MASTER

The human LED display

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The Human LED Display

Master Thesis Feasibility Study

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Abstract

This document is the report of a feasibility study meant as preparation for a thesis project at the Eindhoven University of Technology.

The thesis project is the designing and implementing if a system called the Human LED Display. This is a system in which a large number of distributed devices act as the pixels of a large display. This system is to be deployed in the entertainment industry during concerts and festivals.

In this document, first the two main issues in designing such a system are discussed: the localization of the devices (a device has to know its physical position for it to know which pixel to represent) and the distribution of the video.

Then the possible options for resolving these two issues are discussed. For localization the methods localization by signal strength, by time of flight (both one- and two-way ranging), by angle of arrival are discussed as well as two so-called range-less localization methods: localization by fingerprinting and mesh networking. These are weighed against each other after which localization by time of flight and specifically by one-way ranging is found to be optimal for this application. For video distribution both preloading the video and live-streaming is discussed. Streaming is found to bring flexibility for the operator to the system and is therefore preferred.

Lastly, a plan of approach is discussed with methods of verification, risks and planning.

Contents

Chapter 1

Introduction

Every display consists of millions of pixels. At any given moment, each of these pixels emits a color, depending on their location in the screen. Only by combining all these pixels, a sensible image is formed.

Now, suppose you are at a stadium concert, where every spectator is given a wristband. This wristband on its own is seemingly simple and shows nothing more than some LED's. At the concert however, all spectators come together, all wearing such a wristband. Every wristband would emits a color, as if it were a pixel in a huge screen. Having such a screen would add a completely new element to the show. Show directors would get a new way to allow the audience to become part of the show instead of just being a spectator. The show would not only revolve around the artist, but would become an experience that the audience is a part of.

This thesis project is about attempting to turn this idea into a reality. Goal is to create an architecture and a functional prototype of a wristband. For this two challenges have to be overcome. A wristband has to know both its physical location (which might change during a concert, as people walk around) and the pixel color corresponding to that location to be able to know which color to emit at any given time.

Both this feasibility study and the thesis project will be done at Vention Technologies.

In this document first the context is explained in chapter 2; the market in which the end-product will be deployed and why there would be interest for such a product, and the company, Vention Technologies, at which this project will be carried out. Then the domain of the project is described in chapter 3. First the intended system is specified with requirements and a rationale for these requirements. Next the two issues that make this project non-trivial are described, for each mentioning and explaining options as to how to solve these problems. For both a single solution is chosen in section 3.3. In chapter 4 the final research questions are stated. Finally, in chapter 5 the plan of approach for the thesis project is described.

Chapter 2

Context

This chapter describes the market in which the end-product designed in this thesis project is going to be used, and the company at which this thesis project is going to be performed.

2.1 The market

Over the last few decades record sales have continuously decreased while live concert sales have been going up [1]. Where in the past artists went on concert-tours to promote their record sales, nowadays they sell records as an excuse to continue going on tour. Record sales have been decreasing due to 'competition' of streaming services such as Spotify and Apple Music [2]. For the artist, these new methods of listening to music generate less income [3]. However, artists have been able to compensate for this by going on tour and doing live concerts. People are more and more willing to pay for the experience that artists deliver (see Figure 2.1).

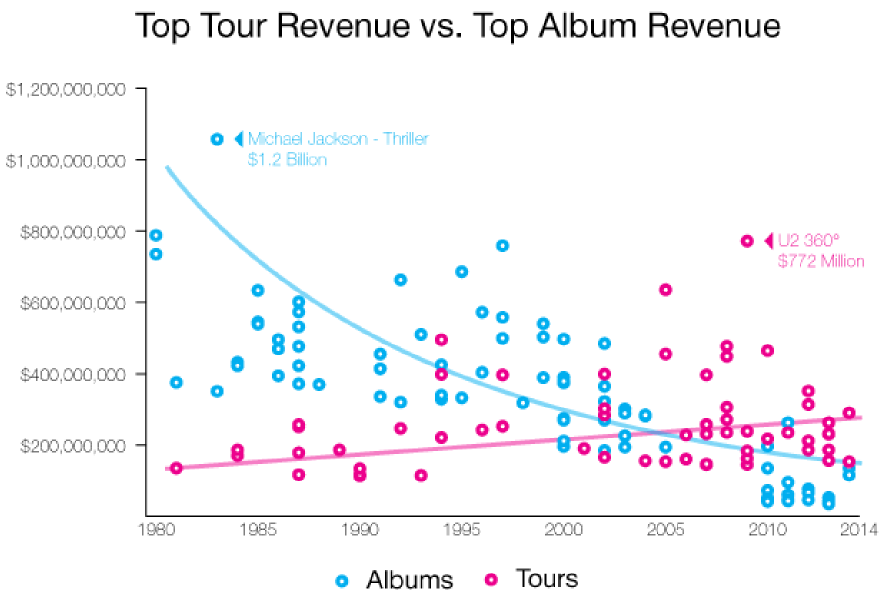


Figure 2.1: Revenue tours versus albums over the last decades. Image from [1]

The concert/ entertainment industry is an industry with constantly evolving trends. Technology is playing a large role in this. Concerts with new technology have the opportunity to wow fans and deliver a unique experience. Having countless concerts all around the globe, all looking to provide an experience, organizers of these events are constantly browsing for new technology.

EventBrite, a multinational event management organization, has performed a small scale study [4] trying to find out what is to be expected of the technology in the near future for the entertainment industry. One of the things that came forward in this study is that "Fans will be able to influence performances in real-time with wearable tech". Unsure is yet how this is going to manifest itself. It is, however, clear that people are keen on being part of the show, rather than being a mere spectator. A system such as described in this thesis project would fit this prediction perfectly.

2.2 The company

The company at which this project takes place is Vention Technologies. In this section the company is introduced and some of its activities related to the topic of this thesis project are discussed.

2.2.1 Vention Technologies

Vention Technologies is a company that is specialized in bringing technological ideas to the market. Customers that have an idea for a technical product, but lack the knowledge or resources to bring this idea to a physical product, come to Vention Technologies. Vention Technologies guides, advises and supports the customer, or completely takes over research and development. Vention Technologies specializes in wireless sensors, primarily focusing on solutions in the Internet of Things domain and Smart Devices.

Vention Technologies has an office at the High Tech Campus in Eindhoven. The High Tech Campus is an area of one square kilometer, home to over 140 companies and institutions, comprising over 10.000 product developers, researchers and engineers. It houses several big companies like NXP, Intel, IBM and Philips research, but is also a place where technology start-ups and scale-ups are situated next to each other to learn from each other and work together.

Vention Technologies is such a scale-up, currently employing 18 engineers, originating from multiple disciplines. Most of these employees have a background at the Eindhoven University of Technology in the programs Electrical Engineering, Software Science and Mechanical Engineering.

2.2.2 Related Activities

Vention Technologies has successfully completed a wide range of projects. In this section two of the projects closely related to the topic of this thesis project are highlighted.

2.2.2.1 The BlinkSight project

Vention Technologies has developed several development boards for the French company BlinkSight. BlinkSight is a company in the process of developing a chip that implements the wireless technology Ultra Wideband (UWB). The development boards act as a proof of concept for the chip. It is used by third-party developers as a reference design, both in hardware and the software written for this board.

BlinkSight currently is in the process of having a first batch of 10.000 chips manufactured, to be distributed to partners for testing purposes.

The BlinkSight project has given Vention Technologies experience with the low level design of a chip designed for localization and with the design of antennas for UWB radio signals.

2.2.2.2 The Focus project

The Focus project entails the development of a general purpose positioning system. Making use of Ultra Wideband, the system consists of anchors, tags and an access point. The anchors are fixed devices that are placed during setup. Localization happens in reference to these anchors.

The tags are the dynamic devices in the system that are to be tracked. The system supports the real-time tracking of five anchors at the same time, with a frequency of 30 Hz. The access point acts as a point of entry for the data generated by the system. All positional data from the tags are sent to the access point, which acts as a gateway between the system and the application using the positional data.

