# A 60 GHz OFDM Indoor Localization System Based on DTDOA

Frank Winkler, Erik Fischer, Eckhard Graß, Gunter Fischer

**Abstract— We present an indoor localization approach for high-performance OFDM (Orthogonal Frequency Division Multiplex) wireless communication systems. The basic idea of the system is the measurement of DTDOA (Differential Time Differences Of Arrival) of a signal sent by a mobile to stationary installed base stations. We show simulation results based on draft parameters for a 60 GHz wireless communication system. Since our proposed solution mainly uses OFDM modules in a special way, it facilitates a cost-efficient implementation of such systems in future.**

***Index Terms* — OFDM, indoor localization, correlation**

## I. INTRODUCTION

Location awareness is a basic need for future wireless network systems [1]. Examples of location-aware services could be the guidance in complex facilities, finding the location of particular persons or objects, and tracking and watching of active badges or tags. First implementations based on Bluetooth terminals, together with the appropriate indoor localization system were reported in [2]. The disadvantage of Bluetooth (small bandwidth, low symbol rate) will be overcome in high-performance Wireless LANs. Application of the TOA/TDOA (Time Of Arrival / Time Difference Of Arrival) approach for an IEEE 802.11 Wireless LAN has been proposed by Li and Pahlavan [3]. Some indoor systems use physical layer (PHY) properties like the received signal strength or bit error rate to estimate the location of a mobile station [4,5]. The "Received Signal Strength Indication" RSSI is available in most RF receivers, there is no need for a special hardware. However, the signal strength in indoor environments depends on non-predictable attenuations, reflections and fading and is therefore not well suited. [6].

In this paper we first present the timing measurement principle DTDOA and discuss a solution of time measurement based on an add-on correlator module in an IEEE 802.11a receiver. Then we investigate the performance of a build-in solution and finally we derive parameters for indoor localization in a 60 GHz high-performance Wireless LAN, currently under development in the WIGWAM project.

Simulation results demonstrate that minor modifications of the OFDM receiver would allow the implementation of the entire localization procedure using existing hardware.

## II. PRINCIPLES OF DIFFERENTIAL TIME DIFFERENCE OF ARRIVAL (DTDOA)

The localization is based on distance measurements between a point of unknown position (mobile transceiver MT) and points at known positions (access point, receiver base station BS). In practice, the propagation time of an electromagnetic wave is measured to calculate the distance. It requires knowledge of the starting time at the transmitter and the time of arrival (TOA) at the receiver. Our setup consists basically of at least four hardware installations, called base stations (BS) and one or more mobile transceivers (MT). By using the DTDOA scheme the base stations do not need to be timely synchronized, they just exchange data with the host-PC. Furthermore we distinguish between two different types of base stations: a master base station (MBS) and three or more slave base stations (SBS). The specific task of the MBS is the initialisation and coordination of the localization process. Every BS has a link to a host-PC using a wired or wireless network. The task of the host-PC is to collect the measured time stamps and to perform all calculations necessary to estimate the position of the mobile transceiver. Fig. 1 gives an impression of the setting.

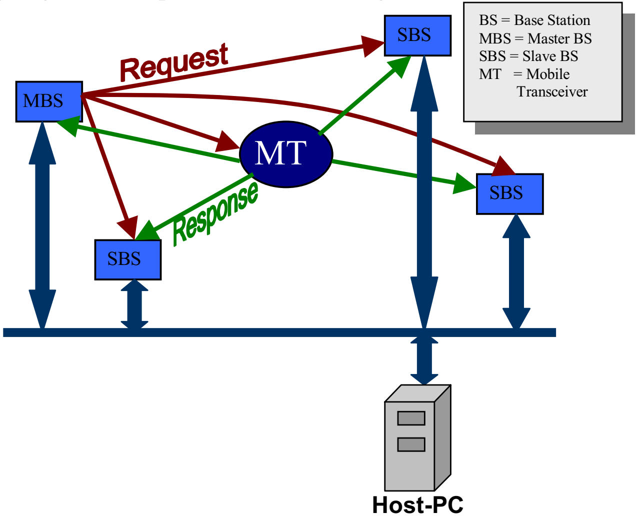


Fig. 1. Localization architecture

The first step of the localization process is the initialisation by the MBS. This is done by sending a specific known pseudo noise (PN) sequence, which will be received by all SBS and MT involved in the localization network. The SBS records the

