Bluetooth Indoor Localization System

Gunter FISCHER[1], Burkhart DIETRICH[1], and Frank WINKLER[2]

[1] IHP – Innovations for High Performance Microelectronics, Germany,
e-mail: (gfischer, dietrich)@ihp-microelectronics.com

[2] Humboldt University Berlin, Germany, e-mail: fwinkler@informatik.hu-berlin.de

Abstract - **We present a Bluetooth indoor localization system, which is intended to have an accuracy of ±1 meter. The major advantage compared to all disclosed systems is the ability to locate any mobile Bluetooth device without additional hardware in the mobile and without any changes in its software. The basic idea of the system is the measurement of time differences of arrival of a signal sent by the mobile to stationary installed base stations. We show first measurement results achieved with a simplified demonstration setup showing meter position accuracy. The demonstration setup consists of a moving transmitter and two stationary time measurement stations including a receiver, a correlation IC and a microcontroller.**

1 Introduction

Localization systems with an accuracy better than ±1 meter are the key enabler for providing position-specific information on mobile devices in buildings and halls. Such location-aware services could be the guidance in complex facilities, finding the location of particular persons or objects (for instance in case of emergency), and tracking and watching of active badges or tags (for instance in high-security areas, airports, storage halls). For a fast and strong market penetration such a service should be embedded in a widely spread mobile system. Cellular phone systems (GSM etc.) and GPS do not provide the required accuracy or indoor capability, respectively. The Bluetooth standard [1] seems to allow this together with the appropriate indoor localization system, which will be presented here. Previously known indoor systems use channel properties like the received signal strength or bit error rate to estimate the location of a mobile [2], [3], [4], [5], or take advantage from other non-radio systems like IrDA [6]. Our system measures the RF signal propagation time with nanosecond accuracy employing a dedicated correlation chip. While additional hardware is required on the base stations, on the mobiles (to be localized) no additional hardware is necessary. This allows to localize any Bluetooth devices, which is a major advantage compared to existing systems [7] requiring dedicated hardware for the mobile, too. In addition, the employment of a fast correlation device enables the time of arrival measurement within one Bluetooth data frame producing only little additional radio traffic. Therefore, the entire localization procedure could be easily introduced in existing applications.

In the next section we will introduce the principle of the applied time measurement for the localization, followed by section 3, which contains some considerations about indoor channel propagation. Section 4 gives an overview about the entire system architecture, while Section 5 describes the implemented correlation IC in more detail. Finally, first measurement results together with a description of the demonstration setup will be presented in Section 6.

2 Principles of Time Measurement

The localization is based on trilateration, often named incorrectly triangulation. It measures the distance between a point of unknown position (mobile M) and three points at known positions (receivers Z_i). In practice, the propagation time of an electromagnetic wave is measured and the distance is calculated by multiplication with the velocity of light. Measuring propagation times requires the knowledge of the starting time at the transmitter and the time of arrival (TOA) at the receiver obliging their clocks to be synchronized. It is possible to omit the start time measurement introducing an additional receiver at a known position and measuring the time differences of arrival (TDOA) at the four receivers of a signal transmitted by the mobile terminal. Note that one receiver is off the plane of the others (Fig. 1). Furthermore, renouncing the time synchronization between the receivers the following scheme called differential time difference of arrival (DTDOA) might be used: The master station Z_0 starts the procedure by transmitting a signal that will be received by the mobile (M) and the three other receivers (Z_i). Once the signal is detected at the receivers, they start an internal counter running on their clocks (Phase 1). Then, the mobile terminal (M) transmits a signal stopping the receiver counters (Phase 2). Taking into account the known distances (or propagation delays) between the master station and the receivers, this scheme allows the calculation of the unknown position from the measured time differences at each of the receivers. The clocks in the receivers can run independently without the need of an overall synchronization. The only remaining source of error is the matching of the independently running clocks of the receivers during the measurement.

In Fig. 1 the scheme for a DTDOA system is drawn. The mobile terminal M is the point of unknown position; the time measuring stations $Z_0 \ldots Z_3$ are the receivers located at known positions. The master station Z_0 itself is a time measuring station. The controller C is a host PC, which initiates the measurement, collects the individual time differences, and finally calculates the position. The connections between the controller and the measurement stations are for communication purposes only (not for synchronization) and could be either wired or wireless.

