Empowering 'Ambient Intelligence' with a Direct Sequence Spread Spectrum CDMA Positioning System

Domenico Porcino, Martin Wilcox

Philips Research Laboratories,
Cross Oak Lane, Redhill, RH1 5HA England

Email:
domenico.porcino@philips.com
martin.wilcox@philips.com

Abstract: Distributed intelligence is set to revolutionise the interface between humans and the surrounding environment. Smart objects will become more and more commonplace in the home of the next decade, in a dynamic network of distributed intelligent elements. One of the most important steps yet to be addressed in this vision is a positioning system able to locate people and objects and allow them to interact in an efficient way. This paper presents an experimental 2.4 GHz Direct Sequence Spread Spectrum system for accurate indoor positioning. The theoretical limits of this technology are presented along with the challenges ahead in delivering the location results with clear and user-friendly logical descriptors.

1. Introduction

The interaction between man and machine is set to change dramatically in the near future. With computational power becoming more and more accessible and easy to embed in almost any shape and material, the presence of intelligent devices will grow exponentially making daily life easier and humanising our contacts with objects and machines. This appearance of distributed intelligence in and around our lives is known as 'Ambient Intelligence' [1].

A growing number of products are already beginning to incorporate electronics to help the users: from intelligent 'white goods' (fridges, washing machines, microwave ovens) to wearable devices (mp3 music players, speakers, health sensors). But we are only at the start of this gradual revolution in our habits.

Many are the challenges still in front of us and numerous the barriers that slow down the powerful interactive experience envisioned for futuristic life scenarios. Among those: the absence of an appropriate auto-recognition and automatic initiation mechanism in the home network (to sense when we arrive home), the necessity of using predetermined and unattractive man-machine interfaces (keyboards or touch screens) and the general 'dumbness' of actual devices which know nothing about where they are and what is their role in the surrounding area.

The future digital environment will have to overcome the problems and barriers of technology producing spaces that are sensitive and responsive to our needs, connecting and organising the exchange of information within the network of thinking devices. Intelligent objects will be aware of where we are and what we require. Our presence, our gestures and our (voice) commands will prompt appropriate reactions.

2. The Importance of Indoor Positioning for 'Ambient Intelligence'

One of the key technical elements allowing the realisation of this vision will be the knowledge of the accurate position of the person and objects.

Already today accurate location mechanisms, such as the Global Positioning System ([2]), are commercially available. Many more will become part of our daily life with the introduction of third generation mobile phones ([3]). But none of these techniques will allow the meter or sub-meter level accuracy within buildings, which is necessary for smart houses. The 'pervasive computing' that will be part of our future requires in fact accurate knowledge of *indoor* position to make any intelligent electronic appliance aware of its surroundings and react to them ([4]).

At the time of writing, dynamic positioning of people, objects or equipment in indoor environments as offices, shopping malls or hospitals, is commercially an almost unexplored area, both in the professional and in the consumer market.

The location sensing technology that will drive the ambient intelligence revolution needs to offer characteristics that are challenging when considered all together: meter (or submeter) level accuracy, large area of coverage (ideally 100-200m^2), multiuser access, privacy observance, automatic set-up, low-cost, user-friendly interface.

Philips Research has been working with these goals in mind to develop the fundamental technology for accurate indoor positioning. The rest of the paper will present the technical background of this location sensing technique. It will also show the theoretical limits of the system, and present some of our ideas on how the information will be delivered to the final user.

3. The Optimal Receiver for Ranging Applications

Classical positioning systems based on RF transmissions estimate the location of a mobile device by calculating -at the receiver- the propagation time (also known as time of flight) of predetermined signals broadcast by the network infrastructure.

By correlating one of the signals transmitted by the infrastructure with a local replica of the same signal generated inside the mobile, it is possible to derive a function, whose maximum is theoretically linked to the time which radio waves take to propagate between source and destination. Considering rays travelling at the speed of light, it is relatively easy to derive a Time Of Flight (TOF) delay estimate and from this the so-called *pseudorange,* i.e. the estimated distance from transmitter to receiver.

