10.09µAh to 12.30µAh. In RPL node

A,B and E have a daily energy consumption increase from 12.51µAh to 15.98µAh, while node C and D have an increase from 12.51µAh to 19.45µAh

Total daily energy consummation in nodes running WirelessHart in current scenario:
Node A, B and E: 10090nAh + 0nAh + 1078,92nAh = 11168,92 = 11.17µAh, an increase of 1078nAh and a node lifetime decrease of 2156 days or almost six years (5.9).
Node C and D: 10090nAh + 0 + 2211.12nAh = 12301.12nAh = 12.30µAh, an increase of 2211nAh and a node lifetime decrease of 4007 days or almost eleven years (10.98).

Total daily energy consummation in nodes running RPL in current scenario:
Node A, B and E: 12510nAh + 0nAh + 3468nAh = 15978 = 15.98µAh, an increase of 3468nAh and a node lifetime decrease of 3906 days or almost eleven years (10.7).
Node C and D: 12510nAh + 0nAh + 6936nAh = 19446nAh = 19.45µAh, an increase of 6936nAh and a node lifetime decrease of 6416 days or almost eighteen years (17.6).

By applying the current scenario the most suffering protocol is RPL with the highest decrease in node lifetime being almost eighteen years. This is our first scenario with the signal to noise ratio within the 0<SNR<10 boundary and it is during this scenario the nodes lifetime severely decreases. It is worth mentioning that these calculations do not include secondary retransmission calculation. That all the retransmissions in this scenario would cause additional retransmissions and maybe even a third layer of retransmissions, but they are not focused on further in this paper.

6.6.2.4 Distance 10m, 10m Scenario four

The distance between nodes on same floor is ten meters and the distance between nodes on different floors is ten meters.

SNR on same floor with distance 10: SNR = -67.60 – (-100) – 20 = 12.4dBm
SNR on different floor with distance 10: SNR = -71.6 – (-100) – 20 = 8.4dBm

From scenario two we get the effect of the “SNR on same floor with distance 10” and from scenario three we get the effect of the “SNR on different floor with distance 10”, we add the result of these scenarios together.

Nodes on same floor, distance between them equals 10 meters:

In WirelessHart nodes A,B and E daily energy consumption increase from 10.09µAh to 10.10µAh, while node C and D have unchanged energy consumption In RPL node A,B and E have a daily energy consumption increase from 12.51µAh to 12.54µAh, while node C and D have an increase from 12.51µAh to 12.52µAh

Nodes on different floor, distance between them equals 10 meters:

In WirelessHart node A,B and E have a daily energy consumption increase from 10.09µAh to 11.17µAh, while node C and D have an increase from 10.09µAh to 12.30µAh. In RPL node A,B and E have a daily energy consumption increase from 12.51µAh to 15.98µAh, while node C and D have an increase from 12.51µAh to 19.45µAh

Total daily energy consummation in nodes running WirelessHart in current scenario:

Node A, B and E: 10090nAh + 13.32nAh + 1078.92nAh = 11182.24 = 11.18µAh, an increase of 1092.24nAh and a node lifetime decrease of 2174 days or almost six years (5.96).

Node C and D: 10090nAh + 0 + 2211.12nAh = 12301.12nAh = 12.30µAh, an increase of 2211nAh and a node lifetime decrease of 4007 days or almost eleven years (10.98).

Total daily energy consummation in nodes running RPL in current scenario:

Node A, B and E: 12510nAh + 34,68nAh + 3468nAh = 16012.68 = 16.01µAh, an increase of 3502,68nAh and a node lifetime decrease of 3932 days or almost eleven years (10.8).

Node C and D: 12510nAh + 17.34nAh + 6936nAh = 19463,34nAh = 19.46µAh, an increase of 6953.34nAh and a node lifetime decrease of 6423 days or almost eighteen years (17.6).

6.6.2.5 Node distance discussion

Four different node distance scenarios have been brought up during this chapter. Some of the results one can observe from these numbers are that the change in distance done between nodes on the same floor does not have an immense impact on the energy consummation for nodes. However once you increase the distance between nodes separated by a floor and fall to the signal to noise ratio boundary that is $0 < SNR < 10$ we have to accommodate for retransmission on every thousand bit. When one have to do a retransmission on every thousand bit the energy consumption increases drastically and reduces the nodes lifetime six to eighteen years, depending on the protocol. The comparison of scenarios is summarized in table 12.