After establishing a piconet with all involved components including the mobile terminal, the master Z_0 initiates the measurement procedure by transmitting the echo-request command at the time t_{start}. This signal arrives after the individual propagation delay $t_{Z_0 Z_i}$ at the i-th time measuring station Z_i at the time t_{1Z_i} (Phase 1):

$$t_{1Z_i} = t_{start} + t_{offset_i} + t_{Z_0 Z_i} \quad . \tag{1}$$

Since the clocks of the base stations are not synchronized, t_{offset_i} represents an individual unknown offset of the clock in each base station. Afterwards, the mobile terminal M transmits the echo-response signal with a certain internal delay t_F, which is approximately the time difference between two data packets in Bluetooth. This signal arrives at the i-th time measuring station at the time t_{2Z_i} (Phase 2):

$$t_{2Z_i} = t_{start} + t_{offset_i} + t_{Z_0 M} + t_F + t_{MZ_i} \, , \tag{2}$$

introducing additional individual propagation delays t_{MZ_i} between the mobile and the base stations. The time differences Δt_i between receiving the echo-request and the echo-response at the time measuring stations Z_i are:

$$\Delta t_i = t_{2Z_i} - t_{1Z_i} = t_{Z_0M} + t_F + t_{MZ_i} - t_{Z_0Z_i} \, . \tag{3}$$

Now, the difference of the arrival times Δt_{ij} at time measuring stations Z_i and Z_j can be calculated:

$$\Delta t_{ij} = \Delta t_i - \Delta t_j = t_{MZ_i} - t_{Z_0Z_i} - t_{MZ_j} + t_{Z_0Z_j} \, , \tag{4}$$

$$t_{MZ_i} - t_{MZ_j} = \Delta t_{ij} + t_{Z_0Z_i} - t_{Z_0Z_j} \, . \tag{5}$$

While the difference of the arrival times Δt_{ij} depends on the actual position of the mobile, the propagation delays $t_{Z_0Z_i}$ and $t_{Z_0Z_j}$ between master and the other base stations are assumed to be known by measurement or by prediction from the distance between them. The described scheme doesn't require the knowledge about the internal delay time t_F between the reception of the echo-request and the transmission of the echo-response signal at the mobile terminal. The starting time t_{start} and the individual clock offsets t_{offset_i} must not be known, too. Therefore, there is no need to synchronize the clocks of the stations. This is important, because the time differences have to be measured with an accuracy of about 1 nanosecond. The measurement of such time delays on a global time scale would require an overall synchronization error of less than 1 nanosecond.

The path differences Δd_{ij} from the mobile to two time measurement stations are given by

$$\Delta dij = c \cdot (t_{MZ_i} - t_{MZ_j}) \, , \tag{6}$$

defining a hyperboloid relative to the position of the stations. The intersection of the hyperboloids of all base station pairs (i,j) determines the coordinates of the mobile in relation to the base stations.

Error terms are not included in the previous calculation. As already mentioned, the main source of error of the time measurement is the possible mismatch of the independently running clocks of the time measurement stations. Estimations show that an accuracy of ±1 ppm of the crystal reference is sufficient for the intended localization accuracy of the system. Additional errors may occur due to the indoor channel propagation, which are discussed next.

3 Indoor Propagation Channel

One severe problem for indoor localization systems is the multipath propagation of radio signals. While the fading reduces the strength of the received signal affecting the communication, possible non-line-of-sight (NLOS) paths could introduce substantial propagation delays in the order of several 10 nanoseconds, which dramatically disturb the time difference of arrival measurement. This effect becomes important, if no strong line-of-sight (LOS) path is available. So-called RAKE receivers [8], [9] are known to resolve multipaths and combine the energy from them. In fact, the effort here to get a resolution of about 3 nanoseconds wouldn't be reasonable. Therefore, the presented system is mainly limited to LOS conditions. To achieve that, the base stations should be installed right into the upper corners of the room. This gives for almost all positions good LOS conditions and eliminates reflections from wall adjacent to the stations. On the other hand, reflections from opposite walls can be assumed to be much smaller than the LOS signal acting merely as a kind of noise.

