

# Swarming

Research document

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# 1 Protocol

## 1.1 Hardware

For the internal communication between the different systems there are multiple protocols to choose from to transmit data. Every subsystem with a microcontroller should be able to communicate with the rest of the system. Because every system should be able to share their information it is necessary to have a multimaster system which allows every system to share their information without being dependent on a single master. To see which protocols are viable multiple protocols will be compared.

Building a modular robot consisting of subsystems, there must be a method to let these "subsystems" communicate with each other to exchange relevant information.

Every subsystem features a micro-controller which must be capable of transmitting and receiving data.

### 1.1.1 TWI

The name TWI stands for "Two wire interface" which strongly resembles Phillips' protocol  $I^2C$ . Like the name suggests the bus is built up using two wires, one is used for the clock signal and the other is used for the data signal. Each of these wires is connected to the powerline through a pull-up resistor so every subsystem connected to the line can pull the line down which other systems can see. TWI can be used as a multimaster system which means every subsystem can send its data without being dependent on a single master.

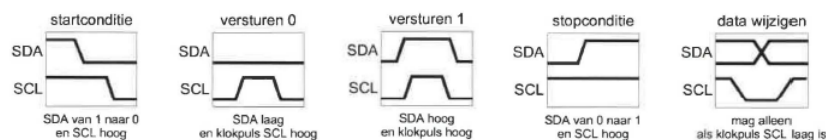


Figure 1: Data conditions

In the above figure multiple data and clock combinations are shown, these combinations define the message start, sending a zero, a one and a stopbit. The system that wants to send information starts a message by changing the datasignal from one to zero on a high clocksignal. All systems that are listening now know one of the systems is going to send a message. Data can be sent by changing the dataline from zero to one or the other way around during a low clocksignal, the other systems will read this bit when the clocksignal becomes high again. Once the system is done sending its message it will let the other systems know by sending a stopbit.



Figure 2: Structure of a TWI message

In the above picture the structure of a message is shown. As explained before the message starts with a startbit after which a small header follows. The header contains information about who is going to be addressed by the message and if you want to read or write. After this the addressed system will respond with an acknowledge to make sure the information has come across. When the acknowledge is received the system will start sending data, followed by an acknowledge from the receiver after every received byte of data. When the system is done sending all of its data and received the last acknowledge it will send the stopbit which means all communication has ended.

I<sup>2</sup>C has a few benefits, because it is a simple serial protocol it only uses two wires. This saves a lot of space in the hardware design. Also, it has the possibility to be used as a multimaster system. The speed of the communication depends on the frequency of the controller that will be used.

### **1.1.2 SPI**

SPI or Serial Peripheral Interface is, like its name suggests, a serial interface. This interface can be connected in two ways, each having its own advantage. How this works will be explained using the following figure.

### **1.1.3 UART**

## **1.2 Software**

## 2 Localization

Building a swarm of robots, location awareness may be required to ensure an more efficient operation. Implementing location awareness into a swarm of robots could result in better cooperation. For example: exploration based tasks can be executed on a much lower time scale. With location awareness the swarm can spread out evenly making sure that every part of the perimeter will be explored thoroughly.

With location awareness it is also possible to divide the swarm into multiple groups. Because the location of every individual is available these individual groups can be formed very quickly by selecting the nearest unit. This also enables quick assists when an individual robot gets stuck or needs to execute a task that require more than one unit.

To determine position, not only distance is required, to determine relative position the angle is also required to determine from which angle the units are relative to yourself. However this can result in multiple solutions, the angle could be mirrored.

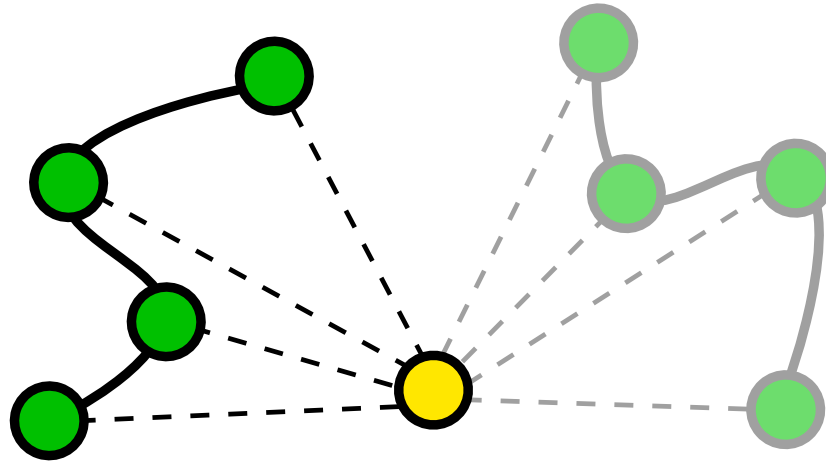


Figure 3: Stationary robot (yellow) cannot compute the relative position of the moving robot (green), since all distance measurements (dashed lines) are invariant to rotations around the stationary robot.[1]

Therefore, in order to leverage the previous trilateration procedure requires coordinating the motion of the robots in a manner that gives every robot a chance to move and ensures that when a robot is moving its neighbors remain stationary. This can also be achieved by the use of stationary anchors.[1]

A more efficient solution would be to retrieve the relative orientation opposite to each other. In combination with the relative distance every robot knows the exact relative position of all the other robots in range of the network.

## 2.1 Relative Distance

Relative distance can be measured using various methods. The most common methods are "*Received Signal Strength Indication*" and "*Time Of Flight*" abbreviated as RSSI and TOF.

### 2.1.1 Received Signal Strength

A method to determine distance can be implemented using Received Signal Strength abbreviated as "RSSI". Typically RSSI is a measure of dBm, which is ten times the logarithm of the ratio of the power (P) at the receiving end and the reference power (Pref). Power at the receiving end is inversely proportional to the square of distance.[2] Hence RSSI could potentially be used as an indicator of the distance at which the sending unit (robot) is located from the receiving unit.[2]

RSSI is defined as ten times the logarithm of the ratio of power of the received signal and a reference power (for example 1mW). It is known that power dissipates from its source as it moves further out. As mentioned earlier the relationship between power and distance is that power is inversely proportional to the square of the distance travelled. [2]

In theory it seems as a suitable implementation for the purpose, determining relative distance between different units. However various test results have shown that RSSI is only reliable under certain circumstances. Test results have shown that if the orientation of the sending or receiving unit changes it becomes very unreliable. The graphs below show the reliability of RSSI when the direction is being altered.[2]

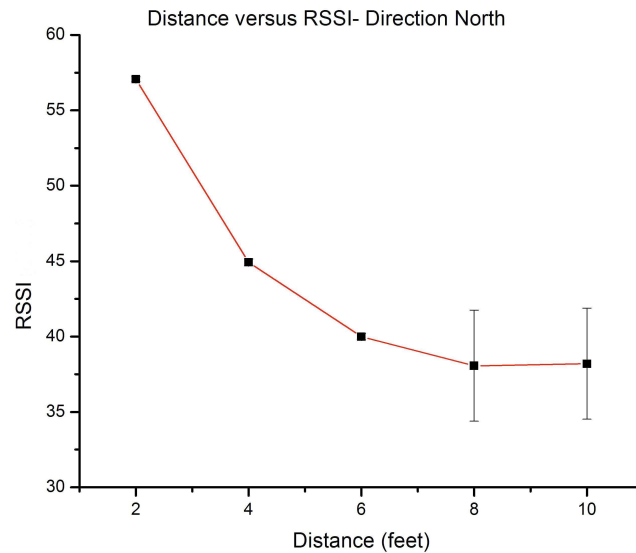


Figure 4: Distance versus RSSI plot showing inverse non linear relationship.[2]



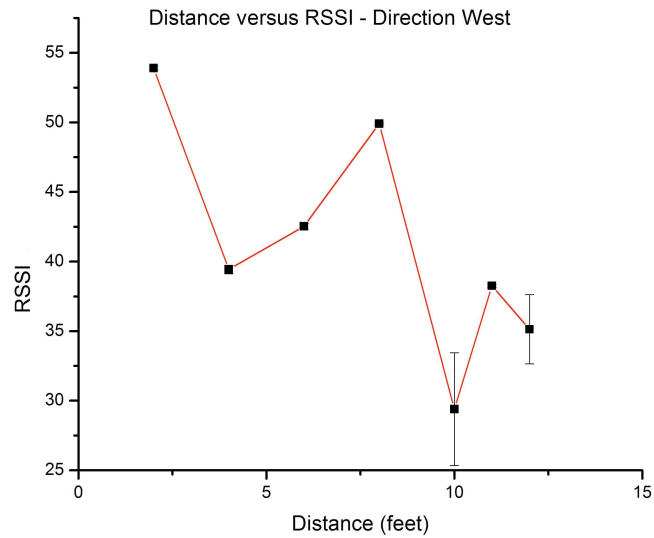


Figure 5: Distance versus RSSI plot showing lack of reliability when tested in a different direction.[2]

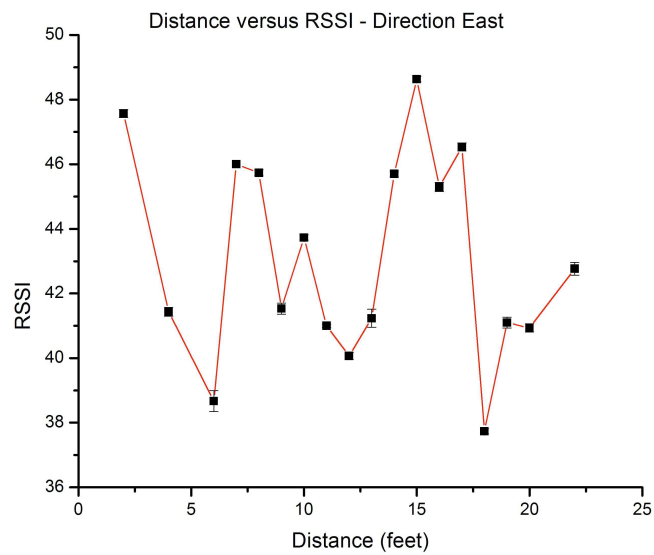


Figure 6: Distance versus RSSI plot showing lack of reliability when tested in a different direction.[2]

Even though RSSI was very promising in many studies, through multi directional experiments it became clear that even under ideal conditions with weather and interference controlled, the RSSI data could not be relied upon. At times the data was correct showing the expected inverse square relation with distance and at other times it didn't.[2]

### 2.1.2 Time Of Flight

Another common method to determine relative distance is Time Of Flight abbreviated as "TOF". Time Of Flight describes a method that measures the time that an particular wave takes to travel a distance through a medium. The wave can be acoustic, electromagnetic and light.