Using three separate pseudorange measures to three transmitters and knowing their coordinates, it is possible to derive a complete 2-D position fix receiving unit via simple trigonometry in a process often called *triangulation* or *trilateration*.

The technological founding block for positioning is therefore the range estimator, whose optimal structure has been known for several decades ([5],[6],[7]). The block scheme of the optimal transmitter and receiver structures is described in Figure 1.

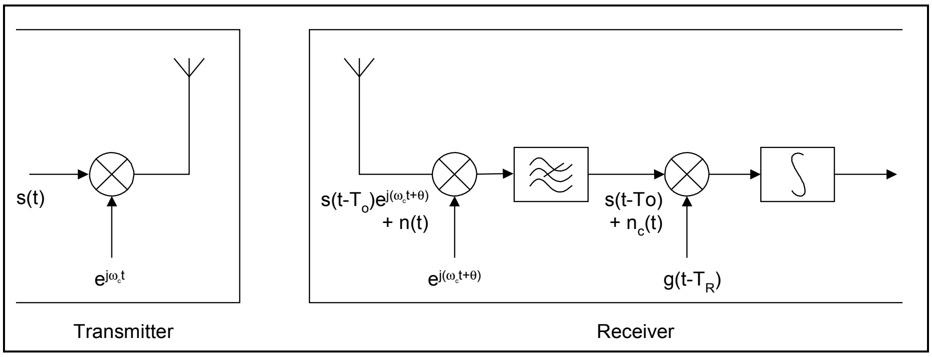

Figure 1: The optimum ranging system

Given a generic signal $s(t)$, with a bandwidth B_S, the transmitted signal can be obtained mixing it onto a carrier frequency ω_c to produce: $\mathcal{R}\{s(t)\cdot e^{j\omega_c \cdot t}\}$, with $\mathcal{R}\{\}$ indicating the real part.

The signal arriving at the receiver $r(t)$ will then be:

$$r(t) = r_1(t) + n(t) = s\left(t - T_0\right)\cdot e^{j\left(\omega_c t + \theta\right)} + n\left(t\right) \qquad \mathbf{(1)}$$

where T_0 is the propagation time between transmitter and receiver (=R/c, with R the distance between transmitter and receiver, and c the speed of propagation in free space), θ is the amount of phase shifting, and $n(t)$ is a noise component.

The optimum receiver mixes the received signal down to baseband coherently with a local oscillator signal $\cdot e^{j\omega_c \cdot t+\theta}$. After the mix down to baseband, the received signal will still be corrupted by the noise component $n_c(t)=n(t)\cdot cos(\omega_c t+\theta)$.

The receiver will then apply some sort of 'gating' function $g(t-T_R)$ to the received signal, with T_R being a guess of the time of arrival. The purpose of this gating function is to put a 'gate' around a certain range $R_R=c\cdot T_R$ and to test whether the transmitter is, in fact, at this range. If the transmitter is at this range, the gate will let the signal through; if not, it will indicate an error signal.

The receiver shown in Figure 1 acts therefore as a proximity detector, signalling when the transmitter is at a particular range from the receiver. By building a bank of parallel receivers, or a tracking receiver which adjusts T_R iteratively to find the correct time, we can test several ranges and gain a continuous measurement of range.

An optimum gating function that minimises the time measurement error T_R-T_0 has been proposed by Mallinckrodt and Sollenberger [5].

From a simple analysis of the Fourier transform of Mallinckrodt's gating function, it is possible to distinguish two parts related respectively to a matched filter for the transmitted signal $s(t)$ and a differentiation function. The optimum receiver will therefore present as gating, a matched filter followed by a differentiator at time T_R.

The (minimum) time measurement error resulting from this optimum structure is:

$$\delta T_R = \frac{1}{\beta\sqrt{(2E/N_o)}} \quad \text{where} \quad \beta^2 = \frac{1}{E}\int_{-\infty}^{\infty}(2\pi f)^2 |R_1(f)|^2 \, df \tag{2}$$

where E is the energy in the received signal $r_1(t)$, calculated from $E = \int_{-\infty}^{\infty} |R_1(f)|^2 \, df$, and β is the effective signal bandwidth. This last parameter is determined not only by the bandwidth B_R of the received signal but also by the shape of the signal spectrum. The value β^2 is often referred to as the mean-square bandwidth or Gabor bandwidth of the signal.