A further improvement can be achieved by using directed antennas (patch antennas) instead of omni directional antennas on the base stations. This in addition prefers the LOS path while NLOS paths are more suppressed. On the other hand, additionally hardware efforts have to be taken, which increase the cost of such a system. Therefore, such directed antennas might be used only, if the base stations are not located in the corners of the room or if a relatively small spot in space should be watched.

Nevertheless, also under NLOS conditions a reasonable localization could be done by taking into account the geometry of the room to be watched, which is usually known, and the velocity of the mobile typically limited to the walking speed indoors. This excludes sudden changes of the location of a mobile, meaning, that stepwise changes in the propagation delay are rather due to changes in the propagation channel like different NLOS paths.

4 System Overview

The basic idea of the system is the measurement of differential time differences of arrival (DTDOA) of a signal sent by the mobile to stationary installed base stations. To allow the localization in three space dimensions, the system consists of four stationary installed time measurement base stations (Fig. 2). In contrast to time-of-arrival (TOA) measurements, the clocks of the measurement stations don't need to be synchronized due to the measurement of time differences. To achieve that, one of the stationary installed Bluetooth stations (master) initiates the connection to the mobile (creating a piconet) and starts the time difference measurement by sending a data packet containing a correlation code. Then, the mobile answers by sending the same data packet again, which stops the measurement. The other time measurement stations (and the master station itself) listen to that radio traffic and measure the time differences of arrival using the correlation hardware. The measurement accuracy is only affected by the clock accuracy of the different base stations and not by the momentary clock count. To keep the system Bluetooth compliant, the L2CAP commands "Echo Request" and "Echo Response" are used, which should not require any changes at the mobile Bluetooth device. After that, the measurement results are collected at a host PC, where the position of the mobile will be calculated and evaluated taking the local coordinates of the base stations into account. The final results are the local coordinates of the mobile in relation to the stationary installed master station and an estimated error calculated from the quality of correlation.

The time measurement accuracy has to be in the order of about 3ns to achieve the required localization accuracy. Feasible system architecture was designed based on Bluetooth components and additional custom correlation ICs at each base station. The aim of these correlation ICs is to determine the time differences with an accuracy of only few nanoseconds while the bit length in Bluetooth is one microsecond. Therefore, the received signal will be over-sampled with a rate of about 64 MSamples. System simulations show that a correlation code length of 200 to 2000 bits should be sufficient. Such code will fit in a single Bluetooth data packet. The expected signal-to-noise ratio (SNR) of the demodulated signal was in the range of 12 to 18 dB.

Each stationary installed time measurement station consists of a Bluetooth module with an unsynchronized data output, a custom correlation IC, and a micro-controller handling the data transfer between the components. All stations are connected (wireless or wired) to a host PC which runs the main software application. This software will control the Bluetooth connection to the mobile, predefine the reference correlation bit sequence, and calculate the current position from the time measurement results.

5 Cross Correlation IC

The heart of time measurement is the correlation IC (Fig. 3) made in 0.25µm-CMOS technology. It performs a cross correlation of the receiving signal in real time with a previously stored pseudo-random (PN) reference code to determine the exact receive time. The incoming signal is over-sampled at the clock rate of the IC (64 MHz) and bit-wise multiplied with the reference code. In total 4096 bits are multiplied in parallel and then summed-up within one clock cycle. For that a special pipelined adder tree (Fig. 4) is used, which provides the sum 24 clock cycles after the multiplication. The adder tree was created by a recursive VHDL description.

Due to typical signal-to-noise ratios of 12 to 18 dB of the received and demodulated signal, the correlation peak is severe rounded, even if the codes match perfectly. System level simulations were done to get an answer about the optimal correlation code length with respect to the signal to noise ratio. Fig. 5 shows an example signal corrupted by noise and Gaussian low pass filtered afterwards. Note, that the corruption of the amplitude will vanish after 1bit-sampling, while the cycle-to-cycle jitter remains and could reach values up to several 10 nanoseconds. Therefore, the numbers of required zero-crossings (or cycles) to achieve the desired timing resolution of 3 nanoseconds remains on a certain level, even if is the sampling rate is increased. For an over-sampling ratio of 64 we found an operation window of 200 to 2000 Bluetooth data bits (bit duration 1 microsecond) depending on the SNR. Since the total correlation bit depth of the actual correlation IC is 4096, only 64 data bits can contribute to the time measurement. That means the localization accuracy target won't be met under harsh radio channel conditions.