---

This work is partly funded by the BMBF under the project acronym WIGWAM. (Wireless Gigabit with Advanced Multimedia Support)

Dr. Frank Winkler, Erik Fischer, are with the Humboldt University Berlin, Germany, e-mail: (fwinkler,efischer)@informatik.hu-berlin.de

Dr. Eckhard Graß, Dr. Gunter Fischer are with the IHP – Innovations for High Performance Microelectronics, Germany, Frankfurt/O, e-mail: (grass, gfischer)@ihp-microelectronics.com).

receiving time precisely based on their local clock.

The mobile transceiver reacts by sending the PN sequence back to all BS at an arbitrary time. This will also be received and precisely recorded by all BS. Now the time difference between reception of the request and the response signal have to be calculated by every single BS. Then the results are transmitted to the host computer afterwards. Due to the fact that the distances between the MBS and all SBS are well known the host is able to normalize the received delta time stamps to a common arbitrary origin just by adding the corresponding propagation time. This is illustrated in Fig. 2.

From this diagram we can also derive a procedure for determination the propagation times between the MT and all BS.

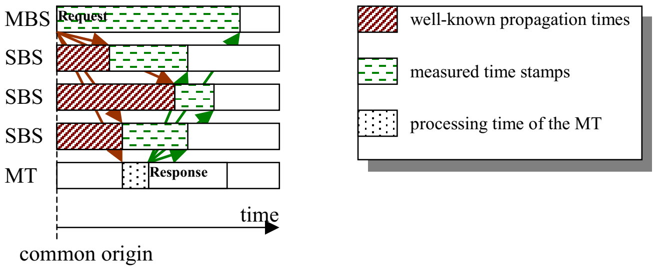


Fig. 2. Signal flow during localization

Using the normalized time stamps we get:

$$t_p(MT,MBS)=\frac{\Delta TS(MBS)-t_c}{2} \tag{1}$$

$$\begin{aligned} t_p(MT,SBS_i) &= t_p(MBS,SBS_i)+\Delta TS(SBS_i) \\ &\quad - t_p(MBS,MT)-t_c \end{aligned} \tag{2}$$

*where ΔTS(BS) is the acquired delta time, tc is the processing time of the MT and tp(X,Y) is the propagation time between X and Y.*

Now we use the pair wise propagation time differences between different base stations to eliminate the processing time $t_c$ of the MT. This is called differential time differences of arrival (DTDOA). In contrast to TDOA no time synchronization is required.

$$\begin{aligned} \Delta t_p(X,Y) &= t_p(MT,X)-t_p(MT,Y) \\ &= t_p(MBS,X)+\Delta TS(X)-t_p(MBS,Y)-\Delta TS(Y) \end{aligned} \tag{3}$$

Thus, in a system using N base stations, we get N-1 propagation time differences (Δ*tp*). We can use the Δ*tp*'s to form a system of N-1 linearly independent equation system and solve it. The solutions of these equations are the sought coordinates of the mobile transceiver. Using more than 4 base stations results in an over-determined set of equations. The results in IV show that this can enhance the accuracy of the localization.

Error terms are not included in the previous calculation; effects of clock accuracy and multipath propagation were discussed in a Bluetooth scenario [2]. The internal clock of a BS must have a high frequency. Careful selected positions for the Stations (i.e. corners or edges) and directed antennas can reduce multipath errors, resulting in an accuracy <1 m for our Bluetooth terminal.

## III. GENERATING TIME OF ARRIVAL EVENTS (TOA) IN OFDM SYSTEMS

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation technique that employs overlapping, orthogonal narrow band signals. It has become one of the most important modulation methods for high-speed Wireless LAN systems today.