For relative distance measurements Time Of Flight is often combined with Time Difference Over Arrival abbreviated as "TDOA". Combining these methods enables relative distance measurements to specific units/nodes. TDOA measures the time difference between the transmission and arrival of a wave. With the velocity of propagation times the travelled time the relative distance between two or more nodes can be determined. However TOF also features certain limitations being clock synchronization, noise, sampling and multipath channel effects.[4]

*Clock Synchronization* TOF ranging systems need to estimate the time of transmission and arrival and comparing this with a common time reference.[4] If the different time references are not perfectly synchronized a time offset error occurs. With the faster the propagation speed, the greater the error in distance.

*Sampling* Using Light or electromagnetic waves to determine the relative distance can add several limitation. Due to the high velocity propagation (being nearly equal to equal of the velocity propagation of light) sampling this signal requires very high clock rates to do so. It would take a 15GHz clock to achieve one centimetre resolution.[11]

in the 1960's, Tektronix invented a sampling method with a oscilloscope that could measure signals in the GHz range without using high speed clocks. This method is called Sequential Equivalent Time Sampling abbreviated as "SETS". The SETS acquires one sample per trigger see figure 7. When a trigger is detected a sample is taken after a very short, but well defined delay. When the next trigger occurs a small time increment "Delta T" is added to this delay and the digitizer takes another sample. This process is repeated many times with "Delta T" added to each previous acquisition, until the time windows is filled.[3] In figure 8 another example of an sinusoidal signal is displayed using the SETS method.

Using the SETS method enables the use of waveform with an velocity propagation nearly equal to equal to the speed of light. However implementing a advanced SETS circuit is required to reach accuracy of less than 1 meter indoors.[4] However using waveforms with a high velocity propagation enables faster data transfers and a larger range.[4]

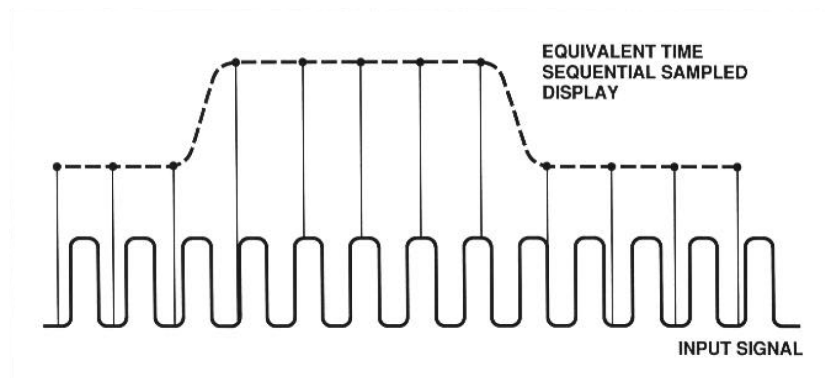


Figure 7: In sequential equivalent time sampling a single sample is taken for each recognized trigger after a delay which is incremented after each cycle.[3]

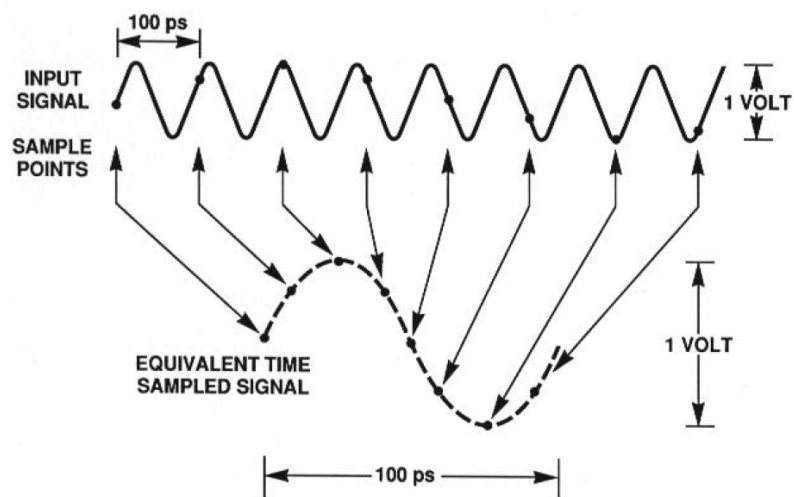


Figure 8: Example equivalent time sampled signal.[3]

## 2.2 Conclusion

Different studies have shown that Received Signal Strength can theoretically measure distance accurately. However RSSI seems to be very unreliable in many circumstances which leads to not being viable for distance measurements with moving robots.

Time Of Flight has been very promising, however using electromagnetic signals (For example RF, WI-FI or Bluetooth) the acceptable accuracy starts at from a minimum range of 1-2 meters which leads to unreliable to no useful information at all in the range of 1-2 meters. This minimum range could be narrowed using an Sequential Equivalent Time Sampling Circuit, however such a circuit is complex to develop. However using waveforms with a lower velocity propagation can lead to accurate close range measurements. In this case Time Of Flight suits better for the required use, being more accurate and reliable see figure 9.[4]

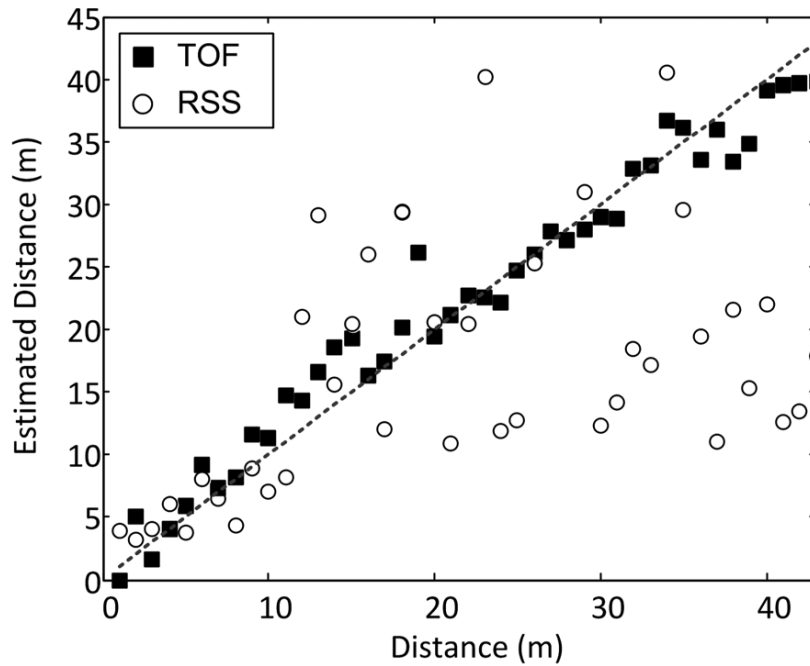


Figure 9: Accuracy RSSI vs TOF.[4]

Determining relative distance does not lead to localization to do so a angle is required.

## 3 Onderzoek

Hier tekst plaatsen

### 3.1 Propulsion, Actuators and Effectors

In this chapter the sub-questions about the propulsion, actuators and effectors are researched and answered. First of all, the possible types of propulsion will be researched. Then the various kinds of actuators with a suitable effector will be considered. Depending on the situation different types of propulsion is used. For example a robot that operates in an environment with water would not be implemented with DC motor drivers and tyres. The robot build in this research should be able to operate on Mars in the future. Therefore the robot cant get stuck easily since that will cost millions, since the robot cannot complete his mission. Since swarming and not propulsion is the main goal of this research a simple way of locomotion would suffice. However there should be the possibility to implement a different kind of propulsion in the future, so that the robot can be used on Mars.

#### 3.1.1 Effectors

The way a robot moves is determined by its effector with his corresponding actuator. Possible types of effectors are:

- Wheels
- Leg(s)
- Catepillar tracks
- Air cushion
- Propeller
- (Superconductor)

Each of these effectors have pro's and con's in different situations. Tyres are easily implemented, but there are various ways to implement these. The amount of tyres used will affect the handling of the robot. With a minimum two tyres, movement can already be realized. The downside is that driving with two wheels is not stable, only with algorithms that can balance the robot stable movement can be accomplished. It would be easier to implement more than two wheels so that the robot is more stable and movement is easier.

Elke van deze effectoren hebben voor en nadelen in verschillende situaties. Wielen zijn eenvoudig te implementeren, er kunnen verschillende aantallen wielen worden aangebracht. Het aantal wielen heeft wel invloed op het rijgedrag van de robot. Met twee wielen kan er worden gereden, mits de robot in balans wordt gehouden. Dit kan worden gedaan door middel van een zwenkwiel, of door een regelsysteem te bedenken dat de twee wielen de robot in balans houden. Dit laatste kost veel energie en is niet eenvoudig. Met drie wielen staat de robot al een stuk stabiel. Het nadeel hiervan is dat sturen soms moeizaam kan zijn. Met vier wielen is de robot nog stabiel en kan er op verschillende

manieren worden gestuurd. De wielen kunnen tegengesteld worden aangedreven waardoor de robot draait. Dit kost wel meer energie dan nodig is aangezien er extra wrijving ontstaat. Een optie is de voorste wielen te laten draaien, waardoor de robot in de richting van de wielen zal voortbewegen. Zoals bij een auto het geval is. Dit is weer lastiger te implementeren aangezien er een soort van stuurmechanisme moet worden bedacht.

### **3.1.2 Actuatoren**

De keuze van de actuator hangt sterk samen met de effectoren.