In order to get a time resolution even better than the sampling rate, we consider the slopes of the correlation triangle instead of simply searching for the peak. On different levels between 0.5 and 1 the rising and falling crossings of the correlation triangle are taken to calculate an overall mean value of the peak time. Depending on the number of levels, the resulting accuracy is improved over the quantization error corresponding to the sampling rate.

The measurement of time differences requires the handling of two correlation events (phase 1 and phase 2) per measurement cycle. Therefore, an integrated dual-port RAM acting as interface to the microcontroller is implemented twice. Each one contains the result of one correlation event. Saving the correlation results in an internal RAM relaxes the requirements for the following microcontroller allows reducing the processor clock speed. Beside the main result additional information about the signal quality are provided from the correlation IC to improve the evaluation of the results by the system software. The internal time base of this IC is a high-speed synchronous 32 bit clock counter [10].

The signal processing, calculation of slopes, error correction and time difference calculation (3) can be done by a 32 bit processor core. The LEON core is a SPARC V8 compatible integer unit developed for space missions [11]. It has been implemented as a highly configurable, synthesizable VHDL model. The Processor was synthesized to a VIRTEX-E architecture, runs at 25 MHz and needs up to 50 ms to calculate the dual slopes.

6 Measurement results

Fig. 6 shows first measurement results achieved with a simplified demonstration setup achieving meter position accuracy. The demonstration setup consists of a moving transmitter and two stationary time measurement stations including a receiver, the correlation IC and a microcontroller. The transmitter sends Bluetooth compliant data packets containing a PN correlation code with a frame rate of 1600 Hz. Approximately 10 measurements per second are performed on each receiver and the changes of the propagation time are illustrated showing the movement of the transmitter. The setup was built in a typical laboratory environment with harsh radio propagation conditions. In order to simplify the setup and due to the properties of the receivers no frequency hopping was used. Therefore, typical multipath and fading problems aroused resulting in localization uncertainties. We used directed antennas on the receivers to improve the situation, but sudden changes in the radio channel, for instance by moving people crossing the LOS, still create a few uncertainties (spikes in Fig. 6). These effects are to be detected and eliminated by the system software in scope of evaluation of the measurement results. Note, that due to the measurement setup (moving transmitter) the measured distance is twice the real distance.

The used demonstration setup doesn't show the full intended functionality (localization in three dimensions) due to the ability of suitable Bluetooth transceivers. Besides fulfilling the Bluetooth specifications the transceivers need to have an analogue output of the received and demodulated signal. This is usually not the case for modern Bluetooth transceivers. The typical situation is that for this internal on-chip signal is either no any external pin provided or the received signal is already resampled with the clock of the baseband processor. Propagation delays in the order of nanoseconds vanish and cannot be detected anymore. Therefore, we used a fairly old development kit (National Semiconductor, RTX 3162), which isn't Bluetooth compliant.

Nevertheless, the demonstration setup clearly shows the ability of such a system to localize Bluetooth devices with an accuracy of ±1 meter. Full functionality is feasible, if Bluetooth transceivers with external available demodulator output are used. The ideal implementation would be a common integration of the correlation IC together with the microcontroller incorporated into Bluetooth access points.

Summary

We have presented a Bluetooth indoor localization system, which is intended to have an accuracy of ±1 meter. The major advantage is the ability to locate any mobile Bluetooth device without additional hardware in the mobile and without any changes in its software. The local position is determined by differential time difference of arrival measurements employing a dedicated cross correlation IC. Due to the differential nature of the time measurements there is no need to synchronize the clocks of the involved measurement stations. The time of arrival measurements require in essence line-of-sight conditions for the indoor radio channel.

The correlation IC is made in a standard 0.25µm-CMOS technology, performing a cross correlation of the receiving signal in real time with a previously stored pseudo-random (PN) reference code to determine the exact receive time. The used adder tree was created by a recursive VHDL description. The demonstration setup consists of a moving transmitter and two stationary time measurement stations including a receiver, the correlation IC and a microcontroller. It shows the ability of such a system to localize Bluetooth devices with an accuracy of ±1 meter.