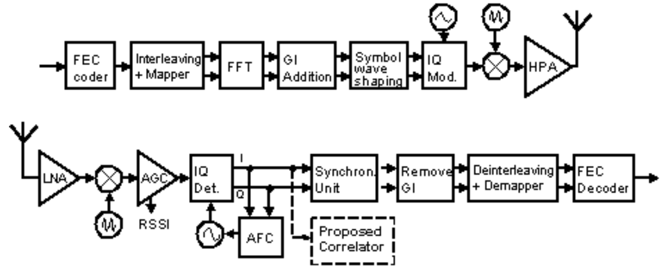


Fig 3. OFDM transmitter and receiver [IEEE802.11a] with the proposed correlation circuit (see III.A)

As shown in Fig. 3, a standard OFDM transmitter consists of a forward error correction unit (FEC), a data interleaver, inverse fast Fourier transformation, guard interval addition, IQ modulation and power amplifier. An OFDM receiver commonly integrates a low noise amplifier, IQ detection, guard interval removing, fast Fourier transform, deinterleaver and error correction. In general this architecture is also suitable for higher frequencies and higher data rates, like the new developed 60 GHz high-speed Wireless LAN.

Tab. 1 compares IEEE 802.11a parameters with the IHP-60 GHz demonstrator currently being developed by the IHP Frankfurt.

| | 64 sample OFDM (IEEE 802.11a-1999) | 256 sample OFDM (IHP-60 GHz draft specification) |
|---|---|---|
| Channel bandwidth | 20 MHz | 400 MHz |
| Subcarriers | 64 | 256 |
| Subcarrier spacing | 312,5 kHz | 1.5625 MHz |
| Guard time | 0.8 µs | 160 ns |
| FFT Period | 3.2 µs | 640 ns |
| Symbol rate | 4 µs | 800 ns |
| Modulation | BPSK, 4,16,64 QAM | BPSK, 4,16,64 QAM |
| Data Subcarrier | 52 | 192 |
| Sampling rate | 50 ns | 2.5 ns |

Tab. 1. Comparison of IEEE802.11a-1999 as described in [10] and IHP-60 GHz OFDM draft parameters

We note that the sample rate and clock frequency of the baseband processor are significantly increased for the new system.

### A. *TOA detection with a dedicated time-domain correlator chip*

First, we briefly review the parameters of today's systems from a localization point of view. As shown in Tab. 1 the standard IEEE 802.11a-1999 uses for the physical layer a 20 MHz bandwidth, which requires sample rates and digital clocks of more than 20 MHz. The IHP single chip baseband processor for IEEE 802.11a standard [9] uses a 80 MHz A/D-converter with decimation filter and a 20 MHz clock for Fourier transform, synchronizer and channel estimator. A training sequence, defined in a PLCP (Physical Layer Convergence Protocol) is used for synchronization. It consists of 10 short and two long symbols. The implementation of OFDM synchronization is commonly based on an auto-correlation function combined with a peak detector. In [7] several improvements was presented to achieve a fast synchronization with power and area efficient circuits. A high resolution cross-correlator is necessary to achieve timing resolution adequate for the localization procedure. Such a complex cross-correlator requires a large number of complex multipliers and big adder trees.

If only the timing information of a maximum correlator peak is sought several simplifications can be done. As shown in Fig. 3 a one bit time domain cross-correlator circuit can work in parallel to the synchronization and FFT unit. A simple signum function creates a single bit input signal from the I or Q OFDM input signal. Ideally, the cross-correlation function of the sign bit gives the same peak information as a computation based on real numbers (Fig. 4). As described in [9] this simplification of calculations can be done if only one significant maximum occurs. This is true for a symbol that is a part of the long training sequence.