The root-mean-square range error will clearly be $\delta R_R = c \cdot \delta T_R$. Thus, for any transmitted signal $s(t)$, the range error of an optimal receiver will be completely determined by the energy received, the noise floor, and the effective bandwidth β.

Taking several measurements from the matched filter in which the noise contributions $n_0(T_R)$ are independent and combining them before applying the differentiation, the estimate of the range will improve. Helstrom [6] shows that in the case where P independent measurements are made, the variance of the time measurement error can be reduced to:

$$\delta T_R^2 = \frac{1}{\beta^2 \sum_{k=1}^{P} (2E/N_o)_k} = \frac{1}{\beta^2 (2E_T/N_o)} \tag{3}$$

where $(E/N_0)_k$ is the energy-to-noise density during the k-th measurement and E_T is the total received energy over all the k measurement periods.

4. Physical Limits on the Accuracy of a Direct Sequence Spread Spectrum Indoor Positioning Receiver

In the case of the Direct Sequence Spread Spectrum (DSSS) receiver used for our experiments, *s(t)* is a *pseudonoise* (PN) code and the receiver structure comprises an antenna, a mixer and a matched filter stage followed by a differentiator (which is approximated with an Early-Late gating block), making this proximity detector close to the optimum theoretical ranging receiver.

The range error generated by the receiver will be determined by its ability to locate the time-of-arrival of the line-of-sight component in the presence of thermal noise. As seen in the classical radar theory presented above, the accuracy with which the receiver can do this estimate is determined by the received line-of-sight energy, the thermal noise floor, and the mean-square bandwidth of the signal.

The mean-square bandwidth of our DSSS signal is equal to the second derivative of the correlation function at its peak, i.e. the ‘sharpness’ of the peak. As long as the bandwidth of the pulse-shaping filter is much greater than the chipping rate, the mean-square bandwidth of the DSSS signal can be approximated by $\beta^2 \approx 2Bf_c$, where B is the bandwidth of the pulse-shaping filter and f_c is the chipping rate.

The root-mean-square (rms) range error in our ideal DSSS receiver will then be:

$$\delta R_R = \sqrt{\frac{B}{f_c}} \frac{c}{2B\sqrt{E_T / N_0}} \tag{4}$$

where c is the speed of propagation in free space, E_T is the total received signal energy (which might be collected from several separate measurements), and N_0 is the thermal noise floor.

In the indoor environment, the measurement of pseudorange is made considerably more difficult by the fact that the receiver not only receives the signal directly from the transmitter, but also from reflections off the walls, ceiling and floor between the transmitter and receiver. This phenomenon is known as 'multipath' and is particularly destructive for range measurements since the correct distance is given by the line-of-sight path and measuring any of the reflected components (which travel further), will give a range error.

To verify whether the application of Ambient Intelligence is physically feasible with this positioning technique, we consider an ‘ideal’ receiver, whose requirements are less stringent than a real receiver. The ideal receiver will perform some averaging to extract as much radio energy as possible and remove the effect of fast-fading, and should be able to identify the line-of-sight component from amongst the multipath components. In [8] the performance of this ideal receiver is calculated -starting from the theoretical rms error of equation (4)- in terms of the accuracy with which a given range can be measured, and the largest range that can be measured to a specified accuracy.