Acknowledgement

The work presented here has been funded partly by the German Ministry of Education and Research in scope of the research project "Ad hoc Wireless Internet". The authors wish to thank Peter Langendörfer for his support, and Ullrich Jagdhold, Jarek Dabrowski, and Erik Fischer for their contributions to this work.

References

[1] Bluetooth
http://www.bluetooth.org

[2] Josef Hallberg, Marcus Nilsson, "Positioning with Bluetooth, IrDA and RFID", Master Thesis, Luleå University of Technology, 2002
http://epubl.luth.se/1402-1617/2002/125/

[3] James Nord, Kåre Synnes, Peter Parnes, "An Architecture for Location Aware Applications", Hawaii's International Conference on System Sciences (HICSS-35), January 7-10 2002,
http://www.cdt.luth.se/projects/alipes/public/Papers/HICSS-35/HICSS-35.pdf

[4] V. Bahl and V. N. Padmanabhan, "RADAR: An In-Building RF-Based User Location and Tracking System", Proc. IEEE Infocom 2000, Tel-Aviv, Israel (March 2000)
http://www.research.microsoft.com/~padmanab/papers/infocom2000.pdf

[5] Silke Feldmann, Kyandoghere Kyamakya, Ana Zapater, Zighuo Lue, "An indoor Bluetooth-based positioning system: concept, Implementation and experimental evaluation", ICWN'03, June 23-26, 2003, Las Vegas, USA
http://projekte.learninglab.uni-hannover.de/pub/bscw.cgi/d27118/An%20Indoor%20Bluetooth-based%20positioning%20system%3A%20concept,%20Implementation%20and%20experimental%20evaluation

[6] Gregory Fung, Ivan Ho, Ming Jiang, Aguilar Lam, Sherman Yin, "Design Specification for the Indoor Positioning System"
http://www3.telus.net/hikari/DesSpec.pdf

[7] Bluesoft Inc.
http://www.bluesoft.co.il/

[8] R. Price and P. E. Green, Jr., "A Communication Technique for Multipath Channels", Proc. IRE, Vol. 46, pp. 555-570 (March 1958)

[9] D. G. Brennan, "Linear Diversity Combining Techniques", Proc. IRE, Vol. 47, pp. 1075-1102 (June 1959)

[10] F. Winkler, H. Gustat, „Synthesizable High-Speed Synchronous Counters of Arbitrary Width", Proc. FDL 02, Marseilles, Sept. 24-27, 2002