### **3.1.3 Aandrijving**

### 3.2 Swarm communication

There are several requirements to realise a robot swarm. Each member of the population needs to communicate with the rest of the swarm. To give the members full freedom of movement it is also usefull to make the communication wireless. It is important that the population size of the swarm is dynamic, because of the scalability of the swarm. As mentioned earlier a swarm does not have a master. So each member needs to be capable to maintain the network. These networks also must be able to reroute around nodes that have been lost. [12][13]

The following subsections are

- Network topology
- Network realibility and robustness
- Routing protocol
- Data distribution
- Wireless mesh network
- Wireless network implementations
- Conclusion

#### 3.2.1 Network topology

Several topologies exist to form a network. Figure 10, 12, 11 and 13 illustrate four network topologies as an example. Each topology has it's own benefits and cons which are discussed in this section.

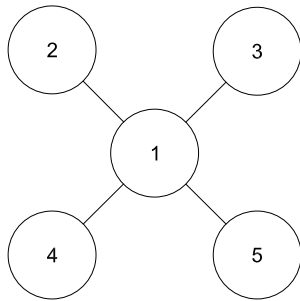


Figure 10: A star network topology, devices are connected to a central device (in this case device 1.)

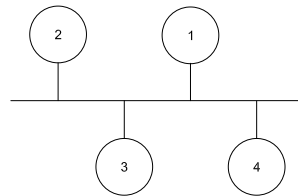


Figure 11: A bus topology, every device is on a common link.

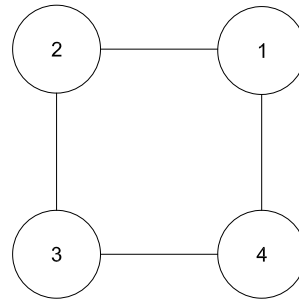


Figure 12: A ring topology, each device is connected to the next nearest device.

#### Star network

The star network in figure 10 uses the device marked as '1' as an central switch to reach out to other devices.[14] When the central device fails the network will stop working. However, when one of the other nodes fail the network is not completely disabled. Because of the central device, all of the information must pass this node. This could result in speed limitations. Mainly because of the central device, the star topology is not suitable as a swarm network. [15]

### Ring network

Devices in a ring network are always connected to two other devices as displayed in figure 12. This means that there are at least three devices in a ring network. The data distribution is unidirectional, with the traffic travelling clockwise or anticlockwise around the ring. [16] This topology has its limitations when one or more devices become isolated due to a device failure or cable break. This problem can be solved by using a dual ring, which makes the network redundant. Because of the network topology, in which  $n$  nodes are connected serially, the communication delay is proportional to the number  $n$  of devices in the network. The bandwidth is also shared between all the devices. [16] It is possible to create a swarm network with a ring network but it is far from ideal.

### Bus network

In a bus network the devices are connected to a linear half-duplex link. [17] A bus network has the advantage that it is easy to connect devices to and it works well in small networks. A disadvantage when using a bus for swarming is that the entire network shuts down when there is a break in the main connection. This makes the network not dynamic.

### Mesh network

To create a network with the characteristics described in the previous section a (wireless) mesh network ((W)MN) is a possible solution. A mesh network relies on communication nodes in which data is distributed. Such a network uses multi-hopping to transport data. [18] All of the communication nodes cooperate in the distribution of data in the network. Each node of the network is connected to one or more nearby in-range node(s) and forwards data on behalf of the other nodes. [19]

There are two types of mesh networks: fully connected and partly connected mesh networks. In a fully connected network each node is directly connected to each other node in the network. This type of network is completely redundant because of the alternative connections when one of them fails. The number of needed connections can be calculated with equation 1 [15]. Where ' $n$ ' is the amount of nodes and ' $c$ ' stands for the needed amount of connections. A fully connected mesh network becomes impractical when the amount of nodes increases.

$$c = \frac{n(n-1)}{2} \quad (1)$$

An partly connected network is still mostly redundant, but has less connections in comparison with a fully connected network. An example of a partly connected mesh network is illustrated in figure 13. [15]

It is possible but not necessary to connect one or more clients of a mesh network to the internet. Thus the client connected to the internet functions as a gateway for the other clients in the network. [20]



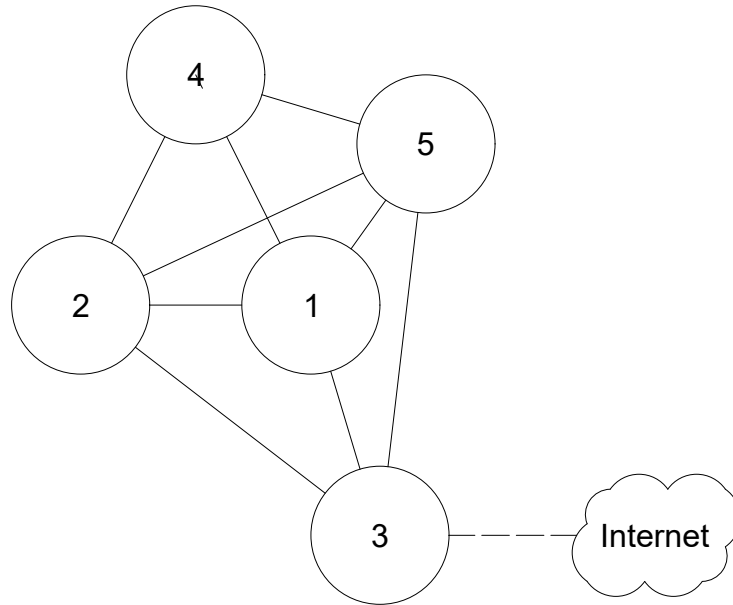


Figure 13: An example of a wireless mesh network with 5 clients and an optional internet connection. The connections made in this example are random.

### Comparison and conclusion

When the network topology's are compared with each other, the mesh network satisfies the desired requirements. Although it is harder to implement due to mutual connections, it has the best data coverage. In this situation, a mesh network would be the best choice.

#### 3.2.2 Network reliability

To ensure a reliable network, self-organization and topology control algorithms are needed.[21] Possibly important and usefull (wireless) network characteristics are [5]:

- Low construction costs
- Energy efficient (power aware)
- Cost aware
- Robust - Able to withstand a lost or broken client or connection
- Guaranteed delivery

Mesh networks can use self-healing algorithms such as Shortest Path Bridging (SPB) to restore and reroute the connection around broken nodes/clients. Shortest path bridging calculates the most favorable connections to the clients with the lowest path costs. [22] Other usefull algorithms such as shortest path, greedy, shortest cost path, cost aware, power aware, are listed in [5] with their characteristics. In this research only the most suitable algorithms will be discussed.

The distance between neighboring nodes can be estimated on the basis of signal strengths or time delays in direct communications. The exact positions can for example be estimated by using positioning systems such as GPS (General positioning system). [23]

The shortest path route protocol uses information such as the hopcount and distance between clients to calculate the shortest route. Hopcount stands for the amount of clients that are passed by. The shortest cost path route protocol also takes account for the energy required for each routing task. The goal of this protocol is to minimize the total energy cost. According to [5] it is not desirable or if possible to avoid to memorize routes or past traffic in mobile ad hoc networks. This is because of the mobility of clients in the network and constantly changing infrastructure.

The scalability of each algorithm means the possibility to adjust the scale of the network by adding or removing clients to the network. According to the research done in [24][25] routing algorithms without geographic locating (precise localisation) are not scalable and won't work well in large networks.

A reliable network has a routing algorithm/protocol that includes distributed operating, loop freedom, demand-based operation and sleep period operation. Loop freedom means that the protocol is able to detect loops in the network and eliminates those. For example, data could be floating around in the network. Sleep period operating means that the clients that are not needed go into a 'sleep mode' when it's temporarily inactive.[5]

### 3.2.3 Data distribution

There are several strategies to distribute a package of data in a network. The following enumeration shows three strategies:

- single-path
- multipath
- flooding

The single-path strategy is an example of the shortest path route protocol. In the single-path strategy only one packet of data is distributed in the network at a time. Which is desirable for the network capacity which is barely affected. Although the capacity is not affected, it is possible that a package is received later, because of a missing or inactive node in the path. [5]

The other strategy, multipath, sends out multiple packets of data through recognizable paths. Flooding strategy literally floods the network with data packages. In case of wireless networks, the single-path strategy is preferred because of the power and bandwidth limitations in wireless networks. [5]

In figure 14 a greedy routing scheme is displayed. The node S contains the data package and D is the destination of the package.

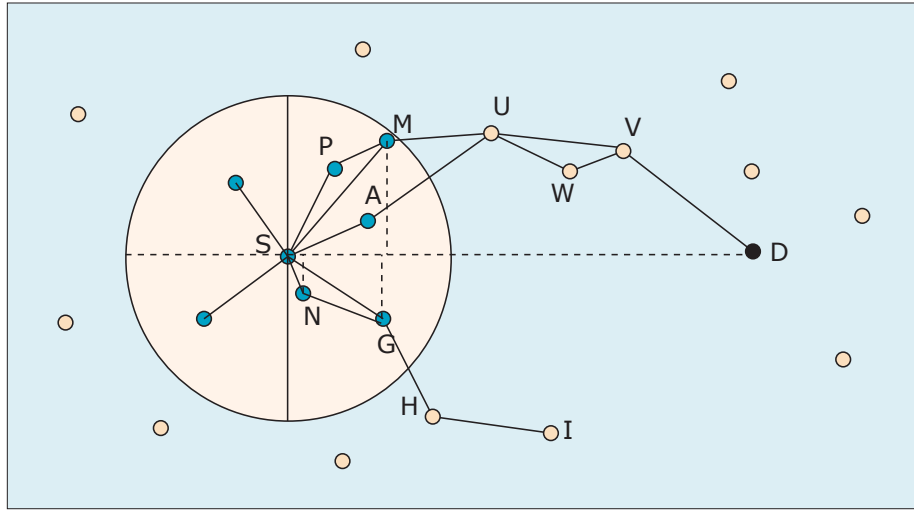


Figure 14: Greedy round scheme found in [5]. "S selects M in MFR path SMUVD, G in greedy path SGHI that fails to deliver, A in direction-based-path SAUWVD, P in power path SPMUWVD, N in NFP/NC path SNGHI that fails to deliver."

The principle of greedy routing is that it is trying to get closer to the destination based on local information. Thus the data package is forwarded to the client/node which is the most suitable from a local point of view. [26] "Greedy schemes have a performance close to performance of optimal shortest path (weighted) algorithm for dense graphs, but have low delivery rates for sparse graphs. Schemes that guarantee delivery may have high communication overhead for sparse graphs." [5] The most efficient algorithm for path bridging depends on the situation where the clients are operating in which is described in [5].