The system is able to perform real-time positioning of tags with a positional accuracy of 10 centimeters. It uses two-way ranging as a localization technique (see Section 3.2.1.2). The positioning is a result of localization based on radio signals, combined with the data of an IMU; a 9-degrees of freedom intertial measurement unit. The two data streams are fused together such that the IMU compensates for situations in which the positioning by radio signal is not able to perform optimally.

The product is set up as a general positioning system, but is developed with the intention to be used during concerts on stage. By tracking the artist, video and lighting effects can be created, based on the position of the artist.

The product resulting from the Focus project has been used during the lighting- and dance show 'Once Upon a Light' during the light festival *Glow* in Eindhoven. Due to the fact that this product is designed to be a general positioning system, with only a minor application specific part, the product has also been used in automated warehouses to guide robots, as a safety mechanism to prevent cranes traveling over humans and in the Virtual Reality gaming context.

The Focus project has brought Vention Technologies in contact with the entertainment industry. Setting up the technology at an event, working with other disciplines in the business and doing shows.

Chapter 3

Domain

This chapter describes the theory and technology of the application domain. First, the intended system is described, its requirements and a rationale for these requirements. Subsequently, the technological problems that have to be overcome are described.

3.1 The intended system

Intended is a system that allows for visitors of a concert to participate as an element in the light show. With every spectator at the concert wearing a wearable device with a colored LED, a large number of lights come together. As one thinks of each of these wearables as a single pixel, a large display can be created: a Human LED Display.

For this purpose the following system is proposed. All spectators will receive a light-emitting device to wear during the show. This wearable has one or more LED's embedded, able to light up in various colors. A central unit in the system acts as an access point for the display. Here, the image to be displayed on the Human LED Display is injected which is wirelessly communicated to the wearables.

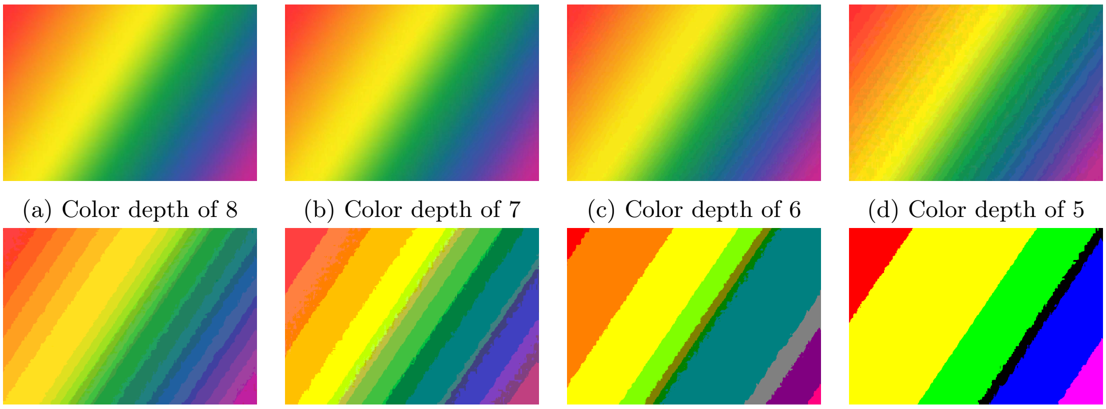
3.1.1 Requirements

Requirements have to be set on the number of wearables, resolution, color depth, frame rate, error in localization, and power consumption. These are set here.

The number of pixels is directly related to the number of wristbands, and with that, the number of spectators supported by the system. Each of the wristbands represent a pixel in the display. As this system is aimed to be used at stadium concerts, most capacities are covered when supporting up to 100.000 wristbands.

The resolution of a display is the number of distinct pixels in each dimension that can be displayed. The resolution of the screen is closely related to the amount of data that has to be transmitted to the wristbands, but also to the amount of computational power the wristbands should be equipped with. The wristband has to retrieve a single pixel from the video stream, to be able to know which color to emit. The higher resolution, the more computationally heavy encoding needs to be applied to be able to transmit this resolution. As an amount of wristbands of up to 100.000 has to be supported, it is not necessary to support a resolution of far over 100.000 pixels. As however the density of spectators is not constant (right in front of the stage there are more people crammed together than in the back of the venue), it is nice to have some more pixels. A resolution of 480 pixels wide and 360 pixels high gives 172.800 unique pixels. When this resolution is mapped to a stadium like the Phillips Stadion in Eindhoven, this corresponds to a pixel representing an area of 25 centimeters by 25 centimeters.

The color depth of a display is the amount of bits used to define each of the three color components (red, green and blue) of a single pixel. The most common way to represent a color



(a) Color depth of 8 (b) Color depth of 7 (c) Color depth of 6 (d) Color depth of 5

(e) Color depth of 4 (f) Color depth of 3 (g) Color depth of 2 (h) Color depth of 1

Figure 3.1: An image representing a rainbow with decreasing color depth

is to have an 8-bit value for each of the three color components. The combination of these three numbers represent one color. Three 8-bit numbers are able to represent 2ˆ24 (= 16.777.216) colors. When using fewer bits, fewer colors can be created. Fewer bits however also results in a smaller video stream which is beneficial for the bandwidth required and processing power needed. Reducing the color depth reduces the load on the system. In Figure 3.1 for a single image representing a scale of colors, the color depth is reduced for every subfigure. Visually, it is sufficient to support a color depth of 4 bits per color component, resulting in 12 bits for every pixel.

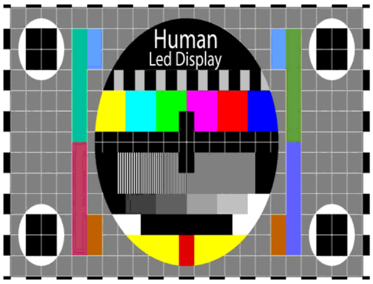
The frame rate of a video represents the frequency at which consecutive images (in this context called frames) appear on a display. As we are speaking about frames of 172.800 pixels, each represented by 12 bits, there is $\sim$ 260 kilo-byte of data to be transmitted for each frame. This however is when we send the raw frames one by one. There are optimizations possible by transmitting only change with respect to the previous frame, or video compression. A human mind is said to be able to see at around 30 frames per second. To fluently see a video this is the minimum frame rate. For simple animations, which are displayed on a huge screen, this frame rate is not necessary. A frame rate of 10 frames per second is sufficient which is the balance between bandwidth required and choppy animations.

Error in localization is the difference between the position measured by localization and the physical, real position. An error in localization manifests itself in pixels displaying an incorrect color. While a wristband should emit the color of the pixel mapped to its physical location, it displays the color of the pixel mapped to position determined by localization. The wristband is not displaying the correct color, but the color corresponding to a pixel *near* the location of the wristband. The larger error in localization, the 'fuzzier' the displayed image becomes. A bound has to be set on the error in localization to prevent the frame displayed to become too unclear. To determine this bound, a small experiment is done to simulate the effect of different bounds. In Figure 3.2a a test image is taken. In every following image the bound is increased. This means that for every pixel, not the correct color, is shown, but the color of a random pixel with a maximum distance (the bound) to its position. The distances used correspond to a situation in which the test image is mapped over the Phillips Stadium (the image then becomes 100 by 50 meters). Looking at Figure 3.2, it is sufficient allow a maximum positional error of 1.00 meter.

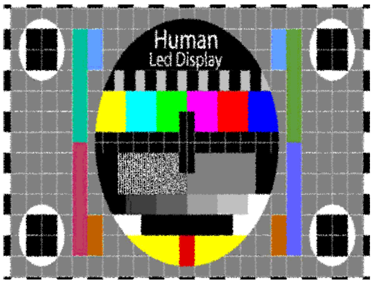
Lastly a bound has to be set on the power consumption of a wristband. At least a wristband has to be capable of operation during a full show. This means the wristband has to last at least three hours.