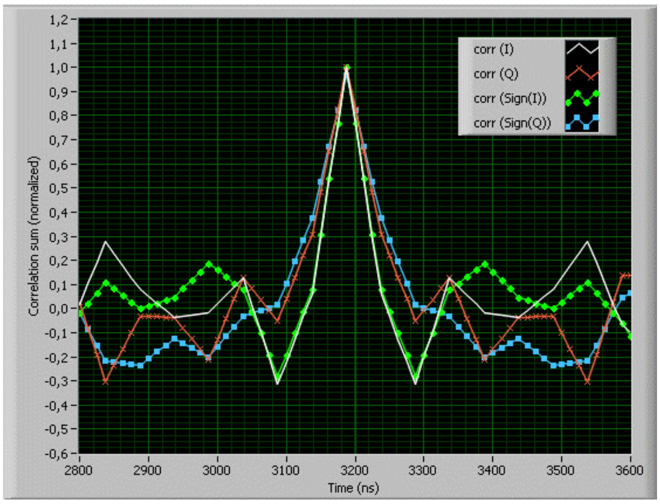


Fig 4. Comparison of a signum and real number cross-correlation (zoom of correlation peak) of a IEEE802.11a PLPC signal, 80 MHz oversampled

The time-domain cross-correlator in [2] was primarily developed for Bluetooth localization, but is also applicable for the IEEE 802.11a standard. With a 4094 bit correlation length and a sample rate of 80 MHz it would be possible to achieve a timing resolution better than 12.5 ns, with a corresponding position accuracy of less than 3.75 m. Two techniques were used in [2] to improve the accuracy down to 1 m:

- multiple measurements and averaging
- intra clock interpolation by using the ascending and descending slope of the correlator function.

The MT doesn't need a time-domain cross-correlator, since it only works as transmitter. However, a correlation chip required for the BS would cause additional cost and power dissipation.

### B. *TOA detection with a high speed Fourier transform*

Another way of performing a cross-correlation utilizes the Fast Fourier transforms FFT and IFFT, which are embedded in every OFDM transceiver anyway. If $s$ is the received signal and $p$ the known preamble symbol (pattern) then the correlation function can be computed as:

$$corr(s,p) = IFFT\{FFT(s) \cdot FFT(flip(p))\} \qquad (5)$$

where 'flip' denotes the reverse order of $p$

The pattern $p$ is constant, so the term $FFT(flip(p)))$ can be stored in a memory. The computational time is the sum of two Fourier transformation times plus the time for a complex multiplication with a indexed table value.

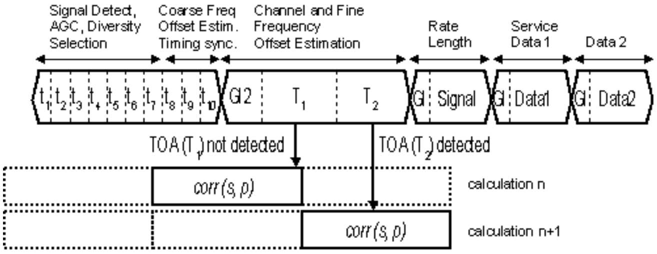


Fig. 5. Trainings sequence for OFDM IEEE 802.11a and unsynchronized Fourier transform sliding windows

From a localization point of view, the cross-correlation should be done with a long OFDM training symbol (Fig. 5). We have to remark that localization has to be performed on the raw data prior to symbol timing synchronization. Therefore, the window for computation the correlation *corr(s,p)* is not predictable. To avoid that the detection of a single training symbol could be missed two symbols should be transmitted in sequence. A 128-point FFT with consecutive windowing over two symbols is preferred, but a 64-point FFT with a half-pattern length and a half symbol-size sliding window can be used as well. Dependent on the sliding window and the reference pattern, none, one, or two cross-correlation peaks are generated. In case of only one peak, no allocation to the first or second training symbol is possible. Both training symbols should be distinguishable.

Today's OFDM synchronization methods [8] are based on auto-correlation procedures that also need two long training symbols $T_1$ and $T_2$ for timing and symbol synchronization.

To simplify localization, we propose an inversion of the second long training symbol $T_2$, which results in a different sign of the cross-correlation function. So the first and second symbol can be distinguished. It affects the auto-correlation for the synchronization procedure in a negligible way, only a sign correction has to be done.