### 3.2.4 Wireless mesh network

A mesh network (MN) is a dynamically self-organized and configured network. [21] As described earlier the swarm network is dynamic in size and mutual distance. Because of the size and mobility of the swarm it is not practical to use wired connections between the members of the swarm. So a wireless mesh network (WMN) is needed. Therefore a wireless connection between the members is necessary.

Despite the practical benefits of wireless networks, today's wireless networks still cannot offer the same level of sustained bandwidth as their wired brethren. The bandwidth is for instance affected by interference from adjacent hops on the same and neighboring paths. [27] One of the most important drawbacks is that each client needs to be in transmitting and receiving range to at least one of the other clients to be connected to the network. [20] Another con is that the data rate falls quickly when increasing the distance between transmitter and receiver, which doesn't or barely apply to wired networks. [27] The complexity of a WMN network is also a main drawback. It is relatively easy to design a WMN, but it is difficult to achieve an optimum performance while ensuring

security and robustness.[20]

Each node or client in the network is able to create an ad hoc network to maintain the mesh connectivity, this is called "client WMN's". These networks are able to reroute around nodes that have been lost. On large scale projects wireless mesh networks are costefficient because of the saving of wired connections.[19]

Nevertheless, the client mobility weigh out the cons described earlier. So solutions must be found to overcome these drawbacks

### 3.2.5 Meshed architecture

Methods to adress meshed networks are:

- Adaptive robust tree (ART)
- Meshed adaptive robust tree (MART)

#### **bbAdaptive robust tree (ART)**

Adaptive robust tree is a meshed tree routing approach to address the nodes. Each node is adaptively addressed during the tree formation. It is desireable that the tree is free of single point failures (SPOF). This means that there is always a redundant path if a node fails, but that's not always possible in non-mesh networks. Each node keeps track of an ART table (ARTT), to map it's branches. In this table the adresses of the connected branches are stored.

ART knows three phases; the initialization, operation and recovery phase. In the initialization phase the tree is formed. The tree formation starts at the root and grows by adding nodes to the tree. The nodes get an adress assigned, when all nodes are joined. Thereafter, the number of nodes are counted in the tree as shown in figure 15.

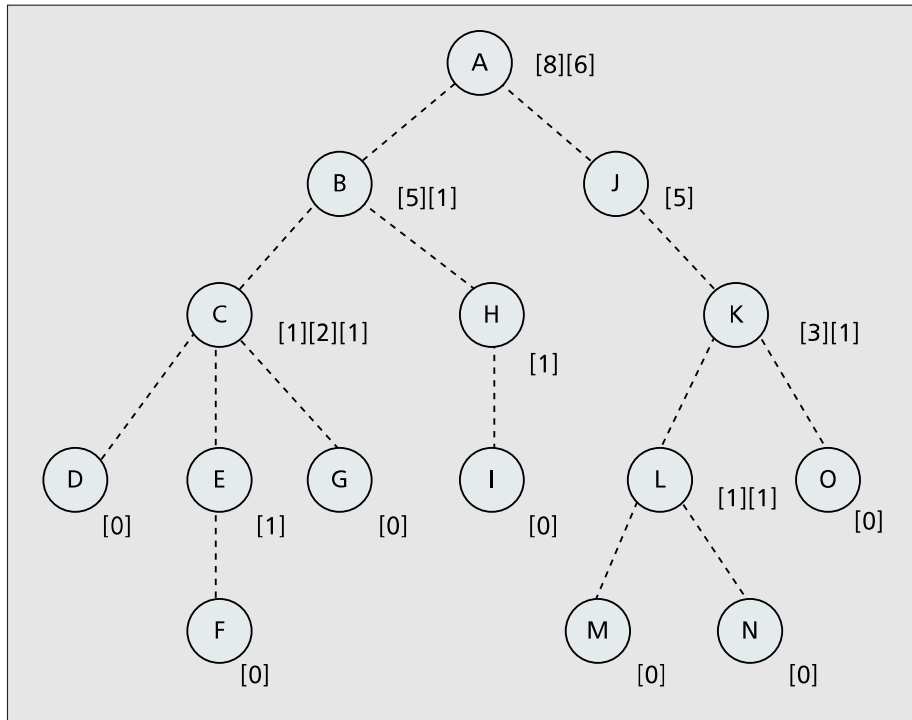


Figure 15: An example of a wireless mesh network with 5 clients and an optional internet connection. The connections made in this example are random.

The following phase is the operation phase, where small amount of nodes are still able to join, but when the change becomes to big, the network goes in to initialization mode again. When a part of the tree becomes broken, the recovery phase becomes active for the affected part.

### **Meshed adaptive robust tree**

With an ART tree it is possible to create a MART (Meshed adaptive robust tree). Figure 16 illustrates a MART, in this figure there are already connections added that make a mesh network. From the point of view from every node in the network, there still is a tree form. In this mesh network, each node has a redundant path if a connection is broken, so it is SPOF free.

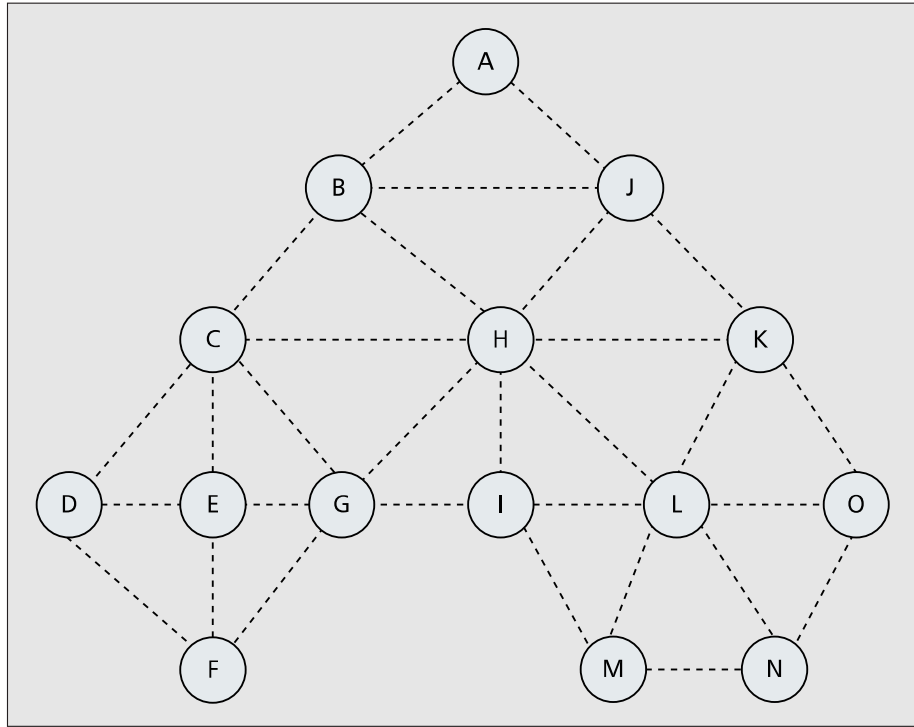


Figure 16: Meshed ART formation, from [6]

With a MART, it is possible to reroute a connection to reduce the path cost in comparison with ART. Most of the time, the transission from ART to MART, removes some SPOFs.

### **Mesh wireless personal area networks**

A mesh wireless personal area networks

#### **3.2.6 Wireless network protocols**

As stated earlier, the communication in the network needs to be wireless. This makes the network flexible in scaling, gives the nodes full freedom of movement and saves physical connections which could be cost efficient.

The following wireless protocols or technologys are defined as short-range (a range of 10-100m) communication protocols [6] [15]:

- IEEE 802.11 a/b/g/ac (Wi-Fi) [28]
- IEEE 802.15.1 (Bluetooth)
- IEEE 802.15.4/5 (ZigBee)
- IEEE 802.15.3 (Ultra-wideband)
- IR IrDA(Infrared)

There are however exceptions, some of the technologys have been evolved and are able to transmit further than 100 meters. WiMax for example is developed to overcome the range problem.

- IEEE 802.16 a (WiMAX)

### IEEE 802.15.1 Bluetooth

Bluetooth is designed for short-range communication which uses wireless radio systems. Bluetooth is mostly used for personal-area networks (PAN). [15] The main purpose of Bluetooth is to create a wireless connection between for example computer peripherals such as; keyboards and mice. These applications are also known as wireless personal area networks (WPAN). [10] Bluetooth is an ad hoc network, which means that the network is formed spontaneously.[29]

Bluetooth uses the industrial scientific and medical (or short: ISM) band for receiving and transmission data. The ISM band ranges from 2,400 to 2,483.5 GHz in the Netherlands. [30] Frequency hopping spread spectrum (FHSS) is used to spread out the power over the full bandwidth. After the transmission of each packet, Bluetooth will hop/change to another channel. The ISM band consists of 79 channels with 1MHz each. Changing frequencies also helps to avoid collision with other networks. But it is still possible that a collision takes place. When a collision happens, the data is resent on another channel until the transmission is successful.

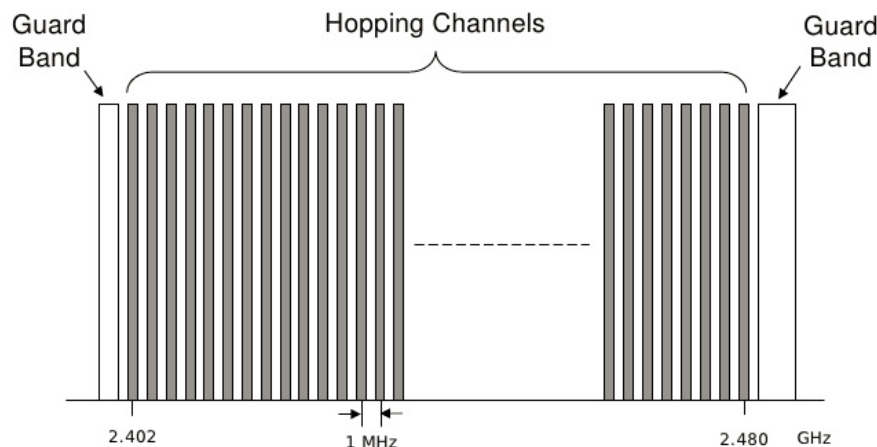


Figure 17: Bluetooth frequency hopping spread spectrum (FHSS) from [7]

Bluetooth consists of two network topologies: a piconet and scatternet. The piconet has one or more slaves serving one master [31]. In a piconet the master synchronizes the master's clock and shares his bluetooth device address at the first connection. The data packet is called a frequency-hopsynchronization packet (FHS packet). The data send in the FHS packet is used to calculate the sequence of frequency hops that all devices in the piconet will follow. Each client in the networks tracks the native- and masters clock, so it will know on which frequency the client needs to transmit or receive.