Summary As explained in section 3.1.1 the requirements of the system are

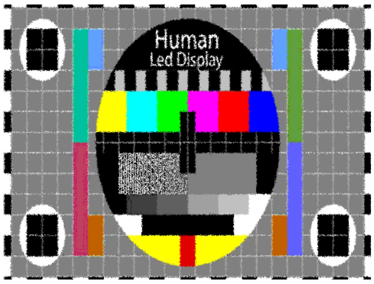
1. The system should support at least 100.000 wristbands.



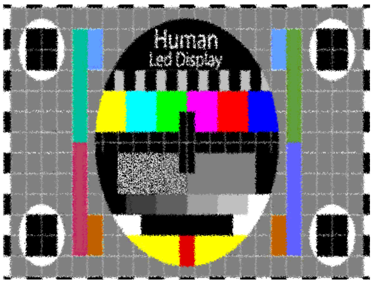
(a) 0.00m error



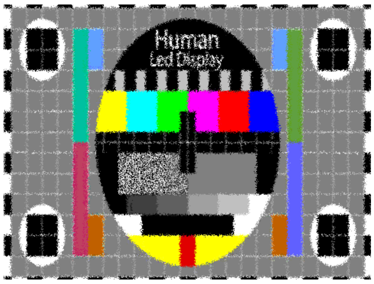
(b) 0.25m error



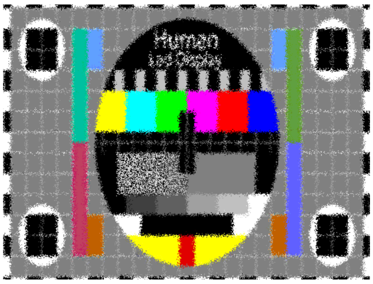
(c) 0.50m error



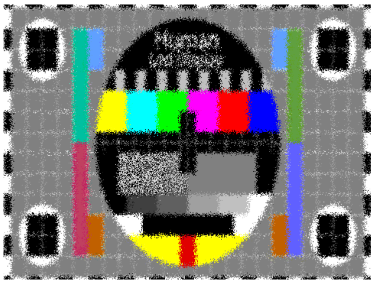
(d) 0.75m error



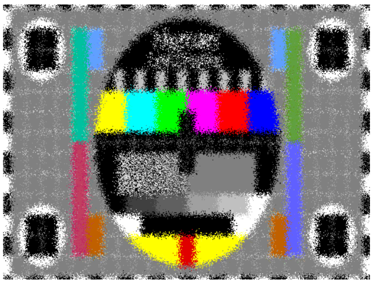
(e) 1.00m error



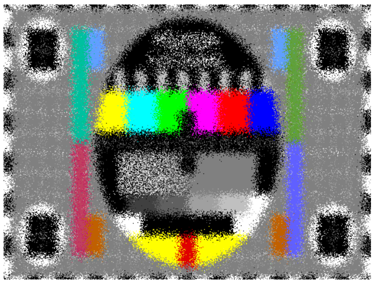
(f) 1.50m error



(g) 2.00m error



(h) 3.00m error



(i) 4.00m error

Figure 3.2: A test image with the amount of localization error variated.

2. A video with a resolution of at least 480 pixels wide and 320 pixels high should be supported.
3. A frame rate of at least 10 frames per second should be supported.
4. At least a color depth of 4 bits per color component (red, green and blue) should be supported.
5. Each wristband should be able to determine its own location within 1.00 meter.
6. The wristband should be able to operate at least three hours.

3.2 Problems

To be able for a wristband to determine which color light a wristband should emit, it has to know two things; the current frame of the video-stream and its physical location as to which pixel the wristband represents. Both pose a problem, explained in detail here.

3.2.1 Localization

For a wristband to be able to determine the color of the pixel it should emit, it should know which pixel to represent. As the image to be displayed is mapped over a physical area, the wristband has to know its own physical location. With this data, the wristband is able to look up the corresponding pixel in the frame to be displayed and emit its color.

In the field of localization it is common to refer to the object to be tracked as a 'tag'. Fixed entities which are used as a reference for the determined position are known as 'anchors'.

There are two ways for a wristband to know its position. One could hard-code this information into the tag, or the tag performs localization in which the tag determines its own position.

By programming each of the tags differently and beforehand telling the tag which pixel it should represent, all needed information is available. This however poses two problems; It requires extensive knowledge over the venue and it requires spectators not to move during the show. For seated venues, tags can be created for each seat. This tag can, be mapped to a position in the video-stream and the system will work. Also, because all spectators are seated, the position of each spectator is (mostly) fixed during the concert. This allows for setting up the system one time, after which it will work during the full show.

Concerts however are often not fully seated. For example in stadium concerts, the rings around the main field are seated, but the people on the main field are standing and walk around. In this setting it is not possible to know beforehand where each of the spectators is going to stand in the field, making setting up the system beforehand impossible.

To make the system support this use-case a more dynamic system is required. By periodically determining the position of a tag, relative to the origin of the video-stream, spectators are no longer bound to a single position. Spectators are allowed to walk around and still have their wearables represent the correct pixel relative to their current position. Also this allows for all tags having exactly the same firmware which is beneficial during the production and distribution process. The frequency at which localization has to be performed is yet to be determined. At most this will be at the same frequency as the frame rate of the video stream. Most likely this localization has to be performed less often as people generally don't walk a lot during concerts and this saves in bandwidth.

Several methods of localization are readily available: localization by signal strength, by time of flight, by angle of arrival, by fingerprinting or by mesh networking. Each are discussed here and are then weighed against each other in terms of scalability (in terms of amount of fixed anchors with respect to the number of tags supported), accuracy (the error between physical position and measured position), hardware required (in terms of cost price), setup required (the amount of system setup before an event) and its susceptibility to its surroundings (with respect to noise and changes in environment).

3.2.1.1 Signal Strength

The Received Signal Strength Indicator is a measure of the power of a received radio signal. This measure can be calculated for every received message. As radio waves propagate through the medium according to the physical inverse-square law, this measure can be mapped to physical distance between the transmitter and receiver. The intensity is inversely proportional to the square of the distance from the source [5].

By collecting several RSSI-values between transmitters (fixed anchors) and the receiver (the dynamic tag), the distances between the receiver and the transmitters can be mapped to the measured signal strength. Using these distances, by trilateration the position relative to these anchors can be determined.

The advantage of using this method is that no additional transmissions have to be made in order to do localization. With every message received, a distance is determined. This means that there is more RF-medium left to transmit data.

The disadvantage of this method is that it is highly unreliable. The RSSI is easily influenced by changing surroundings and conditions. The accuracy is significantly impacted by reflection and absorption from walls. This makes it hard to create one mapping between RSSI and distance for a wide variance of circumstances.

The RSSI measured is highly impacted by noise. In a setting like concerts, a lot of people come together, all wearing connected devices like smartphones. These smartphones interfere with other radio signals in the area.

Determining of distance between a tag and an anchor relies on the fact that there is a unique signal strength for every distance in between. Due to reflections of the radio signals, this might not necessarily be the case. A signal received in line of sight at a distance X might be the same as a signal received via a reflection at distance Y.

3.2.1.2 Time of Flight

The method of using Time of Flight to measure distances between nodes is by measuring the time between transmission on the one node and receiving on the other node: the time the message is actually flying through the air. For this method to be applicable it is necessary for both nodes to either have the same notion of time, or both nodes should measure relative to the same point.

When two nodes have the exact same notion of time (meaning two otherwise independent nodes are initially set to a reference time, and do not differ over time due to clock drift) the one node can transmit a message to the other, containing the time it is transmitted. The receiving node records the time it receives the message and subtracts the time of transmission which was encoded in the message. The resulting time is the so-called Time of Flight. As radio waves traverse the air with the speed of light, this time of flight can be converted to distance by multiplying with the speed of light. Determining for a single tag its distance to multiple anchors, allows for trilateration to determine its position.