The correlation result is comparable to the dedicated correlator in III.A but the four times lower clock frequency of the FFT-based correlator causes a less accurate localization (4 m instead of 1 m). However, some synchronization algorithms do rely on a finer FFT resolution (256 points) anyway. In those cases the same localization accuracy as with the dedicated correlator could be achieved.

### *C. MatLAB Simulation model for localization in high-performance OFDM Systems*

OFDM systems with high data rates require high sampling frequencies as well. As shown in Tab. 1, we expect 400 MHz sampling rates. Synchronization techniques and Fourier transforms have higher complexity and very tight timing constraints. On the other hand, the computation of the signal arrival is much more precise if these problems are solved. Especially the usage of the FFT based method potentially allows a more precise localization with no significant additional area or power consumption penalties. We used a MatLAB model to find out the benefits of this approach.

The following scenario with six base stations was used for the MatLAB simulation model of the IHP-60 GHz OFDM baseband localization approach (Tab. 2, Fig. 6):

| Location (m) | X | Y | Z |
|---|---|---|---|
| Mobil Transceiver (unknown Position) | 2 | 1 | 1 |
| Master Base Station | 4 | 3 | 2 |
| Slave Base Station 1 | 0 | 0 | 0 |
| Slave Base Station 2 | 4 | 0 | 2 |
| Slave Base Station 3 | 0 | 3 | 2 |
| Slave Base Station 4 | 2 | 0 | 2 |
| Slave Base Station 5 | 2 | 3 | 1 |
| Slave Base Station 6 (Master) | 4 | 3 | 2 |

Tab. 2. Location of six stations in a test scenario

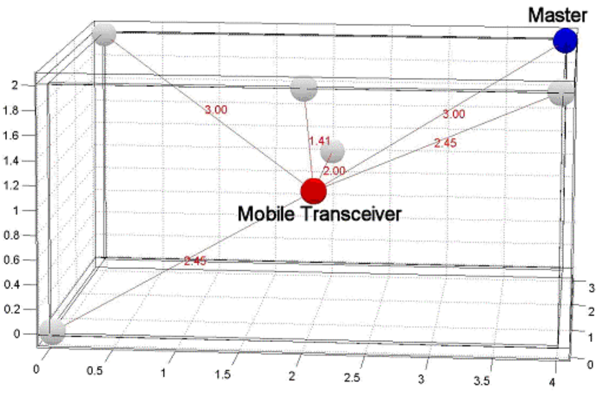


Fig. 6. The MatLAB test scenario (room size 4 x 3 x 2 m³)

The MatLAB model of the mobile transmitter (MT) includes an interleaver, a 64-QAM mapper, inverse Fourier transform cyclic prefix insertion, 1:32 oversampling and IQ modulation with a 5 GHz intermediate frequency. The high oversampling rate allows to include the IQ modulation in the model and a fine-grained position definition. Based on this scenario multiple receivers are modelled. They get their data from a fine grained delayed signal generator which is added by a white noise AWGN channel model with individual parameters.