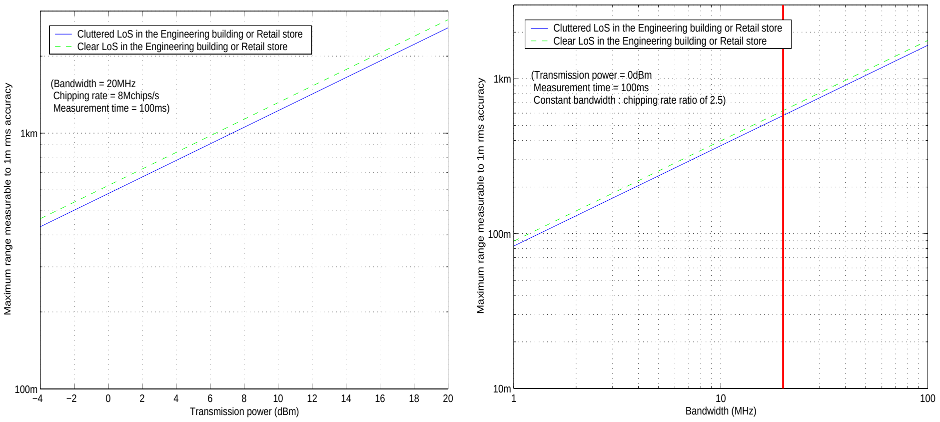

Figure 2: The maximum range measurable for a given power and bandwidth

Results related to the maximum range which can be measured to 1m (rms) accuracy are shown in Figure 2 versus transmitted power and signal bandwidth. These plots indicate the physical limits on Direct-Sequence ranging in the 2.4GHz band and in the propagation environments measured in [9]. Figure 2 demonstrates that the ideal receiver can easily achieve 1m accuracy for ranges of several hundred meters within the power and bandwidth restrictions placed on the 2.4GHz band (transmission power limited to 100mW, useful bandwidth lower than 80MHz, processing gain higher than 10dB [10]). These results are useful both for assessing the feasibility of particular applications and benchmarking the performance of real receivers.

5. The DSSS testbed

The calculations performed in Sections 3 and 4 have shown the theoretical limits of an indoor ranging system, and have also confirmed that the positioning requirements for Ambient Intelligence are achievable with an "ideal" receiver. Philips Research has developed a real prototype of an indoor location system, initially concentrating on a DSSS transceiver.

There are several reasons for this choice: the possibility to use the license-free 2.4 GHz band; easy access to off-the-shelf components for this frequency band; the maturity of DSSS technology; the possibility of recreate a system based on the well-established principles used in the GPS; the automatic and efficient multiple access scheme implicit when using different Pseudo Noise (PN) codes.

An experimental hardware system for indoor positioning has been set-up at Philips Research Laboratories. The system is composed of a transmitter radio board, a set of antennas and a receiver radio board. The transmitter, whose directional transmitting antenna was placed on a doorway pointing towards a long corridor, is able to transmit Gold code sequences (PN sequences) spread over a large frequency band. The chipping rate used was of 8Mchip/s, with a sampling rate of 40 Msample/s. The power effectively transmitted over air was -4dBm, i.e. 0.39mW.

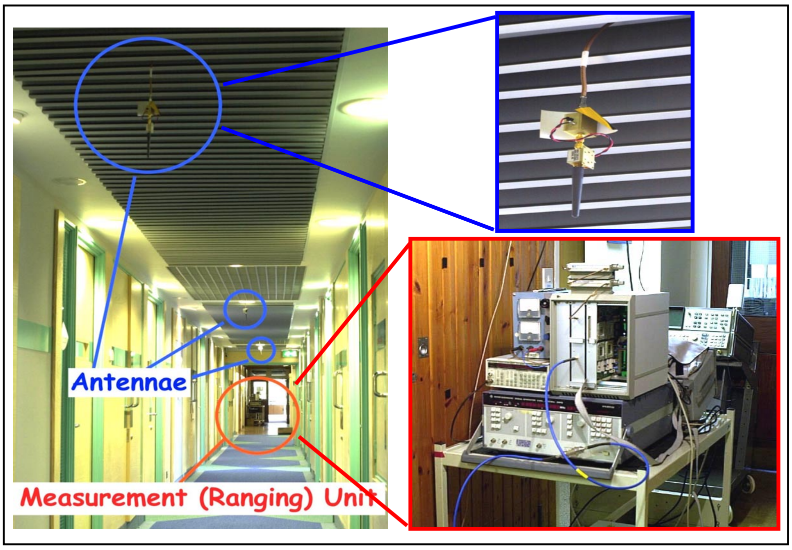

Figure 3: The experimental hardware of a 2.4 GHz DSSS indoor positioning system

A set of 6 antennas were placed 4-5m distant from each other along a narrow (width of about 2m) corridor -as shown in Figure 3- starting 8m from the transmitter and extending to 30m distance.