		Node									
Scenario	**Protocol**	**A**		**B**		**C**		**D**		**E**	
1	Wireless Hart	6.66 nAh	22 days	6.66 nAh	22 days	13 nAh	22 days	13 nAh	22 days	6.66 nAh	22 days
	RPL	26 nAh	43 days	26 nAh	43 days	52 nAh	71 days	52 nAh	71 days	26 nAh	43 days
2	Wireless Hart	20 nAh	44 days	20 nAh	44 days	13 nAh	22 days	13 nAh	22 days	20 nAh	44 days
	RPL	61 nAh	86 days	61 nAh	86 days	69 nAh	100 days	69 nAh	100 days	61 nAh	86 days
3	Wireless Hart	1078 nAh	5.9 year	1078 nAh	5.9 year	2211 nAh	11 year	2211 nAh	11 year	1078 nAh	5.9 year
	RPL	3468 nAh	10.7 year	3468 nAh	10.7 year	6936 nAh	17.6 year	6936 nAh	17.6 year	3468 nAh	10.7 year
4	Wireless Hart	1092 nAh	6 year	1092 nAh	6 year	2211 nAh	11 year	2211 nAh	11 year	1092 nAh	6 year
	RPL	3502 nAh	11 year	3502 nAh	11 year	6953 nAh	18 year	6953 nAh	18 year	3502 nAh	11 year

Table 12: Scenario difference, with increased energy consumption and reduced node lifetime

6.6.3 0dBm vs +5dBm

The calculations done in chapter 4.1 and 4.2 are done with the thought in mind that the network is per node saving power on multi hop instead of single hop which require higher energy consumption. At least it is assumed previously in this thesis that multi hop on 0dBm is more energy conserving than single hop on +5dBm. So if we look at network lifetime, the choice of single hop would in the authors assumption be more energy saving. Since it is the nodes energy consumption that has been investigated in this thesis it will be more energy saved by applying only multi hop. This means that nodes can only send to the closest neighbors. Discussed in chapter four is the numbers of transmissions, and there found that a node experience two transmissions during a superframe. For a single node it is then more energy conservative to have two transmission in 0dBm with 6.1mA than two transmissions in +5dBm with 9.1mA.

The difference between 0dBm and +5dBm is that transmission with a signal strength of +5dBm will require more energy. To simplify the calculation and doing them the same way done in earlier chapters we take the average between the Tx and Rx, 7.5 ((9.1+5.9)/2), and calculate the new energy consumed for each transmission.

From [47] we got the formula:

$C = x * T$

And we now applied it with our new number.

$C = 0.006 * (10 * 2.78 * 10^{-7})$

$= 0.0075 * 0.00000278 = 0.00000002085Ah$

$= 20.85nAh$

WirelessHart:

Added in with the packet time of WirelessHart we get 8.32nAh (3.99*2.085). The cost for a node to perform one transmission running the protocol WirelessHart is 8.32nAh. For one superframe you have one Tx, one Rx and the standby energy consumption.

8.32+8.32+1.11 = 17.75nAh

Every WirelessHart superframe with the new signal strength energy consumption is 17.75nAh. There is sixty superframes during one hour, mentioned in chapter six, so we multiply our new superframe energy usage with sixty:

17.75nAh * 60 = 1065nAh.

Multiply this with the number of hours, 10 equals 10650nAh = 10.65µAh.

Node lifetime, battery capacity divided with daily energy consumption:
225000 / 10.65 = 21126.8 = 57.9 years

This is a reduction in node lifetime by 1173 days, 3.2 years, from when the nodes utilized the 0dBm signal strength.

RPL:
Added in with the packet time of RPL we get 10.82nAh (5.19*2.085). The cost for a node to perform one transmission running the protocol RPL is 10.82nAh. For one superframe you have one Tx, one Rx and the standby energy consumption.
10.82+10.82+1.11 = 22.75nAh

One hour: 22.75*60 = 1365nAh
Daily: 1365 * 10 = 13650nAh = 13.65µAh

Node lifetime, battery capacity divided with daily energy consumption:
225000 / 13.65 = 16483.5 = 45.2 years

This is a reduction in node lifetime by 1502 days, 4.1 years, from when the nodes utilized the 0dBm signal strength.