Each piconet has one master which has an unique Bluetooth device address and clock. A Bluetooth piconet cannot be large. A piconet consists of 8 clients in which one is the 'primary' (master).[29] Because of the frequency hopping, it is possible to have more than one piconets in one area.

A scatternet consists of two or more piconets. It is possible for a client

to participate in more than one piconets, but it can only be a master of one network.

### IEEE 802.15.3 Ultra-wideband

Ultra-wideband is designed for short-range high-speed wireless communication. The bandwidth of UWB is over 100Mbps and can reach speeds up to 480 Mbps [10]. The frequency band of UWB ranges from 3.1 to 10.6 GHz [32]. Although the spectrum is large in comparison with other protocols the signal level is very low so it doesn't interfere with other signals. UWB is an baseband or carrierless communication method.

Because of the 'ultra wide' band UWB has benefits over other technologys. The benefits of UWB are [32][15]:

- High data rates
- Less path los and better immunity to multipath propagation
- Low-cost tranceivers
- Low transmit power and low interference

With UWB it is possible to get high data rates in ranges of 20 to 50 meters. Because of the wide bandwidth of UWB, the material penetration losses are relatively low. As shown in equation 2, the channelcapacity increases linearly with the bandwidth.

$$C = B \log_2(1 + \frac{S}{N}) \quad (2)$$

Because of the absence of sending a carrier, the transceiver build can be relatively simple. [32] The disadvantage is however, the transmitpower must be low for commerical use. This results in a low transmitting range about 30 meters according to [15].

### IEEE 802.15.4 ZigBee

Zigbee is usually used in personal operating spaces (POS) or personal-area networks (PAN) of about 10 meters. [15] However, there are devices based on Zigbee that can reach up to 1500 meters of span when the target is in line of sight [33]. It is designed for simple devices that consume minimal power and operate in a personal operating space. Applications as sensors. These applications are also known as low-rate wireless personal area networks (LR-WPAN). [10] Zigbee uses the ISM 900 MHz or, just like Bluetooth and WiFi, the 2,4 GHz ISM band to communicate. Zigbee uses direct sequence spread spectrum (DSSS) with 16 channels and 2 MHz bandwidth.

There are proven implementations of networks with ZigBee. It is possible to create a reliable self-organized mesh network which is able to use multi-hopping [10].

Zigbee is known for the low power consumption which results in long battery lifetime [34]. There are two types of devices in a LR-WPAN network: A full-functioning device and a reduced-functioning device. Full-functioning devices can be used as a 'Master' or coordinator or as a client. These devices can talk to eachother or to reduced-functioning devices. A RFD is used for simple transmit tasks such as switches or simple inout/output operations. Just like Bluetooth, the coordinator or master, will setup the network.

### IEEE 802.11 Wi-Fi

Wireless local area networks (WLANs) or IEEE 802.11 is popularly known as



Wi-Fi (Wireless Fidelity) [20]. With a Wi-Fi connection it is possible for the clients to connect to the internet with broadband speeds. Consumer WiFi usually uses one or two ISM frequency bands: 2,4 and 5 GHz. The 2,4 GHz unlicensed ISM band used for IEEE 802.11b/g/n extends from 2.4 to 2,4835 GHz with a total bandwidth of 83.5MHz. The 5 GHz ISM band used for IEEE 802.11a extends from 5.15 to 5.25 GHz with a power limitation of 50mW, 5.25 to 5.35 GHz with 250mW and 5.725 to 5.825 GHz with 1W of power.[15] The benefit of using the 5 GHz ISM band is that there are a lot less interference from appliances like microwaves, Bluetooth products and a number of other services. The downside of 5 GHz is however, the transmission range decreases greatly because 5 GHz signals are absorbed faster in comparison with 2,4 GHz signals. [15] There are also Wi-Fi standards which use the 3,6 and 60 GHz band. The 3,6 GHz band is used by the IEEE 802.11y-2008 standard. and the 60 GHz band for the IEEE 802.11ad protocol. The 802.11 standard defines two services: the basic set (BSS) and the extended service set (ESS). The basic service set without an access point is an ad hoc network and only consists of access points.

Wi-Fi uses direct sequence spread spectrum (DSSS) with complementary code keying (CDK) with 14 possible channels on the 2,4 GHz band. With DSSS it is possible that multiple signals use the same channel. However to prevent interference the channel selection must be critically considered. Each channel has a bandwidth of 22 MHz and is 5MHz apart, see figure 18. [15] Because of the span of each channel, the channels overlap.

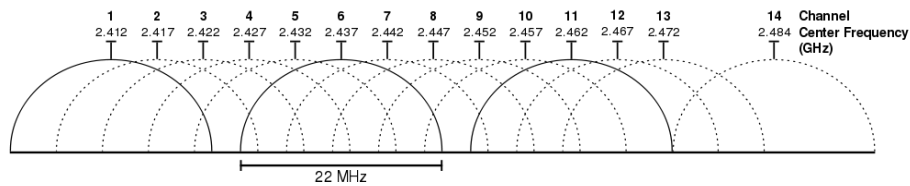


Figure 18: Illustration of the Wi-Fi channels on the 2,4 GHz band. [8]

Wi-Fi doesn't use frequency hopping to avoid data collisions. This forms a problem when there are hidden nodes in the network. A hidden node is illustrated in figure 19. The circles indicate the transmission range of each node. In figure 19 'A' is not in the transmission range of 'C', which makes 'A' invisible to 'C'. In this situation node A and C are not aware of each other. Therefore one of the nodes can think that it is the only active node in the network.

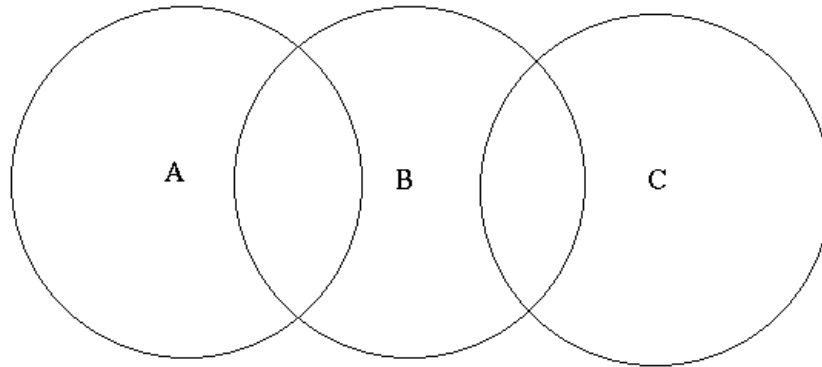


Figure 19: Illustrates the hidden node problem with three nodes.

In the following situation there will be a collision of information:

- Node 'A' sends data to node 'B'.
- Simultaneously node 'C' is also sending information to node 'B'.

Using handshake frames (CSMA/CD - CA) can be a solution to prevent a collision from happening when there is a hidden node. With 802.11, the used handshake frames are CTS (clear to send) and RTS (request to send). The solution is given in figure 20. Where node 'A' send an RTS to 'B' and 'B' responds with an CTS to node 'A' and 'C'. Node 'C' didn't send an RTS, so the node knows that it needs to wait. The waiting duration of data transmission is contained in the CTS message which is send by node 'B'. [29]

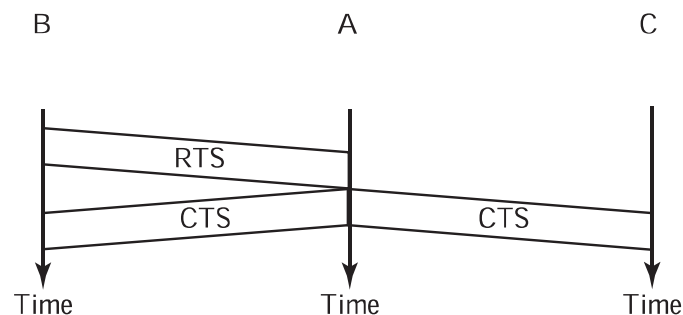


Figure 20: Gives an example of the hidden node problem given in 19

As mentioned before, using handshake frames can be a solution to prevent a data collision from happening in case of a hidden node. However, in a exposed node problem, this method will cause data transmission inefficiency. [29] Figure 21 illustrates the exposed node problem. In figure ?? the following situation is illustrated:

- Node 'A' wants to send information to the node 'B'.

- Node 'C' also wants to send information to node 'D'.
- Because node 'C' receives an RTS, it doesn't get permission to send an RTS itself.

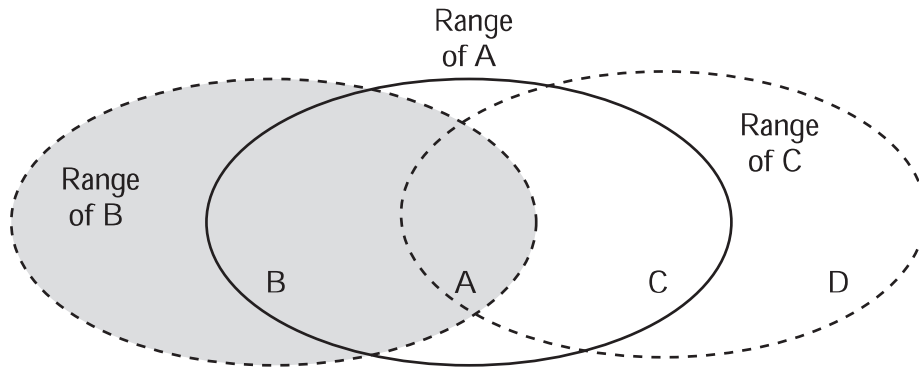


Figure 21: The exposed node problem with four nodes and two nodes who want to send information.