The receiver board was connected to the different antennas via a switch activated via a "virtual" control panel written in the GUI program controlling the main operations. The receiving antennas were all connected to the receiving board with the same amount of cable (40m each). The received signal was digitised, acquired and analysed in a PC with signal processing algorithms written with Matlab. Single shot measures were used and no averaging over them was done.

Table 1. Summary of parameters used for the experimental work

Parameter	Value
Frequency	2.4 GHz
Chip Rate	8 Mchip/s
Sampling Rate	40 Msample/s
Power	-4dBm, i.e. 0.39mW
TX-RX Separation	8m, 13.5m, 17.5m, 21.2m, 27.2m, 30.8m

The first set of results clearly show that an accurate (to a few meters) system based on spread spectrum systems is achievable indoors with DSSS technology.

6. Logical Positioning

As described earlier in this paper, the problem of positioning an object can be reduced to the solution and combination of multiple ranging equations. The final result offered by the positioning technology of choice will be either in terms of simple range from the transmitter (probably expressed in meters of distance) or in terms of absolute coordinates (or latitude, longitude, altitude) of the target object.

A clear limit of this approach is that the description of the position of an object in terms of coordinates or longitude and latitude is only very rarely useful to the user. Most outdoor commercial positioning systems (as GPS receivers) already today offer information on a geographical map and not only in terms of coordinates.

For the large majority of cases, the user will in fact not be interested in the exact coordinates of the objects he is looking for, but will be looking for a position relative to something he is familiar with. In the context of an intelligent environment, the position information must be translated into human understandable terms. As a simple example, when a user asks the intelligent home "Where are my car keys?", he will expect a response in terms of: "Your car keys are on the table in front of the TV", and not "Your keys are at longitude x and latitude y".

The approach of a 'relative' positioning is fundamental for the success of indoor location and context-aware intelligent systems. While the problem of delivering the appropriate information could be handled at the application layer, a more radical approach, that makes use of signal characteristics measured at the physical layer, should be followed. The complications of defining accurate 'logical descriptors' should be disconnected from the application designer and standardised as much as possible in order to stimulate a market of real-live applications.

A 'plug and play' positioning technology block that translates the raw coordinates into logical descriptor is therefore necessary.

Philips Research has started investigating the background for the definition of a set of Application Programming Interfaces (API) for indoor location. Preliminary conclusions show the necessity to develop a common interface formalising a process of location request/response, the appropriate descriptors and a full hierarchy of objects within the specific location environment context.

The Geographic Markup Language (GML), which has been developed to help the programmers writing applications using location-response information, could be an appropriate mean for defining the semantic descriptors and passing them to the ranging device. GML is based on the eXtensible Markup Language (XML), which is a well known and standardised (in W3C) form of describing information.

Long is still the work in front of us and many the challenges to be overcome. An effective translation of position information into human understandable, logical representation will need at least: the dynamic formation of a map or pseudo-map of the indoor intelligent environment, an efficient (and hierarchical) storage and retrieval of map information and an effective parsing of the hierarchical maps in GML, given the context from which the request comes.

Work will be continued in each of these areas in the near future.

6. Conclusions

This paper has discussed the importance of location information on the Philips vision of ‘Ambient Intelligence’ environments, in which context-aware devices will help our daily tasks and will dramatically simplify and humanise the interaction between man and machine. The single most challenging technology block necessary to enable this vision is an accurate positioning system with a set of logical descriptors representing meaningful information to the end user. The paper described a Philips testbed architecture based on a Direct Sequence Spread Spectrum CDMA system for indoor accurate positioning and presented calculations of theoretical limits of such technology in ideal conditions. Attention has also been dedicated to describing the challenges and future work items necessary to guarantee that a formal set of logical descriptors is defined, disconnecting this task from the application layer.

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