[11] J. Gaisler, "LEON-1 VHDL Model"
http://www.estec.esa.nl/wsmwww/leon/

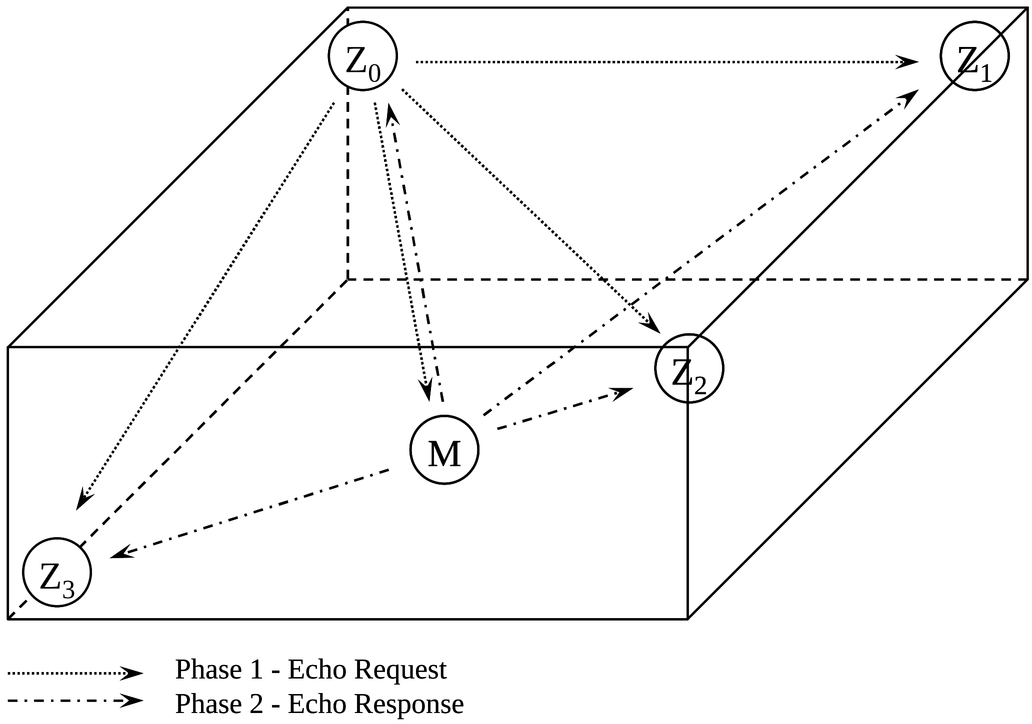

Fig. 1: Principle of the differential time difference of arrival measurement, Phase 1: correlation code sent by master station, Phase 2: correlation code sent back by mobile device

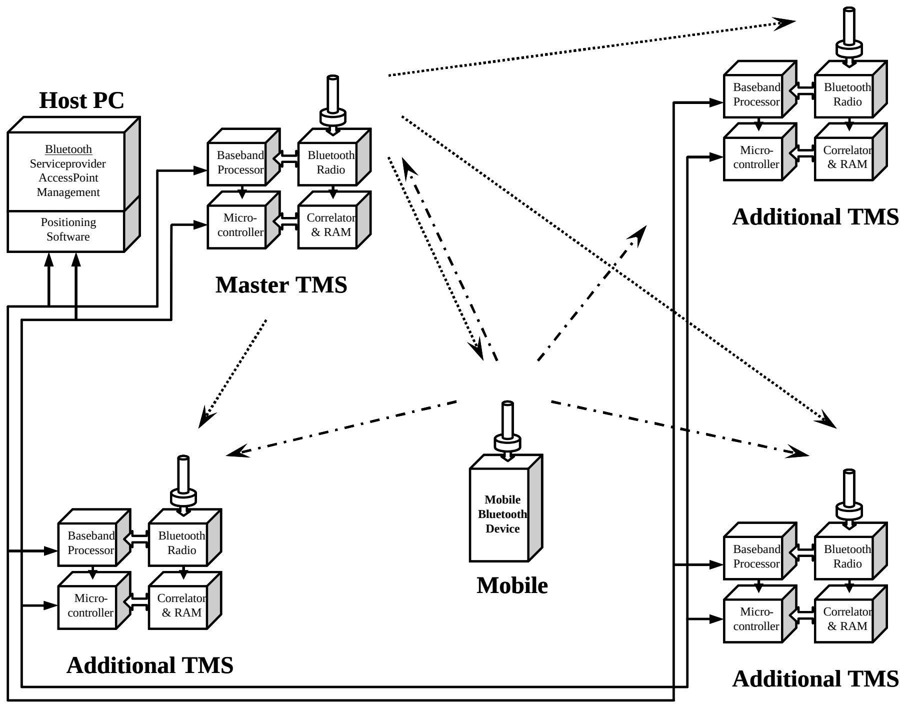

Fig. 2: Indoor localization system based on Bluetooth components, microcontrollers, and additional correlation ICs