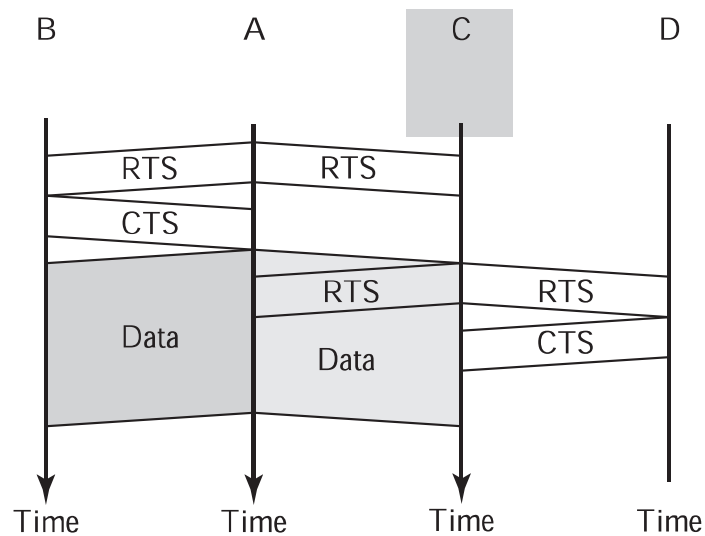


Figure 22: Gives an example of the exposed node problem given in ??

### IR Infrared

Infrared is possibly the most widespread wireless technology for short-distance data communication. [15] It is primarily used for remote control between computers and televisions. The short-range distance with infrared communications is typically about 1 to 9 meters. [15] Infrared travels with the speed of light which is 299792458 meters per second. [35] In comparison with the other discussed protocols this technology is based on light instead of radio frequency signals. Because of the origin of this technology, there must be a clear (no obstacles block the sight) line of sight (LOS) between the transmitter and receiver.

This disadvantage makes the technology not suitable for the communication in a complex swarm network.

### IEEE 802.16 WiMAX

WiMAX is a wireless metropolitan-area network (MAN network). WiMAX is defined by the IEEE 802.16 standard. The main reason for developing this standard was to deliver consumers wireless broadband speeds. WiMAX is a long-distance data communication technology. WiMAX knows three topology structures: Point-to-point (P2P), point-to-multipoint (PMP) and mesh mode.

### Summerization and comparison

To summerize the given information from the protocols, table 1 is made. This table displays the most important characteristics of each protocol.

Table 1: A table with a summerazing of the protocols. The table is based on information from [10]. Infrared is not included due to the line of sight problem.

Standard	Bluetooth	Ultra-wide band	ZigBee	Wi-Fi
IEEE spec.	802.15.1	802.15.3a	802.15.4	802.11a/b/g
Frequency band	2.4 GHz	3.1-10.6 GHz	868/915 MHz; 2,4 GHz	2,4GHz; 5GHz
Max signal rate	1Mb/s	110Mb/s	250Kb/s	54Mb/s
Nominal range	10m	10m	10-100m	100m
Channel bandwidth	1 MHz	500 MHz - 7.5 GHz	0.3/0.6 MHz; 2MHz	22 MHz
Basic cell	Piconet	Piconet	Star	BSS
Extension basic cell	Scatternet	Peer-to-peer, mesh	Cluster tree, mesh	ESS, mesh
Max cell nodes	8 [15]	8	>65000[15]	2007

Each characteristic of the protocol is compared with eachother in this chapter. And for each comparison the most suitable and unsuitable characteric is given pros and cons. This way a recommendation can be made.

### Network size

The networksize of each of the protocols is expendable. This is shown in table 1. A Bluetooth piconet for example can be part of a scatternet, which overlooks serveral other piconets. However, each piconet must have a master as mentioned before, a master in a swarm network is not desirable. Bluetooth also doesn't have mesh network support yet (begin 2016). [36] This gives Bluetooth the biggest disadvantage in contrast to the other protocols. In comparison with ZigBee which has the biggest possible network size.

### Transmission time

The transmission latency between nodes can be calculated with equation 3.[10] The data size ( $N_{data}$ ), the maximum payload size ( $N_{maxPld}$ ), the overhead size ( $N_{ovhd}$ ), the bit time ( $T_{bit}$ ) and the propagation time ( $T_{prop}$ ) between devices form the transmission latency ( $T_{tx}$ ).

$$T_{tx} = (N_{data} + \left( \frac{N_{data}}{N_{maxPld}} N_{ovhd} \right) T_{bit} + T_{prop}) \quad (3)$$

When the data payload size increases the transmission time increases as shown in [10]. In comparison to the other protocols, UWB has the lowest bit time which results in the fastest tranmission time followed by Wi-Fi. Where ZigBee followed by Bluetooth have the slowest tranmission time.

As mentioned earlier, the density of a Wi-Fi network, contributes to the network latency due to the exposed node problem.[15]

#### Data distribution per square meter

Research done in [9] makes a data distribution comparison between Wi-Fi, Bluetooth and Ultra-wideband. Because of the crowding in the spectrum and the growing demand for wireless data capability at high bandwidth it favors systems just not to have a high-peak bit rate, but also high spatial capacity. Spatial capacity is defined as bits/sec/square-meter. [9] Table 2 gives the spatial capacity of each protocol.

Table 2: Spatial capacity of different protocols, based on information from [9]

Protocol	Spatial capacity
Wi-Fi IEEE 802.11b	1.000
Wi-Fi IEEE 802.11a	83.000
Bluetooth IEEE 802.15.4	30.000
UWB IEEE 802.15.3a	1.000.000

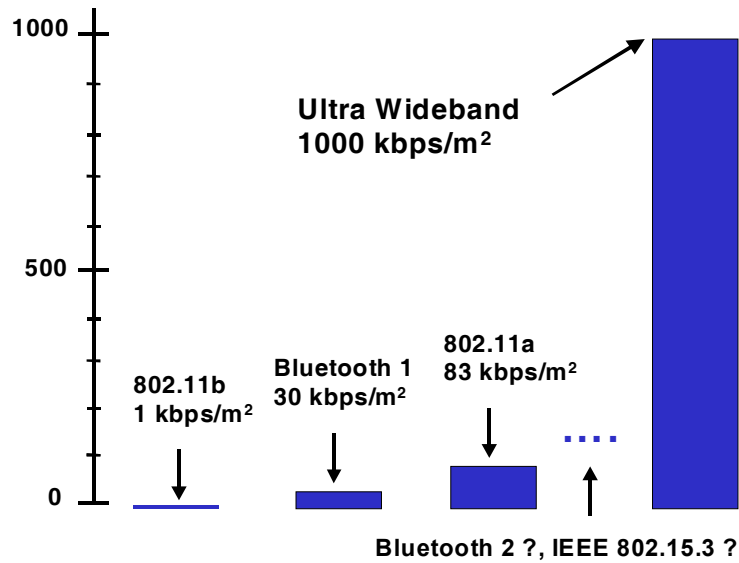


Figure 23: Comparison of the spatial capacity for each protocol, found in [9].

#### Protocol complexity

The protocol complexity can be compared by the number of primitives and events in a set situation. When there are more primitives or events in a certain protocol, it indicates the complexity. [10] As indicated in figure 24 Bluetooth is by far the most complex protocol compared to the other protocols.

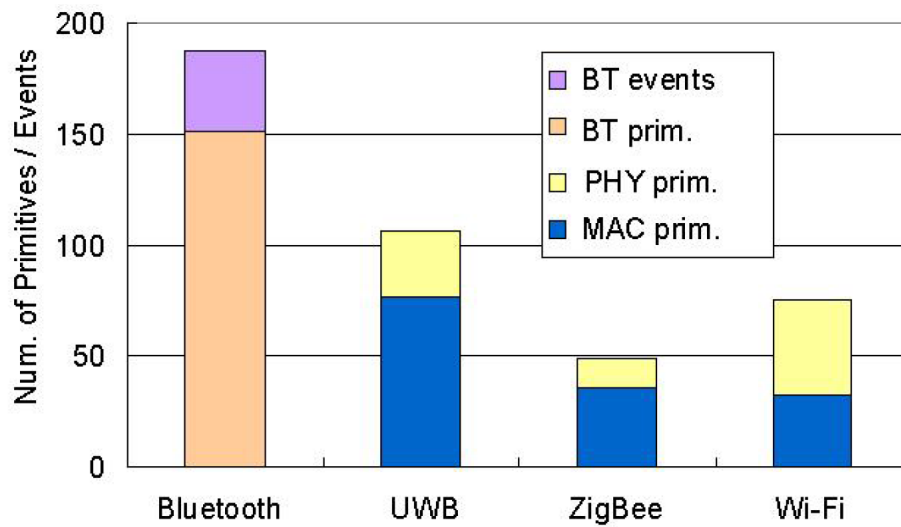


Figure 24: Comparison of the complexity for each protocol, found in [10].

Each of the discussed protocols has its own complexity. The research done in [10] compares them in data coding efficiency versus the data size. The data coding efficiency is based on the data and message size. The average ratio between the data and message size is the data coding efficiency percentage.

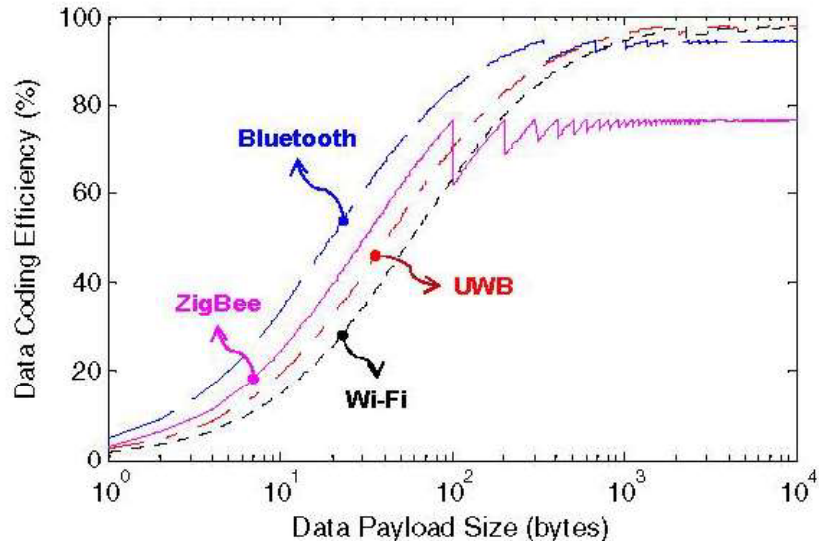


Figure 25: Comparison of the data coding efficiency for each protocol, found in [10].