L, path loss between two nodes on same floor, distance 5 meters:
20 log 2400 + 28 log 5 + 0 - 28 = 67.6 + 19.57 – 28 = 59.17 dB

L, path loss between two nodes on different floors, distance 5 meters:
20 log 2400 + 28 log 5 + 4 – 28 = 67.6 + 19.57 + 4 – 28 = 63.17 dB

$P_{Rx} = P_{Tx} + g_{tx} + g_{rx} - L_{tap}$

P_Rx on same floor then equals -54.17dB
P_Rx on different floor then equals -58.17dB

SNR on same floor, distance five meters: SNR = -54.17 – (-100) – 20 = 25.83dBm
SNR on differen floor, distance five meters: SNR = -58.17 – (-100) – 20 = 21.83dBm

Both the signal to noise ratios is between above 20dBm and will therefore not have any retransmissions, in our current scenario with 5 meters between the nodes on same floor and different floors.

WirelessHart:

Daily energy consumption by a node running WirelessHart including the retransmissions with 0dBm:

Node A, B and E: 10.10µAh

Node C and D: 10.10µAh

Retransmission and 0dBm is still favored over +5dBm and zero retransmissions because the daily usage is less, 10.65µAh > 10.10µAh.

RPL:

Daily energy consumption by a node running RPL including the retransmissions with 0dBm:

Node A, B and E: 12.54µAh

Node C and D: 12.56µAh

Retransmission and 0dBm is still favored over +5dBm and zero retransmissions because the daily usage is less, 13.65µAh > 12.54µAh or 12.56µAh, visually illustrated in figure 18.

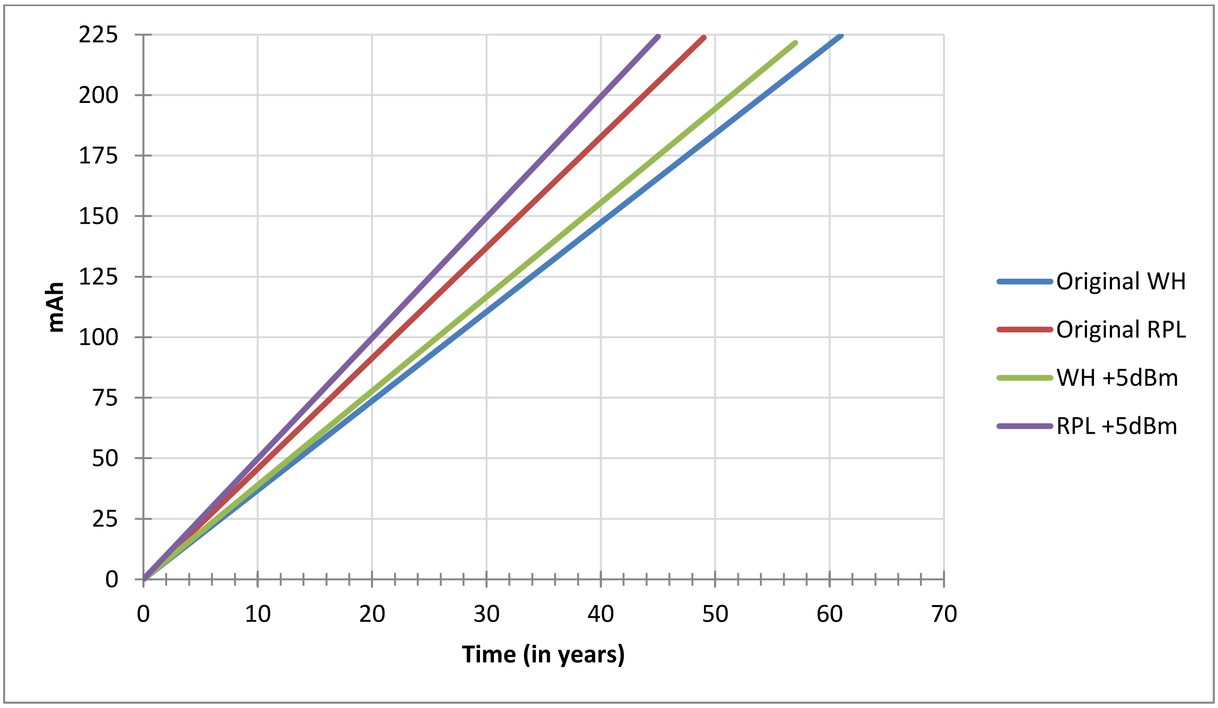

Figure 18: 0dBm vs +5dBm

6.6.4 Multi-hop vs single-hop

The routing headers causing the most of network traffic is necessary and cannot bypass or jump over nodes because it is vital routing information the neighbors need. Multi-hop is relevant for the application data, it is ten of these every day two from each node.