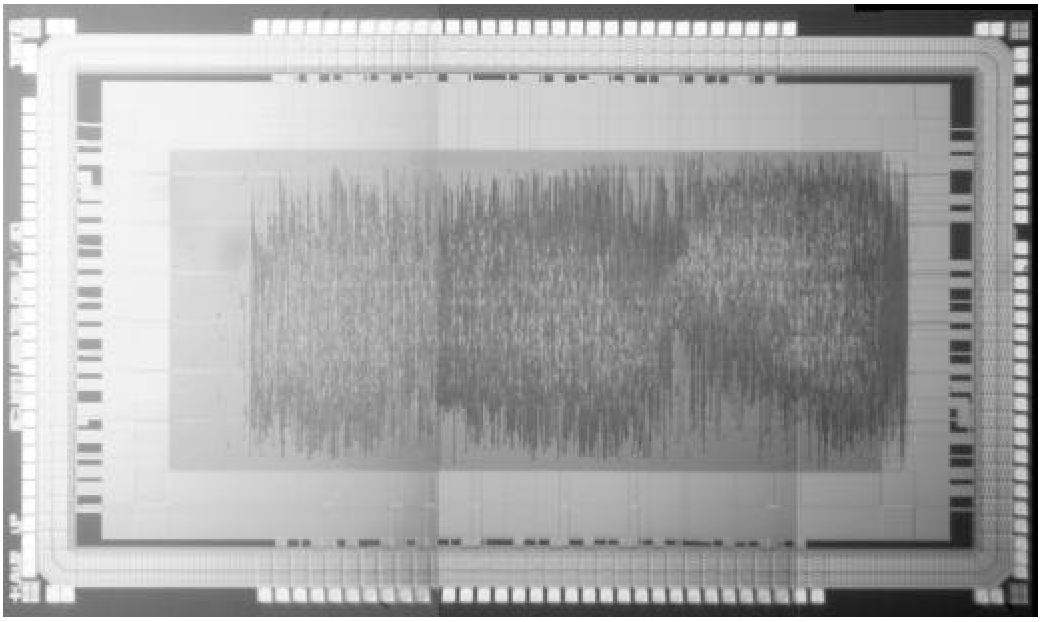

Fig. 3: Die photograph of the correlation IC with a die size of 3.5 x 6.7 mm^2.