Figure 25 illustrates the data coding efficiency for each protocol. Bluetooth for example has the best data coding efficiency when using a small amount of bytes (around 339 bytes). Wi-Fi and UWB on the other hand are more efficient for large data sizes. Where Zigbee saturates on 80 percent efficiency when the

data size increases.

### Interference

Ultrawideband operates in the 3.1 - 10.6 GHz range. This region is used by satellites, radars, broadband wireless and wireless networks.

### Power consumption

The power consumption of each protocol depends on the used hardware. To make a valid comparison, the paper [10] made a selection of average hardware. The comparison in figure 26 gives an indication of the average power consumption of each protocol. Bluetooth and ZigBee both consume about 100mW where the power consumption of UWB and Wi-Fi is about 700mW. Figure 25 gives the normalized energy consumption of each protocol. The normalized energy is given in mJ/Mb. The normalized energy consumption indicates that ZigBee and Bluetooth both use more energy to transceive the same amount of information. UWB is the most efficient protocol to transceive information.

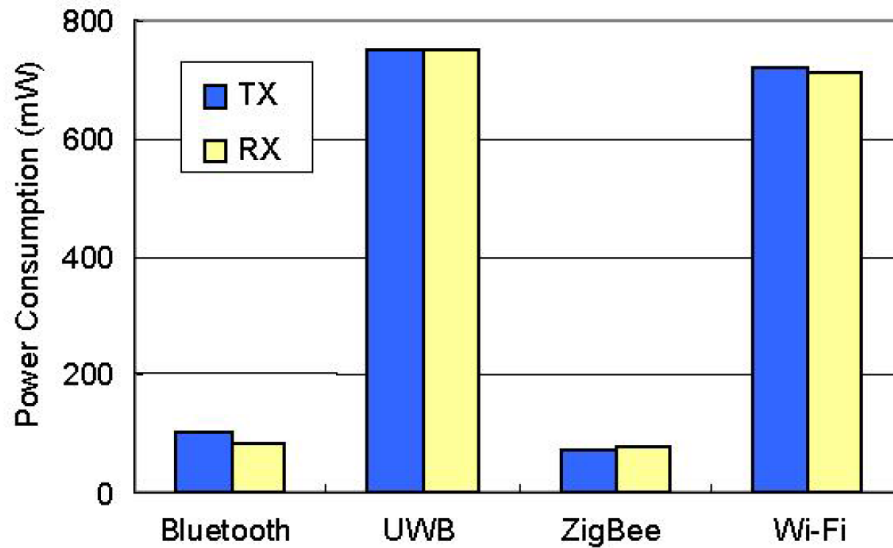


Figure 26: Comparison of the power consumption for each protocol, found in [10].

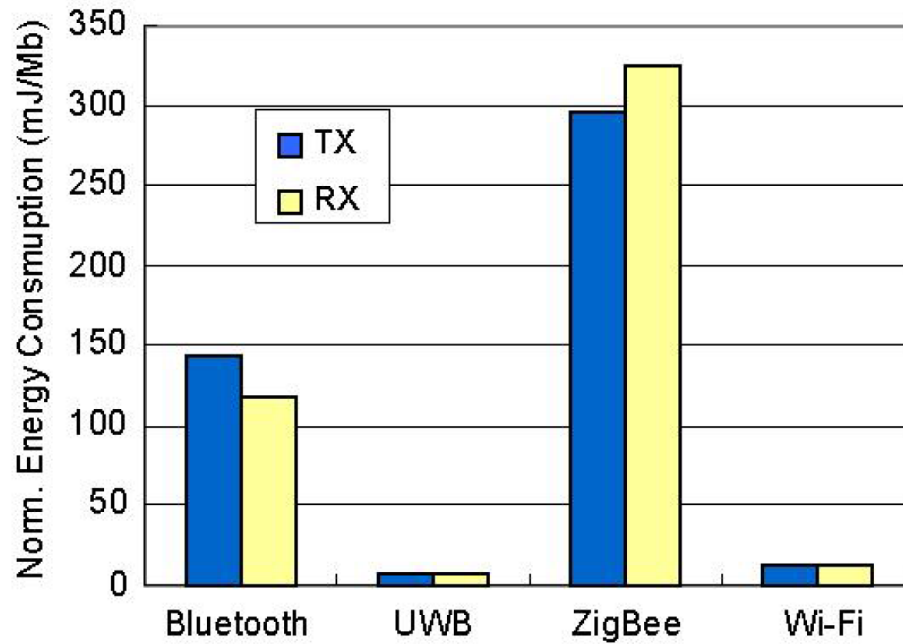


Figure 27: Comparison of the normalized energy consumption for each protocol, found in [10].

### Conclusion

The final comparison is made in table 3. There have been some adjustments in naming the characteristics to make the table fit the page. 'Rate' is the transceiving data rate, 'Range' is the transceiving data range, 'Scalability' of the protocol on large and small scale projects, 'Efficiency' means the data coding efficiency, 'Complexity' is the protocol complexity, 'Capacity' stands for the data distribution per square meter, 'Consumption' means the energy consumption.

Table 3: The comparison of the protocols. The characteristics of each of the protocols get evaluated. The scoring is based on a number between zero and one, where zero is bad and one is good. The total score gives the best protocol for this situation.

Protocol	Rate	Range	Scalability	Efficiency	Complexity	Capacity	Interference	Consumption	Total
Wi-Fi	1	0,5	0,75	0,7	0,75	0,1	0,5	1	5,3
Bluetooth	0	0	0	1	0	0	0,75	0,25	2
ZigBee	0	0,5	1	0,9	1	-	0,5	1	4,9
UWB	1	1	1	0,8	0,5	1	1	0,25	6,55

The information from table 3 results in the graph in figure 28. The protocol with the highest score has the best characteristics to apply in the swarm network. The conclusion is that ultra-wideband is the best option followed by Wi-Fi, ZigBee and Bluetooth.



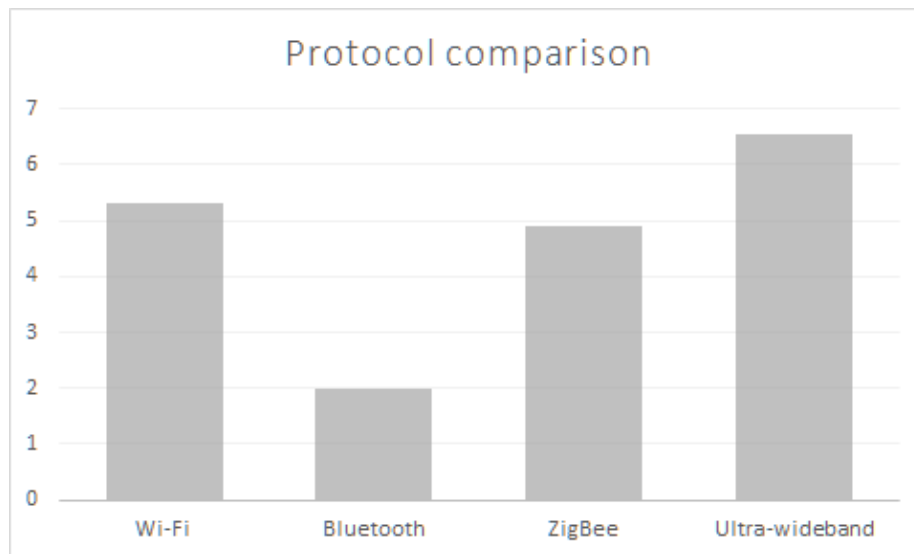


Figure 28: Total scores for each reviewed protocol.

### 3.2.7 Conclusion

In this section an substudy in swarm communication is made. The results of the substudy have resulted in recommendations for the implementation of the swarming module. An enumeration of the recommendations are given below:

- The connection must be wireless due to the mobility of swarm members.
- Scaling on large-scale projects is not possible without using geographic locating (precise locating). [24][25].
- The network must be reliable, so it must use self-organization and topology control algorithms. [21]
- The most suitable communication protocol in the described situation is ultra-wideband.

**\*\*Matthijs\*\*** Nog onderzoeken afmaken:

- Inleiding uitbreiden
- Unicasting, multi-casting and broadcasting
- Figuur aanpassen meshed ART
- Network reliability
- WiMAX
- Interference
- Data distribution
- Volledige conclusie
- Structuur

### 3.3 Sensors

For close range obstacle avoidance, the robots will need some kind of proximity sensing technique. The sensor needs to differentiate between different "treats" for the robot to function properly. For example; when the sensor detects a small hill, which the robot can move over it should not trigger the robot to move away from it. But when it detects a big obstacle it should trigger the robot to move away. This is important because the robots will eventually be expected to move across rough terrain (like Mars). In the next paragraphs some different proximity sensor techniques will be discussed. Price is also a important factor while comparing these techniques. Multiple robots must be made on a tight budget, so costs should be cut where possible.

#### 3.3.1 Ultrasoon sensor

Een veel gebruikte proximity sensor op simpele robots is de ultrasoonsensor. Dit komt omdat deze in vergelijking tot andere sensoren een goedkope oplossing is. Een ultrasoon sensor stuurt een ultrasoon geluid uit dit geluid wordt teruggekaatst tegen het object en vervolgens weer opgevangen door de sensor. De tijd die het geluid er over gedaan heeft wordt gemeten. Met een simpel reken-sommetje wordt vervolgens de afstand bepaald. Een probleem met de ultrasoon sensor is dat het moeilijk is om te discrimineren tussen verschillende objecten. Hierdoor wordt het moeilijk om onderscheid te maken tussen bijvoorbeeld een heuvelkje (waar de robot wel overheen kan) en een obstakel die de robot moet ontwijken. Door de atmosfeer op mars wordt geluid ernstig gedempt hierdoor is ultrasoon niet implementeerbaar op mars [37]. Voor testen op aarde is het echter wel een goed werkend en bewezen techniek.