The following assumption about how packets traverse through the network is severe simplification, both WirelessHart and RPL have strict routines concerning packet travel route but a deep study on these protocols routing is to extensive for this papers scope.

Transmission of application from node C and E will be the same. These nodes have a direct connection to the access point and will transmit application data directly. Node A have the shortest path to the access point through node C, so node D transfers through node E. We chose to have node B transmit through node A and C in order to reach the access point. See visual representation in figure 17.

Node B can also transmit through node D and E, depends on where the pressure is best fitted. Node C will under current settings be the only node to transmit two additional application data packets. Node A and E will have to transmit one additional application data, while node B and D only send their own application data.

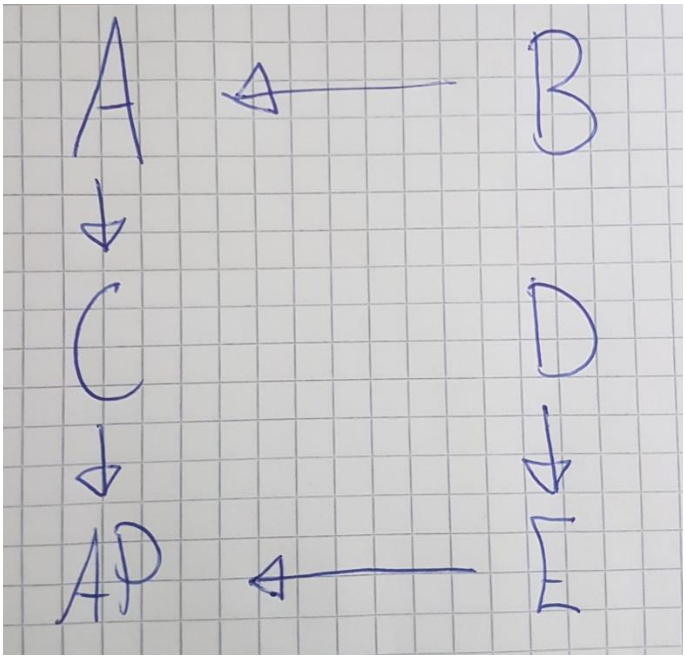

Figure 19: Single-hop packet direction

6.6.4.1 Multi-hop

WirelessHart:

WH app: 14.49nAh

Node A: A daily increase of two application packets (from B), 2*14.49nAh = 28.98nAh

Node B: Have none additional application data packet transmissions.

Node C: Have a daily increase of four application packets, two from A and two from B, 4*14.49 = 57.96nAh

Node D: Have none additional application data packet transmissions.

Node E: Have a daily increase of two application packets (from D), 2*14.49nAh = 28.98nAh

Adding the additional energy consumption to the original model found in 6.1.3 we get that node A and E suffers a lifetime decrease of 57 days and node C suffers 132 day lifetime decrease. Node A and E have a daily usage of 10.12µAh, while C have 10.15µAh.

RPL:

RPL app: 18.51nAh

Node A: A daily increase of two application packets (from B), 2*18.51nAh = 37.02nAh

Node B: Have none additional application data packet transmissions.

Node C: Have a daily increase of four application packets, two from A and two from B,

4*18.51 = 74.04nAh
Node D: Have none additional application data packet transmissions.
Node E: Have a daily increase of two application packets (from D), 2*18.51nAh = 37.02nAh

Adding the additional energy consumption to the original model found in 6.1.3 we get that node A and E suffers a lifetime decrease of 57 days and node C suffers 100 day lifetime decrease. Node A and E have a daily usage of 12.55µAh, while C have 12.58µAh.

6.6.4.2 Single-hop

Assumptions for single-hop is that all nodes is transmitting with +5dBm to reach further and that node B still have to use one relay node, in this case node C. Utilizing the same calculations as in 6.1.1 we find that the additional application data cost 8.3pAh and from 6.6.3 that one transmission in +5dBm cost 10.65µAh for WirelessHart and 13.65µAh for RPL.