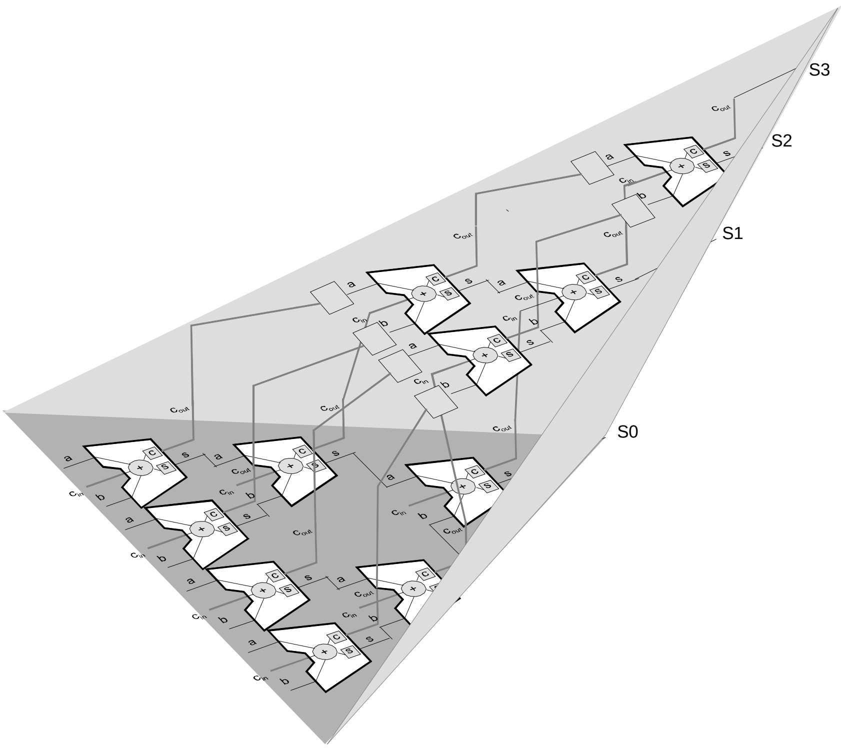

Fig.4: High speed adder tree, created by a recursive VHDL code

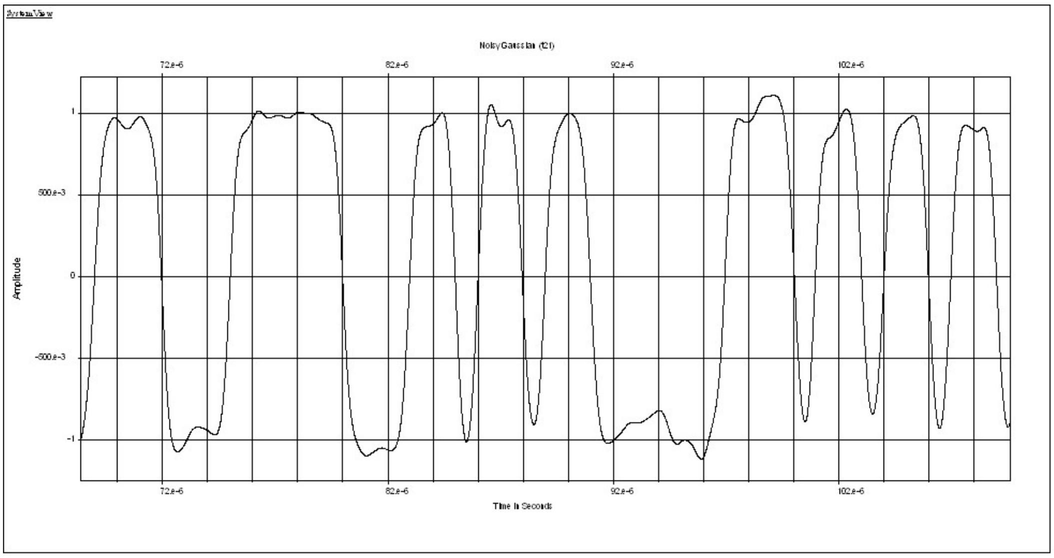

Fig. 5: Simulation of a demodulated Bluetooth data signal corrupted by noise and Gaussian low pass filtered

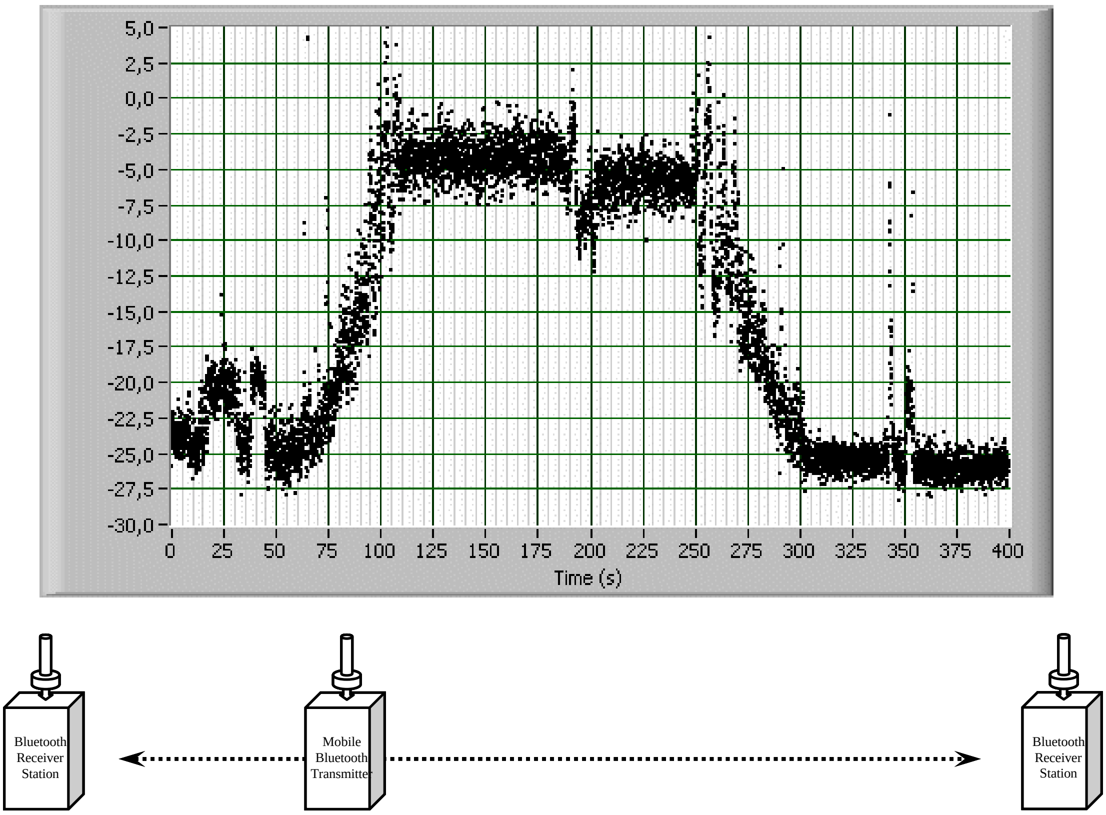

Fig. 6: Measurement setup and measured distance in meter (twice the real distance) of a moving transmitter between two receivers along a straight line; between t = 60 – 110 seconds: moving forward from receiver 1 to 2; between t = 250 – 300 seconds: moving backwards from receiver 2 to 1