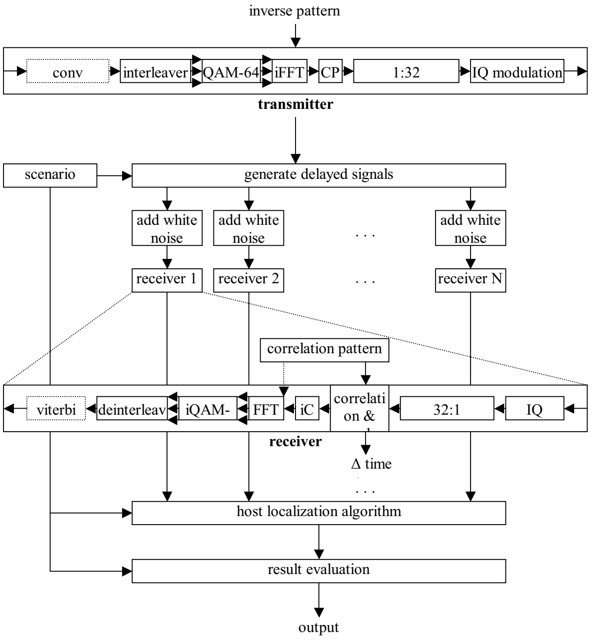


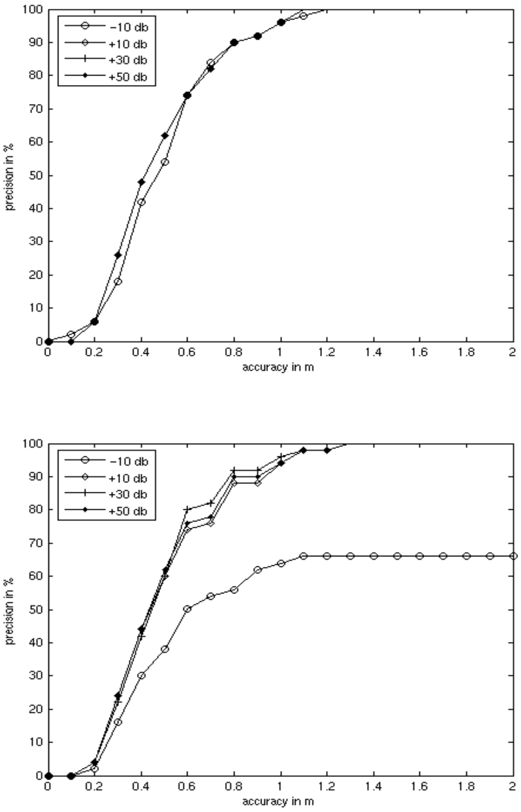
Fig. 7. The MatLAB computation model

Each BS receiver is an instance of the same MatLAB model. It includes an IQ demodulation, 32:1 subsampling, correlation and peak detection, cyclic prefix removing, a Fourier transform, and a deinterleaver for signal reconstruction. The host PC is modelled by a host localization algorithm and result calculation unit. All models are joined together as shown in Fig. 7. To pre-calculate the frequency domain sequence for transmitting, the sought time domain PN pattern can be applied to the receiver's FFT, QAM demapper (iQAM) and deinterleaver. Due to the capability of QAM 64 modulation schemes, the localization model is not restricted to training symbols with simple BPSK modulation. The iQAM performs a rounding function for complex values. So the inverse signal path of the transmitter does not reconstruct the same PN sequence in the time domain. Nevertheless, the cross-correlation result with a time domain signal generated by the inverse signal path is nearly as good as the cross-correlation with the original PN sequence. For different values of the signal to noise ratio (SNR) several localization simulations were carried out.

## IV. RESULTS

Ideally, a localization system should report positions accurately and consistently from measurement to measurement. As example, an inexpensive base station can locate positions within 2 m for approximately 90 percent of measurements. More complex systems usually provide much better results, reaching 0.5 m accuracy at 90 percent of the measurements. The distance denotes the accuracy for a single measurement. The percentage denotes the precision, or how often we can expect that accuracy. The following simulation experiment is to obtain statistical results about the precision and accuracy.

In our simulation model the position of the MT was changed randomly and the localization was measured using the model of Fig. 7. Comparing the results with the mathematical model – calculated directly from Fig. 6 – we get the percentage of localization results that does not exceed a given accuracy. As shown in Fig. 8a with any given SNR we can provide a precision of 95% for an accuracy of 1 m with a complex number calculation (Fig. 8a), whereas at a SNR of –10 db, the precision reduces to 60 % if the signum function is used (Fig. 8b). Increasing the room size and decreasing the number of BS reduces the precision significantly (Fig. 9).



a)

b)

Fig. 8. Precision dependent on the required accuracy for different SNR levels (a) complex number and (b) signum function cross-correlation. (In (a) the curves +10,+30,and +50 dB are identical.)