The accuracy of localization when using Time of Flight is determined by the ability to accurately measure the time of transmission and the time of arrival. As the speed of light is 299.792.458 m/s, a radio wave covers 30 cm every nanosecond (one billionth of a second). This means that measurements should have a resolution of smaller than a nanosecond to get centimeter accuracy.

Two implementations using time of flight are two-way ranging and one-way ranging that both implement a different way of dealing with out-of-sync clocks.

Two-way ranging Two-way ranging is the process of an initiator sending a message and a responder sending a message back. The time of flight is calculated by measuring the timespan between the sending of the requesting message and the receiving of the response. As the responders needs some time to process the incoming message and generate a response message, this timespan consists of this time of processing (ToP) and twice the time of flight (from the initiator to the responder and from the responder back to the initiator); see Equation 3.1. The time of processing is calculated on the responding node before actually responding. This allows for embedding this timespan in the respond message. This way the tag has all the information it needs to calculate the time of flight of a message between the two nodes. This time of flight can then be converted to distance with the speed of light (see Equation 3.2).

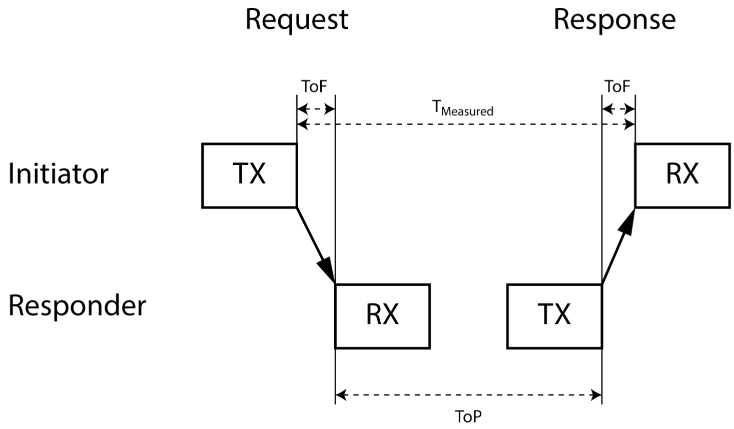


Figure 3.3: Schematic representation of the time of flight protocol.

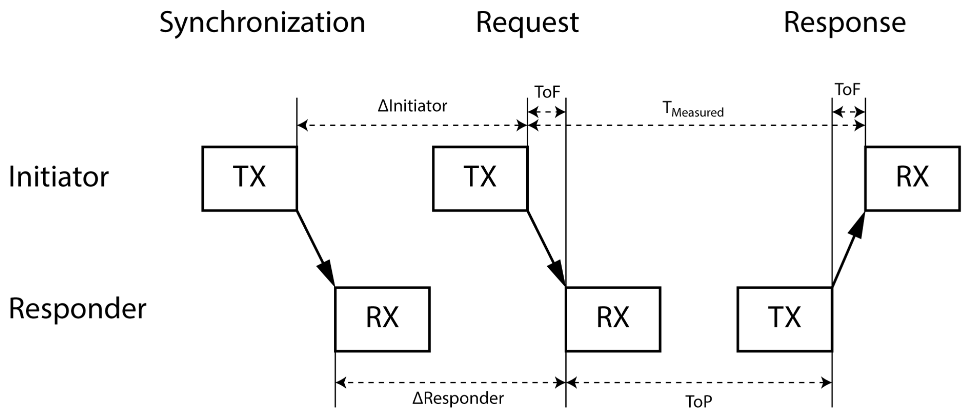


Figure 3.4: Schematic representation of the time of flight protocol with compensation for clock drift.

$$ToF = \frac{T_{Measured} - ToP}{2} \tag{3.1}$$

$$d = ToF * c \tag{3.2}$$

As stated earlier, we have to take into account differences in clockspeed between the two nodes that are ranging. Suppose a minor difference between the clocks on both nodes. This would invalidate the formula to calculate the time of flight, as the time between sending the request and receiving the response (measured in clock-ticks of the clock on the tag, $T_{Measured}$), is no longer comparable to the processing time of the responder (measured in clock-ticks of the clock on the responder, ToP). As both nodes have no information about the other's clock, it is not possible the compensate for this in the formula. To provide this information, an additional transmission is added to the protocol. Before the requesting message, a synchronization message is sent from the initiator to the responder [6]. Only after a predefined time delay ($\Delta Initiator$) the request message is sent. The anchor receives both synchronization and request message and records the timespan between receiving these ($\Delta Responder$). Both the initiator and the responder know what time delay is used, and the time of flight for both messages is equal. Any difference between the predefined time delay and the time stamp of the synchronization message subtracted from the requesting message, is a difference in clock speed. A compensation factor can be calculated and be used to determine a ToP that is comparable (See Equation 3.3).

$$ToP' = ToP + (ToP * \frac{\Delta Initiator - \Delta Responder}{\Delta Initiator}) \tag{3.3}$$

Support for the tracking of multiple tags in the same system is possible with this protocol, but comes at a cost. With tags as the initiator, the tags themselves initiate ranging. The anchors only act in response to these message. Supporting multiple tags can be done by giving each tag a timeslot in which it is allowed to range with the anchors. By this time division multiplexing, transmissions are undisturbed by other nodes and every tag is able to perform its ranging. It does however decreases the amount of ranging samples per time unit. Instead of a single tag constantly ranging, time has to be divided over the tags in the system.

One-way ranging Where in two-way ranging the problem of having a notion of time is solved by only taking into account timespans, in one-way ranging the clocks are synchronized to create one global instance of time. This allows for sending only one message, from the tag to the anchors. All anchors (in range) receive this message and store the timestamp of reception. As this timestamp can be compared to timestamps of other anchors, the time *difference* of arrival (TDOA) can be determined (see Figure 3.5). This TDOA can be converted to a position with a method called multilateration [7]. It makes use of the principle that the anchor that received the message first, is the anchor closest to the tag.

As only one message has to be sent for each tag to determine its position, more tags can be deployed in the same system compared to two-way ranging. The number of tags is limited by time division multiplexing that has to be implemented to prevent tags from broadcasting a message at the same time. This does require some form of clock synchronization, but this is only with the purpose of not interfering with each other. There is no need for high accuracy. It is also possible to implement an ALOHA protocol [8]. This basically allows tags to transmit at will and conform to a back-off period when a collision is detected.

The accuracy of a system with this architecture is determined by the precision of the synchronization of the anchors. Both the frequency of the clocks and the initial value have to be equalized for all anchors to create a global time.

Note that in one-way ranging, the tag is broadcasting a message with the anchors continuously receiving. This results in the calculated position of the tag at the side of the anchors. In the Human LED Display, it is only interesting for a wristband (the tag) to know its own position, not for a central system (the anchors) to know the position of all the wristbands. For the Human LED Display it is therefore more interesting to turn the traditional one-way ranging and multilateration protocol around and let the anchors broadcast periodically and the tags continuously receive. As there is no communication back from the wristbands, and all processing is done on the wristband itself, this architecture allows for a theoretical infinite amount of wristbands in the system. Reversing the traditional one-way ranging protocol introduces several issues that have to taken into account. See section 3.3.1 for a more detailed description.

3.2.1.3 Angle of arrival

A different way of determining position is angular based. By determining the angle between the one and the other node, a direction can be determined where the one node is located relative to the other. By determining this direction, relative to multiple nodes, a position can be calculated.