WirelessHart:
The daily energy consumption when transmitting in +5dBm was found in 6.6.3 to be 10.65µAh.
Node A, B, D, E: 10650nAh + 8.33nAh = 10658.33 = 10.66µAh
Node C: 10650nAh + (2*8.33nAh) = 10666.66 = 10.67µAh

RPL:
The daily energy consumption when transmitting in +5dBm were found in 6.6.3 to be 13.65µAh.
Node A, B, D, E: 13650nAh + 10.83nAh = 13660.83 = 13.66µAh
Node C: 13650nAh + (2*10.83nAh) = 13671.66 = 13.67µAh

All the nodes consume more energy with the single-hop +5dBm than with 0dBm multi-hop.

6.6.5 Size of headers – Packet size

The size of the routing headers is the differentiating factor in this paper. We can observe that RPL with the largest headers have the smallest node lifetime. As we see in figure 16 in chapter 6.1.3 the difference between the nodes lifetime is 12 years. The topic and a comparison are discussed in chapter 4.2, and there the author concludes that RPL utilizes 31.55mAh more energy each year than WirelessHart.

6.6.6 Payload size – Application data

The payload or application data is in this paper set to ten bits and sent two times from each node during a day. As mentioned in chapter 6.6.4.1 the result of the application data is the decrease of node lifetime varying from 57 days to 132 days depending on the protocol. This may seem like much, but when you have a lifetime of 49 or 61 years 132 days is not a large lifetime decrease.

RPL headers, 44 bit mentioned in chapter 4.1.2, are not included in the transmission of application data. This lapsed the authors mind when calculating the energy consumption increase from application data in chapter 6.1.2. As we have discovered the application data did not make a large difference in a nodes lifetime, thus this 44 bit with energy calculated will not be as influential.

6.6.7 Duty cycle

The duty cycle is about how often the nodes duties are cycled. The current energy consumption model from chapter 6.1.3 has a duty cycle of four minutes transmission every hour in ten hours. This could be going on for the entire day, but we say that while the inhabitant of the house is either at work or sleep the network will be in either sleep or shutdown in order to save the most energy. The duty cycle is discussed more in chapter 6.5.

From the model mentioned in chapter 6.1.3 we have a node lifetime of 49 to 61 years which is in many cases adequate and we will that enough. But as in many wireless sensor networks unforeseen occurrences can happen, and if we then want to approve the node lifetime we can alter the duty cycle.

As seen generally in chapter six is that transmitting or receiving is the leading cause of energy consumption. In our current energy consumption model we are transmitting every four second, the node lifetime should improve if we double that transmit interval:

WirelessHart:
14.43nAh pr superframe, 30 times an hour equals 432.9nAh.
Daily: (432.9 *10) + (2*14.49) + 1400 = 5757.98nAh = 5.76µAh

225000/5.76 = 39062.5 days -> 107 years

PRL:
18.45nAh pr superframe, 30 times an hour equals 553.5nAh.
Daily: (553.5 *10) + (2*18.51) + 1400 = 6972.02nAh = 6.97µAh

225000/6.97 = 32281.2 days -> 88 years

So if we halve the superframe interval, by that also halving the transmission frequency, we drastically increase the nodes lifetime. We take the same scenario, but we double instead of halving:

WirelessHart:
14.43nAh pr superframe, 120 times an hour equals 1731.6nAh.
Daily: (1731.6 *10) + (2*14.49) + 1400 = 18744.98nAh = 18.74µAh

225000/18.74 = 12006.4 days -> 32.9 years

PRL:
18.45nAh pr superframe, 120 times an hour equals 2214nAh.
Daily: (2214 *10) + (2*18.51) + 1400 = 23577.02nAh = 23.58µAh

225000/23.58 = 9541.99 days -> 26 years

So if we double the superframe interval, by that also doubling the transmission frequency, we drastically decrease the nodes lifetime. This is visually illustrated in figure 20.