#### 3.3.2 Lidar sensor

Lidar staat voor "Light detection and ranging". Deze sensor werkt volgens het zelfde principe als de ultrasoon sensor. Het is al bewezen dat de lidar techniek werkt op Mars. Met de Phoenix missie is er een lidar systeem gebruikt om wolken en atmosferische stof te meten[38]. Het licht van de laser kon wolken meten op meerdere kilometers hoogte. Omdat licht zich zeer snel verplaatst, moet de elektronica in een lidar sensor ook snel zijn. Hierdoor is de prijs in vergelijking tot de ultrasoon sensor hoog.

#### 3.3.3 Mechanische sensor

Eén mechanische proximity sensor bestaat meestal uit twee onderdelen. Dit zijn de actuator, dit is meestal een simpele druk schakelaar. En de arm of "bumper", dit is het deel dat het object aanstoot en zorgt dat de mechanische kracht op de schakelaar wordt uitgeoefend figuur 29 . De kracht van deze techniek is zijn eenvoudigheid. Er hoeven geen ingewikkelde signalen verwerkt te worden, enkel het aan of uit signaal van de actuator. Een groot nadeel van deze techniek is dat de sensor fysiek tegen een object aan moet komen om het te detecteren. In een zwerm van relatief fragiele robots is dit niet ideaal. Wanneer de robots zich op ruiger terrein bevinden, zal het gebruik van een "bumper" of arm ook niet ideaal zijn, deze kan namelijk vast blijven zitten tegen of achter obstakels.

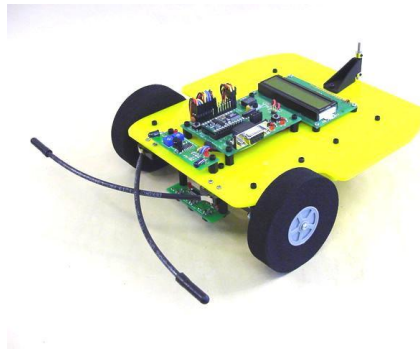


Figure 29: Robot met mechanische proximity sensor

#### 3.3.4 Sensor choice for the robot

Now the question is which of the different sensor techniques proposed, is the best to implement on the swarm robots. While answering this question the following points will be taken into account:

- The sensor must be easy to reproduce because multiple robots must be made from the swarm.
- The budget is limited, therefore the sensor price should be cheap compared to the total price of one robot.
- Energy usage should be as low as possible to increase the operation time per robot.
- For budget reasons there has been chosen to not take into account if the sensor would work on Mars.

Looking at these points it becomes clear that the lidar sensor wouldn't be the best choice. It doesn't really have any outstanding pros compared to the other two techniques and it's much more expensive. Currently the cheapest lidar sensor would cost about 100€. The ultrasonic and mechanical sensor wouldn't cost more than a few Euro's. As talked about before the mechanical sensor has a few drawbacks compared to the ultrasonic sensor. For these reasons the ultrasonic sensor seems the best choice. The only issue left to solve is how to sense the difference between obstacles which the robot has to avoid, and things the robot doesn't have to avoid, but still might be detected by the sensor. This will be discussed in the next paragraph.

#### 3.3.5 Obstacle discrimination with an ultrasonic sensor

An ultrasonic sensor is usually used to detect if there is some obstacle in the way. In this case there is made no difference made between a obstacle that the robot can move over, or a obstacle that should be avoided. For example: a small slope or hill might be detected as an obstacle, but in truth the robot can move over it. The robots developed for this program will eventually be able to cross harsh terrain. In this case the proximity sensor will need to discriminate between these situations. Working with ultrasonic waves there are multiple domains to

work with. These are time, frequency and amplitude. Time is used to determine the distance between the object and the sensor. The change in frequency and/or amplitude contains information about the shape of the object[?]. In the paper "Object recognition with ultrasonic sensor" is concluded that looking at the amplitude over time contains enough information to discriminate between object[?]. The example is given of an object with separated surfaces of 3,5cm, the echo from the second surface will be delayed by 0,2msec relative to the echo from the first surface. This delay can be easily detected with a microprocessor. The reason looking at frequency isn't the first choice is because of the higher hardware requirements it would require to properly sample the signal.

## 4 Bibliography

### References

- [1] *Distributed Range-Based Relative Localization of Robot Swarms*, Harvard University, 1 2014.
- [2] *Is RSSI a Reliable Parameter in Sensor Localization Algorithms – An Experimental Study*, State University of New York at Buffalo, 1 2010.
- [3] *Sampling Oscilloscope Techniques*, Tektronix, 1 1960.
- [4] *Radio Frequency Time-of-Flight Distance Measurement for Low-Cost Wireless Sensor Localization*, University of California And San Diego, 3 2011.
- [5] *Position-Based Routing in Ad Hoc Networks*, University of Ottawa and Universidad Nacional Autonoma de Mexico, 6 2002.
- [6] Y.-B. K. D. S. M.J. Lee, J. Zheng, “Emerging standards for wireless mesh technology.”
- [7] J. Paynter. Can bluetooth and 802.11b/g/n wi-fi devices coexist? [Online]. Available: <http://www.frequentieland.nl/draadloos/rlnbanden.htm>
- [8] J. Lendino. How to boost your wi-fi speed by choosing the right channel. [Online]. Available: <http://www.extremetech.com/computing/179344-how-to-boost-your-wifi-speed-by-choosing-the-right-channel>
- [9] S. S. D. L. J. Foerster, E. Green, “Ultra-wideband technology for short- or medium-range wireless communications.”
- [10] Y.-W. S. J.-S. Lee and C.-C. Shen, “A comparative study of wireless protocols: Bluetooth, uwb, zigbee and wi-fi.”
- [11] *Open source, TOF laser rangefinder*, Arduino Forums, 1 2014, <https://forum.arduino.cc/index.php?topic=213774.0>.
- [12] Wikipedia. Swarm robotica. [Online]. Available: [https://en.wikipedia.org/wiki/Swarm\\_robotics](https://en.wikipedia.org/wiki/Swarm_robotics)
- [13] *Swarm Intelligence and Its Applications in Swarm Robotics*, D.A. Aleksandar Jevtic, 1 2015, vertrouwelijk.
- [14] Wikipedia. Star network. [Online]. Available: [https://en.wikipedia.org/wiki/Star\\_network](https://en.wikipedia.org/wiki/Star_network)
- [15] L. E. F. Jr., *Principles of electronic communication systems*. Avenue of the Americas, NY: McGraw-Hill, 2008.
- [16] Wikipedia. Ring network. [Online]. Available: [https://en.wikipedia.org/wiki/Ring\\_network](https://en.wikipedia.org/wiki/Ring_network)
- [17] Technopedia. Bus topology. [Online]. Available: <https://www.techopedia.com/definition/17045/bus-topology>

- [18] M. K. V. R. V. S. G. H. T. Braun, A. Kassler, "Multi-hop wireless networks."
- [19] Wikipedia. Mesh networking. [Online]. Available: [https://en.wikipedia.org/wiki/Mesh\\_networking](https://en.wikipedia.org/wiki/Mesh_networking)
- [20] M. L. Sichitiu, "Wireless mesh networks: Opportunities and challenges."
- [21] *A Survey on Wireless Mesh Networks*, Georgia institute of technology, 9 2005.
- [22] *Shortest Path Bridging*, M. Seaman, 1 2005.
- [23] J. Hightower and G. Borriello, "Location systems for ubiquitous computing."
- [24] A. P. R. Jain and R. Sengupta, "Geographical routing using partial information for wireless ad hoc networks."
- [25] J. L. et al., "A scalable location service for geographic ad hoc routing."
- [26] Wikipedia. Geographic routing. [Online]. Available: [https://en.wikipedia.org/wiki/Geographic\\_routing](https://en.wikipedia.org/wiki/Geographic_routing)
- [27] A. Raniwala, "Architecture and algorithms for an ieee 802.11-based multi-channel wireless mesh network."
- [28] IEEE. Official ieee 802.11 working group project timelines - 2016-02-02. [Online]. Available: [http://grouper.ieee.org/groups/802/11/Reports/802.11\\_Timelines.htm](http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm)
- [29] B. Forouzan, *TCP/IP Protocol Suite Fourth Edition*. Avenue of the Americas, NY: McGraw-Hill, 2010.
- [30] P. Anker. Beschikbaarheid van frequentiebanden voor rans. [Online]. Available: <http://intelligenthospitaltoday.com/can-bluetooth-and-802-11bgn-wi-fi-devices-coexist/>
- [31] J. Bray. Masters and slaves: Roles in a bluetooth piconet. [Online]. Available: <http://www.informit.com/articles/article.aspx?p=21324>
- [32] W. S. W. Zhuang and Q. Bi, "Ultra-wideband wireless communications."
- [33] Wikipedia. Zigbee. [Online]. Available: [https://en.wikipedia.org/wiki/ZigBee#Radio\\_hardware](https://en.wikipedia.org/wiki/ZigBee#Radio_hardware)
- [34] J.-S. Lee, "Performance evaluation of ieee 802.15.4 for low-rate wireless personal area networks," 2006.
- [35] Nasa. How fast is the speed of light? [Online]. Available: [https://www.grc.nasa.gov/www/k-12/Numbers/Math/Mathematical\\_Thinking/how\\_fast\\_is\\_the\\_speed.htm](https://www.grc.nasa.gov/www/k-12/Numbers/Math/Mathematical_Thinking/how_fast_is_the_speed.htm)
- [36] B. SIG. Bluetooth technology to gain longer range faster speed mesh networking in 2016. [Online]. Available: <https://www.bluetooth.com/news/pressreleases/2015/11/11/bluetooth-technology-to-gain-longer-range-faster-speed-mesh-networking-in-2016>

- [37] A. D. Hanford. Computer simulations of propagation of sound on mars. [Online]. Available: <http://acoustics.org/pressroom/httpdocs/151st/Hanford.html>
- [38] *Lidar on the Phoenix mission to Mars*, James Whiteway, 6 2008, vertrouwelijk.