The way this is done is in hardware rather than in software. There are receiving nodes and broadcasting nodes. Receiving nodes have to be equipped with not one receiving antenna, but an array of receiving antennas. When a message is transmitted by the broadcasting node, this

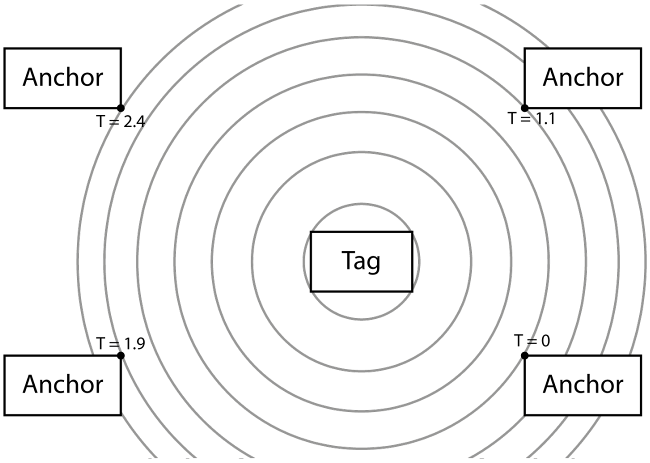


Figure 3.5: Time difference of arrival from a single message broadcasted from the tag.

message is received by all of the antennas on the receiving node. Dependent on the angle between the antenna array and the broadcasting node, there is a difference in time between receiving the same message on the one antenna and on the other. As the antenna array is fixed in hardware, this difference in time can be converted to an angle using the length of the electronic trace between the chip and the antenna. Having two or more angles, the positions of the receiving nodes and the orientation of these receiving nodes, the position of the broadcasting node can be calculated using triangulation.

Note that the information of the angle is located at each of the receiving nodes. This means that to be able to perform triangulation, all information has to be transferred to a central node in the system. Angle of arrival has to use one broadcasted message from the broadcasting node to the receiving nodes, and each of the receiving nodes have to transmit their calculated angle to a central node.

The accuracy of angle measurements is dependent on the accuracy of measuring the difference in receiving times between the antennas. As the distance between two antennas in the array is usually no more than 10 centimeters, the difference in time is sub-nanoseconds.

When combining angle of arrival and two-way ranging, one is able to determine the position of a tag, relative to a single anchor. As the angle of arrival method is able to determine the angle between the anchor and the tag, and two-way ranging is able to determine the distance in between, all the information needed is available.

3.2.1.4 Range-less localization

Two-way ranging and angle of arrival are both ranging techniques. They both measure some unit relative to fixed anchors and determine their position based on these measurements. Two methods of localization that perform localization using different kind of measurements are fingerprinting and mesh networking.

Fingerprinting Fingerprinting is the act of mapping out the values of a sensor, over the location in which you want to do localization [9][5]. By having a sensor measure a unique value for every location, measuring this same value again later suggests one is at that same location again. This means that fingerprinting is highly susceptible to changes in the environment. When an area is mapped, and the environment changes (different weather, night and day, objects that are placed in the area), localization might point to the wrong position.

Fingerprinting can be done using radio signals by for example using RSSI values. The anchors transmit a message, the tag receives this message from multiple anchors, measures the respective RSSI values and looks for a spot on the map where this combination of RSSI values has occurred

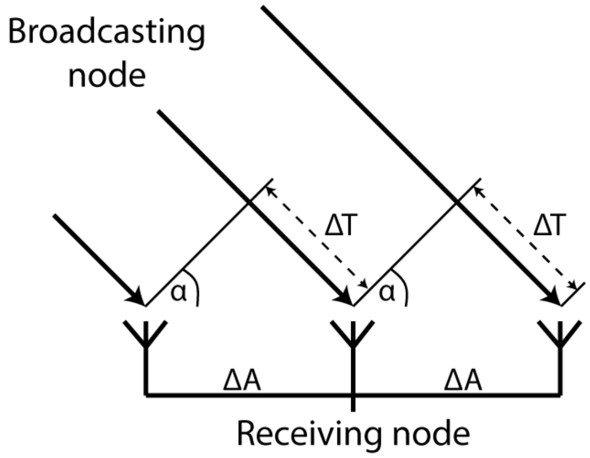


Figure 3.6: A transmission arrives at multiple time stamps at a single receiving node.

before. Note that this is different from the localization method based on RSSI discussed above as there the RSSI values were converted to distances which then are used by trilateration. Here the RSSI values are taken as-is. Another example of sensor that can be used is the magnetometer of a mobile smart phone. In an application built by IndoorAtlas [10], the magnetic field of the earth is mapped and is used for localization.

Mesh networking Mesh networking uses the presence of nodes and the absence of others to determine its own position. By setting up the system such that each node maintains neighbor lists, the unit knows in which vicinity it is located.

The system would act as a large graph.

Obviously the operation of the system is highly dependent on the distribution of the tags. A single isolated tag is unable to determine a position.

A system using mesh networking is able to scale with the area covered. By increasing the tracking area, only the neighbor lists of the tags near the edge of the graph will increase. Other nodes have no notion of this change.

As nodes only are in contact with its surrounding nodes, data to be inserted into the system has to travel through a multitude of nodes to arrive at nodes far from the source. This results in a latency that increases as the route from source to destination becomes longer.

An advantage of this method is the fact that neighbors are physically very close (within 10 meters). This allows for transmitting messages with a low transmitting power. This is beneficial to the energy consumption of the individual nodes.

A non-trivial task is to generate a position from a list of neighbors for each tag: Topological data has to be transformed to geographical data. This is an entire problem on its own and does not fall within the scope of this research.

3.2.1.5 Applicability of methods to the application

For each of the methods discussed above, the question has to be asked whether they are applicable to the system at hand. An overview of each method's strong and weak sides are displayed in Table 3.1. Each method is shortly discussed.

Signal Strength Localization using signal strength is highly impacted by noise. As the system is deployed during concerts, where many people come together, all carrying a mobile device, the environment is noisy. This makes localization via RSSI not suitable.

	Scalability	Accuracy	Hardware required	Setup required	Susceptible to surroundings
Signal Strength	+	-	0	−	-
Two-way ranging	-	+	0	0	+
One-way ranging	+	+	0	0	+
Angle of Arrival	-	+	−	0	+
Fingerprinting	+	-	+	−	-
Mesh Networking	+	-	0	0	-

Table 3.1: Applicability of each of the localization methods to the application in question

Two-way ranging Two-way ranging would yield an accuracy better than is needed for the Human LED Display. The scalability however is an issue. Because of the fact that one has to implement time division multiplexing, more wristbands in the system would result in less time for a wristband to perform ranging.

One-way ranging Reversed one-way ranging is the most promising candidate for the Human LED Display. It is scalable, gives the accuracy needed, does not require specialized hardware other than a radio antenna, and is not susceptible to changes in its surroundings.

Angle of Arrival Using the method of determining the angle of arrival could be implemented in two ways. Either the wristband would become the broadcasting node with fixed anchors as receiving nodes, or vice versa. With the wristband being the broadcasting node, time division multiplexing would have to be implemented to prevent wristbands to broadcast at the same time. This makes the system not scalable. Making the wristband the receiving node with the fixed anchors as the broadcasting nodes would require the wristbands to have the antenna array. This would both make the wristband costly and large in form factor; two qualities not desirable.

Fingerprinting Using fingerprinting would be a cost-efficient way to implement localization as many sensors can be used. It does however require a lengthy setup process as the complete area to be tracked has to be mapped. There is also the risk of the mapped area to change with the presence of the audience.

Mesh Networking Mesh networking makes use of its neighbors to determine its own position. This makes the method very scalable. It is however not trivial to get from a relational graph to positional data in an system that is not centrally managed. This is not in the scope of this research.

3.2.2 Video Distribution

The second problem to be overcome in the creation of the Human LED Display is the distribution of the video stream. For the wristbands to, together, act as a display, each wristband has to know which color to emit. This color depends on the video stream and time. For the wristband to extract this color, the video has to be available to the wristband. This can happen in two ways, either the video is readily available on the wristband or the video is streamed, in real time, towards the wristband.

3.2.2.1 Preloading

Having the video readily available on the device, is easier than having to send the video towards the device. No transmission and receiving has to be taken into account and the full available wireless medium can be used to perform localization. It also results in robustness in the system as it is a variable less: one thing that is fixed and less likely to go wrong. This however comes at a heavy cost.