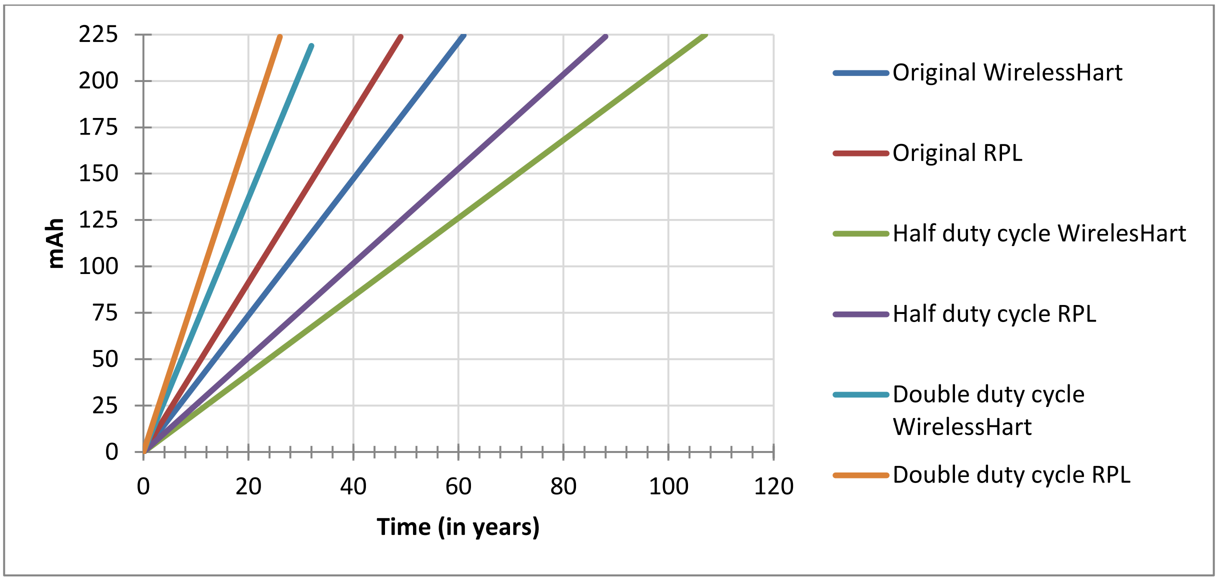

Figure 20: Different duty cycles

7 Conclusion

This thesis has mentioned the theory involving a wireless sensor network, compared the two protocols power usage and calculated on different energy consumption scenarios a wireless sensor node can encounter.

The first energy comparison between WirelessHart and RPL revealed that the general node lifetime is 12 years less running the RPL protocol. This lifetime difference is because of the differentiating header sizes. The protocols in themselves are not the important aspect, rather that the differentiating header sizes make such an impact on the lifetime. The choice of protocol does not have so much of an impact as header size has.

Retransmissions in a wireless sensor network are almost inevitable, either someone or something may obstruct the transmission by being in the line of sight or a transmission is wrongly received. When theoretical retransmission probability was calculated in different scenarios we found that as long as the retransmissions were above the thousand bit boundary, the negative impact on the battery was low. Once you had to retransmit every thousand bit the energy consumption spiked, lowering the node lifetime between six to eighteen years depending on the protocol and node. This was calculated in four different scenarios during the previous chapter where the distance between nodes was compared.

The distance between nodes was compared to each other in four scenarios, and there was only one aspect that gave the largest increase in energy consumption. That was when you increased the distance between nodes on different floors to ten meters, then the signal to noise ratio fell below our boundary and the nodes had to retransmit every thousand bit.

The next important energy aspect studied in this paper is the duty cycle, and we discovered that when we halved or doubled the duty cycle, the power usage in a node varied. When the duty cycle was halved the theoretical lifetime of a node is between 88 – 107 years. When a node lifetime is so long it would be susceptible to a large lifetime decrease by only a small negative energy deviation. On the other hand, when we double the duty cycle, the node lifetime shrank to between 26-32 years. Twenty-six years is in itself a lot and sufficient in many cases, but if this network experience the worst case node distance scenario, where node lifetime was decreased by eighteen years, the node lifetime is now eight years. Other deviations will of course also play a negative role one the network from there.

There were other aspects influencing the power usage but these were small and made little difference in the node lifetime. The author wanted to only enlighten aspects with larger consequences for node lifetime.

As a final recommendation when setting up a WSN the author advises having five meters between the nodes or less, choose a duty cycle that fits your scenario but keep in mind this greatly affects the node lifetime, avoid as many retransmissions as possible and the protocol with the smallest headers will consume less energy.

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Attachment

No attachments