## V. CONCLUSION

Several methods of DTDOA based localization calculations were presented. High performance Wireless LAN systems offer a new possibility of indoor localization with DTDOA methods by using OFDM preambles without significantly increasing the hardware costs. This requires that the physical layer supports the usage of the high resolution FFT for cross correlation purposes prior to timing synchronization. Further work is in progress to investigate implementation aspects and to include more accurate channel models for a 60 GHz indoor scenario.

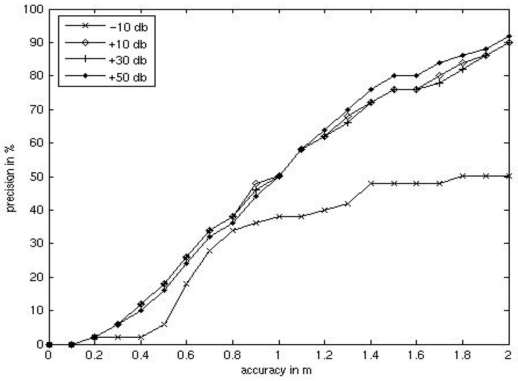


Fig. 9. Precision dependant on the required accuracy for 4 BS only and a 5 times “stretched” room size (20 x 15 x 10 $m^3$) at different SNR levels using signum function cross correlation.

For definition of future Wireless LAN standards, localization aspects should be taken into consideration at an early stage. In particular localization-friendly training sequences can significantly enhance the performance of the algorithms. First simulation results yield localization accuracies of around 0.5 m for indoor purposes. This can be achieved with little extra hardware and without the use of the unreliable receive signal strength (RSSI).

## REFERENCES

[1] Eberspächer et. al. The Book of Visions 2000, IST - WSI Project, November 2000. Available http://www.wireless-world-research.org/general_info/ Bookofvisions/BookofVisions2000.pdf,

[2] G. Fischer, B. Dietrich, F. Winkler, Bluetooth indoor localization system, in: Hannoversche Beiträge zur Nachrichtentechnik HBN Band 0.1, Shaker Verlag 2004.

[3] Xinrong Li, Kaveh Pahlavan, Matti Latva.aho, Mika Ylianttila, Comparison of Indoor Geolocation Methods in DSSS and OFDM Wireless LAN Systems, VTC 2000 - Worcester Polytechnic, 2000. Available: http://www.tik.ee.ethz.ch/~beutel/projects/picopositioning/comparison_indoor_wlan_pos.pdf

[4] L. Wiebking, L. Reindl, M. Christmann, D. Mastela, M.Vossiek, Local Positioning Radar, in: Hannoversche Beiträge zur Nachrichtentechnik HBN Band 0.1, Shaker Verlag 2004.

[5] P. Bahl, V. N. Padmanabhan: RADAR: An In-Building RF-based User Location and Tracking System, Proceedings of IEEE INFOCOM 2000, Israel , March 2000.

[6] S. Feldmann, K. Kyamakya, A. Zapater, Z. Lue, An indoor Bluetooth-based positioning system: concept, Implementation and experimental evaluation. Available: http://projekte.learninglab.uni-hannover.de/pub

[7] A. Troya, Synchronization and Channel Estimation in OFDM: Algorithms for Efficient Implementation of WLAN Systems, Dissertation, Brandenburgische Technische Universität Cottbus 2004.

[8] A. Troya, k. Maharatna, M. Krstić. E. Grass. R. Kraemer, OFDM synchronizer implementation for an IEEE 802.11a compliant modem, Proc. of the IASTED Int. Conference on Wireless and Optical Communications, 152 (2002), Banff, WOC 2002.

[9] M. Sullivan, Multiplication substitutions enable fast algorithm implementations in FPGAs, Personal Engineering & Instrumentation News, pps 67-72. June 1995. Available: http://archive.chipcenter.com/dsp/DSP991208F1.html

[10] IEEE Std 802.11a-1999, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, High-speed Physical Layer in the 5 GHz Band, IEEE Computer Society 1999.