The system is completely stripped of flexibility. Wristband have to be be preloaded with content before the event, and are unique for each event. This poses logistical difficulties. Content for the display has to be delivered well before the event, and wristbands have to be manufactured for each event specifically making the wristbands not recyclable for multiple events. This is not ideal.

Another issue with this method is concerning storage. With using preloading of the video, the complete video should fit in storage on every wristband. This would add a significant storage requirement to the wristband which would not be beneficial to the cost.

3.2.2.2 Streaming

By streaming the video to the device in real time, the system is flexible. It gives full control over the image to the video operator. Graphics are often live-rendered during concerts. Streaming the data to the Human LED Display in real time allows for this as well.

Streaming suffers from a trade-off between data rate (the amount of data needed to be transmitted) and computation power. The more a video is encoded, the more computational power is needed for this compression.

Video encoding When we have a video stream, a raw video stream of 10 frames per second with a resolution of 480 by 320 pixels, 20.736.000 bits are transmitted every second (= 480 pixels ∗ 320 pixels ∗ 12 bit per pixel ∗ 10 frames per second). It is however not necessary to transmit every individual frame. There are general "rules" in video that allows for reduction of data. For example, when in one frame the grass is green, it is very likely that in the next frame a piece of green grass is visible right around that same area.

A way to do this by for example making use of the H.264 codec. It makes use of reference frames (so-called I-Frames) which consists out of the encoded data of a single frame. Other frames use this I-Frame as a reference.

This reference frame is divided into 8 pixel by 8 pixel blocks (called macro blocks). On each macro block a Discrete Cosine Transform is executed. This is a mathematical algorithm which transforms spatial coordinates into frequency variation, which are easy to encode and transmit. Next the actual compression takes place. It 'selects' which pixels are significant to the human eye and which are not. The important pixels are kept while the others are discarded. This is done using a quantization matrix which is the essence of the codec. After this step the blocks have to be converted to a stream. Here additional optimizations are possible by run length encoding (when there are five zeros in a row, do not write five zeros but write a zero and the amount of times this zero is to be repeated)[11] and Huffman encoding [12] (looking for repeating sequences of bits and map these sequences to shorter sequences).

Once we have this reference frame, intermediate frames are able to use the fact that a lot of information is the same. There are P-Frames that look back at the previous frame and look for differences. There are also B-Frames that on top of looking backwards, also look at the next frame. A sequence of I-Frames, P-Frames and B-Frames are called a Group of Pictures.

Requirements Looking at the application at hand, the video encoding has to both be computationally light, and result in a low data rate stream. When heavy compression is implemented, the video stream becomes small and a larger video can be transmitted (larger in resolution, more bits per color, higher frame rate). It however requires heavier hardware on the side of the wristband to be able to decode. Heavier hardware means a larger energy consumption and a higher cost price which are both not desirable.

On top of that one has to take into account the available bandwidth. The hardware that is going to be used (see Section 5.2) is equipped with an Ultra Wide-band chip with a maximum bandwidth of 6.8 Mb/s.

3.3 Possible solutions

As stated above, for the application in question, there are two non-trivial parts. One the one hand there is localization; determining which pixel the wristband should represent. On the other hand there is the question of how the video stream is going to be delivered to the wristband.

3.3.1 Reversed one-way ranging

As briefly discussed in Section 3.2.1.2, a reversed implementation of one-way ranging promises to meet all requirements set for the Human LED Display. In traditional one-way ranging the anchors are continuously listening for messages and the tags send 'blink' messages. Reversing the protocol means having the tags listen and the anchors periodically sending blink messages. This leaves the result of the protocol (the position of the tag) at the correct side of the architecture - on the tag.

The protocol is able to perform localization by measuring the time difference of arrival. When the anchors would all send a message at the same time, the tag receives all these message at different timestamps, correlated to the distance between the anchor and the tag. When an anchor is further away, the propagation time of the message is longer and the message will arrive at the tag later.

Reversing the protocol leaves the mathematics of turning time difference into positional data the same. The same data is retrieved and can be directly inputted into the multilateration calculations.

3.3.1.1 Clock synchronization

To be able to draw conclusions from the differences in time of reception in the tag, it is required to know when these message are sent. As the message origin from different sources (the different anchors), a global time has to be created. Only with a global time the different timestamps can be compared

If each of the anchors were to use its own free-running clock then the anchors would drift from synchronization very quickly. Even if a high accuracy crystal oscillator was used, that is compensated for changes in temperature, with a tight frequency tolerance (for example 1 ppm, meaning that after 1.000.000 million clock ticks, between two clocks there might be a deviation of one tick), the local times of the anchors would drift apart very quickly. A 1 ppm error results in a nanosecond drift every interval of a millisecond. As every nanosecond corresponds to 30 cm, this is well outside the limit required. It is therefore imperative to have clock synchronization with an extremely high accuracy.

Anchors In order to have a notion of a global time, clock synchronization has to be implemented. In a wired system this can be done in two ways: in a purely distributed system having devices negotiate over a global clock, or by having a central unit in the system define the clock which is distributed to all other devices. Having a wireless system creates additional problems with possible colliding synchronization packets and additional latencies [13]. The Human LED Display will be deployed during events like festivals and concerts. These circumstances allow for a setup-process of the system. On top of that during these situations lots of stage-technology has to be set up. Most of these technologies rely on wired communication for robustness. It is therefore no problem for the anchors of the Human LED Display to be wired as well. Because of this robustness, in this research only wired synchronization will be discussed.

Wired clock synchronization by having units negotiate over a global clock is a problem for which many different solutions are made. Berkeley algorithm [14][15] for example makes use of a master node in the system which tries to estimate the average clock of all units the system. It then distributes this clock. By periodically averaging and distributing, nodes converge to a synchronized system.

Wired clock synchronization by having a central unit dictate the clock of all units in the system is straight forward. A single unit in the system generates a clock signal, which is distributed by wire to all nodes in the system, which adopt this clock.

This makes each unit have a clock with the same frequency, but not yet the same notion of time. For this the offset of the clock has to be equal as well. Equalizing this can be done with a synchronization signal. A control signal can be distributed to all nodes, having each of these nodes reset the value of the clock at time of arrival of this signal. This leaves only one offset between the clock generating unit and each of the anchors: the propagation delay of the signals over the cable. This however is directly proportional to the length of cable between the units and can be compensated for [16].

As the architecture of the Human LED Display defines an access point as a central node in the system, with all anchors connected by wire to distribute video, this access point can also act as a clock generating unit. By having the access point as a master unit which distributes its clock to all anchors, a synchronized system is created.

Tags When the anchors are synchronized, messages can be send to the tag at known timestamps. To determine the difference between reception of messages however, we also have to make sure that the clock of the tag is synchronized with the clock of the anchors. Here only an equal frequency of clocks is important. A different time bias is irrelevant as the algorithm only uses time spans as opposed to timestamps.

To synchronize this clock frequency we make use of the periodic transmission of the anchors. Every anchor transmits its blink message with a predefined frequency. Assuming that blink messages are transmitted fast enough, such that between two blink messages the tag has not (or barely) moved, the time span between transmission is equal to the time span between reception. When this is not the case, a correction can be applied on the side of the tag to straighten this out, just as described in Section 3.2.1.2 for two-way ranging.

3.3.1.2 Multilateration

Multilateration is the process of converting a set of time difference of arrivals to a position. In two way ranging the *distance* between an anchor and a tag is determined. Here, with the known position of the anchor, one knows that the tag has to be located somewhere on the surface of a sphere around the anchor with as radius the determined distance. With one-way ranging the *difference* in time of flight is known between two anchors (acting as broadcasting nodes). This results in knowing that the tag (acting as the receiving node) is somewhere on the surface of one of the sides of a two-sheeted hyperboloid with as foci the two anchors (see Figure 3.7). With multiple pairs of anchors, each having a hyperboloid, the position of the tag can be calculated by taking the crossing point of the hyperboloids.

Solving for a linear problem Although calculating the crossing point of multiple hyperboloids is a non-linear problem, by turning it into a linear problem, the result can be approximated [17][18]. This linearization makes the calculation less computationally heavy, which makes the calculation more suitable for small embedded processors as in this application. This linearization does however require 4 anchors to have sent a blink message to the tag. The calculation needs the difference between a single anchor to three different anchors to be able to calculate a position. This linearization does not affect accuracy of the calculation.

We define a matrix A and a vector b:

$$\overrightarrow{a}_{ijc} = 2(v(t_j - t_c)(\overrightarrow{p}_i - \overrightarrow{p}_c) - v(t_i - t_c)(\overrightarrow{p}_j - \overrightarrow{p}_c)) \in \mathbb{R}^3, \tag{3.4}$$

$$\begin{aligned} b_{ijc} = 2(v(t_i - t_c)(v^2(t_j - t_c)^2 - \overrightarrow{p}_j^T - \overrightarrow{p}_j) \\ +(v(t_i - t_c)(-v(t_j - t_c))\overrightarrow{p}_c^T - \overrightarrow{p}_c \\ +v(t_j - t_c)(\overrightarrow{p}_i^T \overrightarrow{p}_i - v^2(t_i - t_c)^2) \in \mathbb{R}, \end{aligned} \tag{3.5}$$

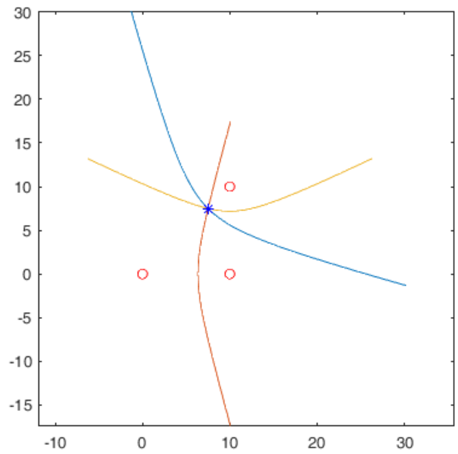


Figure 3.7: A 2d setup with three anchors and a tag. The hyperbola of differences between the anchors cross at the location of the tag.

with c the anchor that has the shortest distance to the tag (the smallest time of flight), i and j two unique other anchors, t_i the time at which the blink message from anchor i arrived at the tag, and $\overrightarrow{p}_i$ the position of anchor i.

This can be expressed as

$$Ax = b, \tag{3.6}$$

where each pair i,j creates the matrix A and vector b defined by $b_{ijc} \in b \in \mathbb{R}^3$ and $\overrightarrow{a}_{ijc} \in A \in \mathbb{R}^{3*3}$ such that $\overrightarrow{a}^T_{ijc}$ are the rows of A. This can be solved by computing the inverse of A such that

$$\hat{x} = A^{-1}b. \tag{3.7}$$

3.3.2 Data-stream optimization and video compression

The application in question is very specific. It is an application where both positioning and data streams have to be transmitted over the same medium. It might be beneficial to combine these streams and let the one make use of the other. For example in the video stream there is usage of current time stamps. This is necessary (with a far greater precision) for localization as well.

A single wristband represents one single pixel of the video. Optimally a video compression method would be used in which a full frame is compressed on the side of the access point, and only a single pixel is decompressed at the side of the wristband. This way the least amount of computation is needed in the wristband.

This video compression is also needed to reduce the bandwidth required in the system. A higher compression rate allows for less data to be streamed for each frame.

Although video compression by making use the H.264 codec does not allow for the decompression of one single pixel, it does allow for decompression of one single block of pixels. This macro block of 8 pixels by 8 pixels is significantly smaller than having to decompress the complete frame to be able to get the color of a single pixel.

Chapter 4

Research Questions

The challenges in this thesis revolves around two main subjects: the localization of a large amount of mobile devices, and the wireless transmission of large amounts of data to those same devices. Also the combination of these two poses a challenge. This is results in three corresponding research questions:

4.1 Localization

How would one set up a scalable system in which a significant amount (100.000) of nodes is able to perform localization?

4.2 Video Distribution

How would one set up a system in which a device is able to extract the color of a single pixel from a video stream, with the least amount of computational power required?

4.3 Combining Localization and Video Distribution

How would one set up a system in which a large quantity of data is required to be transmitted, next to controlling data (such as messages needed for localization)?

Chapter 5

Project Plan

5.1 System overview

The proposed system consists of a single access point, a limited amount of anchors, and a large quantity of wristbands (tags), as seen in Figure 5.1. The system allows for a video stream to be displayed with wristbands as its pixels.

There is a single unit called an access point. This is a node in which the video stream is inserted into the system. It is in direct connection with all anchors by wire. The access point is the master node in the system. It generates the clock to which all anchors are synchronized and distributes the video stream to all anchors.

The anchors are placed at known, fixed locations. The number of anchors needed at a venue is dependent on the size of the venue and the range of the anchors. At least four anchors should be present in every system as this is the number a wristband at least needs to perform multilateration. Anchors are allowed to have a large power consumption and to have computationally powerful hardware, allowing computational demanding software. Anchors have to be set up before the event starts. Anchors transmit data such that wristbands are able to determine their position, and the complete video stream.

Wristbands are to be handed out to spectators and should be considered as one-time use items. The wristbands are small in energy consumption, cost and form factor. They are powered by a small battery that allows for several hours of operation. To ensure scalability, wristbands determine for themselves where they are located. Each wristband decodes the videostream that is transmitted by the anchors and extracts the correct pixel color to display. This way the amount of wristbands is theoretically unbounded.

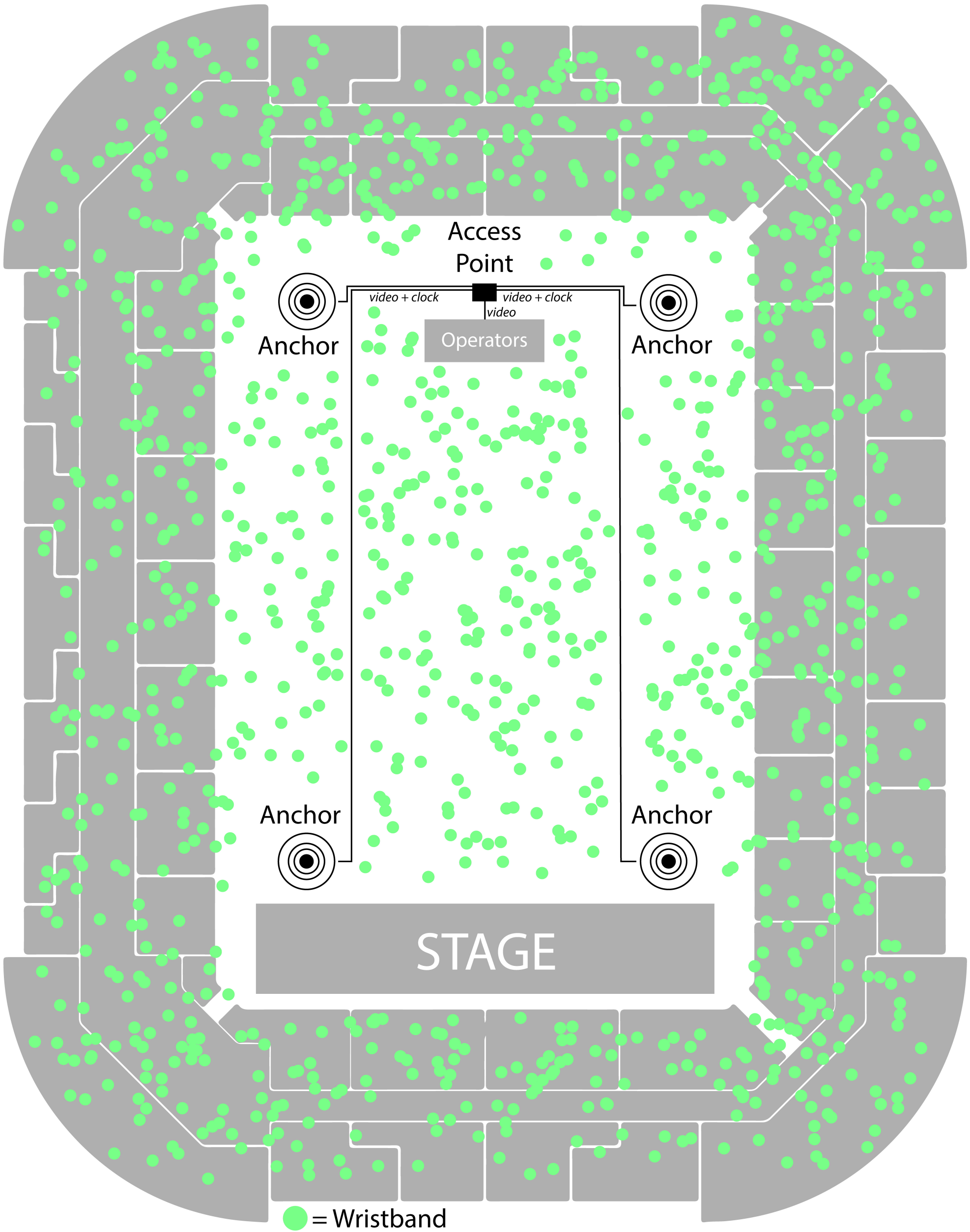


Figure 5.1: Schematic representation of the system as deployed in the Phillips Stadion.

5.2 Implementation and deliverables

For development and testing, hardware to emulate an access point, anchors, and wristbands, will be provided by Vention Technologies. This hardware is for each unit the same and is equipped with a microprocessor designed by NXP (LPC 11u37) [19], and an Ultra Wide-Band RF module build by Decawave (DWM1000) [20]. The PCB (as seen in Figure 5.2) also has a RGB LED to display colors, can be powered by either battery or micro USB port and has a software configurable button. An IMU (a 9-degrees of freedom inertial sensor) [21] is available as well on the board. This IMU, however, is for the application at hand less interesting as it would be too costly to equip each wristband with this chip.

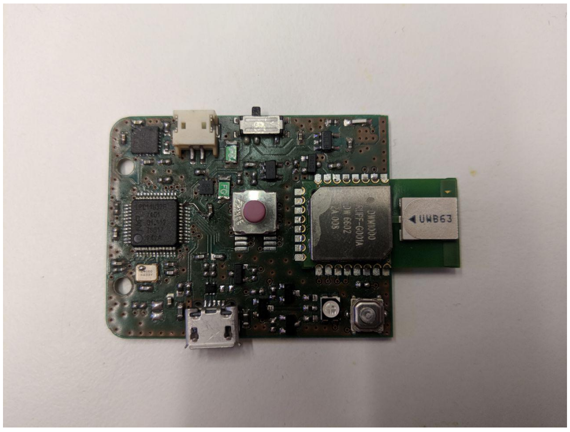


Figure 5.2: The hardware available to be used.

This hardware should be capable of fulfilling all requirements set for this application in Section 3.1.1. It is however not optimal. For a full scale deployment of the system, specialized hardware has to be created to take into account cost price and form factor. Since this hardware isn't application specific, it is not possible to do accurate measurements of power consumption. This is why the requirement set in Section 3.1.1 stating that the wristband should be capable of three hours operation, cannot be verified and will not be considered further in this research.

The deliverables for this project are

1 wristband

1 access point

4 anchors

Together these form a system which should fulfil the requirements as set in Section 3.1.1 and act as a proof of concept.

5.3 Verification

At the end of the thesis project a working prototype system should be presented. This system should consist of at least four anchors and one tag. The system has to fulfill all requirements as set in section 3.1.1.

Localization accuracy is to be verified in two ways. One covers static positions of the tag, while the other is moving.

1. A tag is placed somewhere in the covered area. The tag performs localization more than a thousand times and logs the measured location. Localization is accurate enough when 95% (two sigma in a normal distribution) of the measured positions are closer than one meter to the physical location of the tag (Requirement 5 in Section 3.1.1).

2. A tag is moved though the covered area in a repeated way. This for example by having a toy train setup, place the tag on the train and let the train continuously run in circles. The tag performs localization and logs the measured location and the actual physical position it is (where the train is on the track). Localization is accurate enough when 95% (two sigma in a normal distribution) of the measured positions are closer than one meter to the physical location of the tag (Requirement 5 in Section 3.1.1).

The capability of a wristband to display a pixel of a video can be verified by hard-coding a position of the wristband in the video into the tag. This way video reception and processing can be tested independently of localization. Transmitting a monochrome color that changes over time as a video towards the wristband, should have the wristband light up with the colors in the video, independent of the position that is coded into the tag.

Data-stream performance is to be verified by setting up the complete system (with both video distribution and localization active) and check requirements 2, 3, and 4 as stated in Section 3.1.1. As the data-stream performance covers both the messages needed by localization and the transmission of the video, this cannot be tested individually. The system has to be tested with multiple anchors in play. This because one has to take into account that anchors are not allowed to transmit data over the same medium at the same time. Some form of multiplexing will have to be implemented.

Scalability, related to requirement 1 in Section 3.1.1, is an important part of the functionality of the end-product. It is however not feasible to have a 100.000 wristbands produced and test the system with all devices at the same time. This is why scalability is to be proven by the system architecture.

5.4 Risks

In every projects there are certain risks one has to take into account during planning and preparation. These risks do not pose a problem if a proper protocol of handling is in place.

Time constraint The rules of carrying out a thesis project state that the time spent on the project is allowed to extend to 9 months (as opposed to the planned 6 months) without any problem. This covers risks of falling ill and other minor delays.

Technical In technical development projects there is always the chance of hitting roadblocks and having to deal with unforeseen circumstances. It might for instance not be technically possible to deliver a system that fulfills the requirements that are set. If this is the case, an effort will be made to deliver a system that fulfill as many requirements as possible. Also a detailed analysis will be delivered as to why and how this requirement was not met.

Another thing one has to take into account is the knowledge needed to carry out such a technical project. This project deals with embedded systems, wireless communication, localization and video processings, which all on their own are challenging subjects. It is key to have experts on all these subjects available such that when having questions you can ask them instead of letting these questions block the progress of the project. Knowledge on all these subjects is readily available within Vention Technologies. Would it however be the case that more specific questions arise, one can ask students, professors or researchers at the university.

Project organization As the nature of this project is concerning the combination of research and product development, it might be the case that during the project, new ideas arise. This might lead to a completely different system architecture and completely different requirements. This is difficult to take into account when having to plan ahead. To cover this, it is key to really put thought into setting the requirements and discuss these at length with the client. This way both client and developer can sign of on the requirements and both know what is going to be created.

On top of that it is important to have weekly meetings such that possible changes, problems or issues can be handled immediately and the project can be steered in the desired direction.

5.5 Planning

The thesis project will take 6 months (= 26 weeks) and will start after approval of this feasibility study. First focus will be put on localization, after which data stream optimizations will be focused on. In Figure 5.3 a preliminary planning of the project is visible.

Week	**What**
	Localization
0 - 4	Implementing clock synchronization
5 - 6	Testing accuracy of clock synchronization
5 - 6	Documenting clock synchronization
7 - 8	Implementing multilateration
9	Documenting multilateration
10 - 11	Testing positioning system (both clock synchronization and multilateration)
10 - 11	Documenting positioning
	Data stream optimization
12 - 13	Research about possible transcoding methods
14	Implementing encoder
15	Implementing decoder
14 - 16	Documenting transcoding methods
17 - 18	Combining video and localization
19	Performance testing
20	Documenting stream merging
20 - 22	Performance testing system
23	Writing Conclusion
24 - 26	Finishing report

Figure 5.3: A global, preliminary planning.

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