RESOLUTION: Reconfigurable Systems for Mobile Local Communication and Positioning

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Abstract—RESOLUTION aims at developing a wireless three-dimensional (3-D) local positioning system with measurement accuracy in the centimetre regime and real-time ability. A novel frequency modulated continuous wave (FMCW) radar principle with pulsed active reflector is employed. This High-Precision-Localisation-System (HPLS) will be implemented together with common WLAN systems that are used for data communication purposes.

Due to its high data rate capabilities and large potential bandwidth, the 802.11a/n standard allocated bandwidth around 5.5 GHz is applied. Special emphasis is given to the system’s reconfigurability by efficiently using inherent synergies between the WLAN system and the HPLS approach. To allow multifunctional tasks, highly integrated system on chip (SoC) frontends will be designed on advanced CMOS or BiCMOS technology. Smart power and adaptive performance control will be applied to minimise the power consumption according to application needs. In order to enhance performance and coverage range, the transceiver features adaptive antenna combining (AAC) in the radio frequency (RF) receiver. AAC significantly decreases the power consumption, size and costs, since the number of multiple components is reduced to a minimum.

Because of the high 3-D resolution and real-time ability, which can be achieved in indoor environments with strong multipath effects and fading, novel local positioning applications, e.g. for smart factories, robotics, interactive guiding, object tracking and augmented reality are presumably leading to a large economic potential.

Index Terms—Adaptive Antenna Combining, High-Precision-Localisation-System, voltage controlled oscillator

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I. INTRODUCTION

The major goal of RESOLUTION is to reach highest positioning resolution in indoor environments employing a novel radar based approach, promising robustness in the presence of multipath propagation effects, the High-Precision-Localisation-System (HPLS). It is a radar localisation system based on synchronized Frequency Modulated Continuous Wave (FMCW) frequency ramps. The general setup consists of several stations, fixed reference stations and mobile stations to be localised, equipped with the same radar-architecture.

The stations’ architecture consists of the RF-Frontend including the voltage controlled oscillator (VCO) for frequency-ramp generation, the mixer for down-conversion and the RX- and TX-paths with a low noise power amplifier (LNA) and a power amplifier (PA), and the baseband-unit for controlling and signal-processing. Figure 1 shows the basic architecture of the HPLS. The synthesizer generates the frequency ramp that can be transmitted or sent to the mixer for down-conversion of a received signal. The A/D-converter is the interface to the baseband unit, where the signal is processed by the DSP.

The implementation of such a HPLS positioning system into a low cost WLAN transceiver and the exploitation of the inherent reconfigurability is a major goal of RESOLUTION. Different types of reconfigurability can be exploited including: 1. reuse of circuits, 2. multifunctional circuits, and 3. switching of components [1]. Advantages of the reconfigurable approaches are lower overall costs, smaller system size and higher market potential.

Adaptive Antenna Combining (AAC) helps to mitigate the impact of intersymbol interference and even profitably exploit the diversity gain inherent in multipath propagation. RESOLUTION focuses on multiple active antennas in the receiver path, where each active antenna is weighted by vector \( \mathbf{w} \). It is optimised to maximise the quality of the available signal. As illustrated in Figure 1 \( \mathbf{w} \) can be adjusted in the baseband.

The transceiver should be capable of being powered by a battery. Hence, the minimisation of power consumption is important and will be achieved by adaptive performance control. A major consumer of supply power is the power amplifier. Thus, smart power control is essential for the power...
amplifier. Furthermore, the number of activated antennas in the AAC receiver can be matched with the individual requirements. Due to their improved sensitivity, AAC allows for decreased transmit power and/or higher performance.

Integrated systems which will feature HPLS, WLAN and AAC functionality is designed in RESOLUTION. Special care is taken to meet the requirements in terms of performance, reconfigurability, size and power consumption. Advanced CMOS technology will be employed to decrease the costs in mass fabrication. In order to maximise the performance in terms of gain, noise and power consumption, sub-micron technology is applied. Among the major challenges are the low output voltage of the aggressively scaled transistors and the high losses of passive devices due to the low substrate resistivity. In this context, advanced circuits will be designed within RESOLUTION, e.g. the power amplifier, LNA and the mixer.

Optionally, for specific components, the use of BiCMOS will be considered to allow fruitful comparisons regarding performance and cost. BiCMOS devices exhibit improved properties for amplifiers and oscillators. At given performance, the cost of BiCMOS technologies is very similar to CMOS-only technologies, while providing more flexibility.

II. SYSTEM ANALYSES AND DESIGN

The network consists of four different devices:

- Access points (AP): The WLAN network is provided by at least one access point. Larger environments require more access points whose locations would be optimized for coverage and throughput purposes. Commercially available software packages are available to help organize a wireless data network.

- HPLS base stations (BS): The HPLS infrastructure is configured to yield maximum location precision. The BSs serve as absolute spatial references for the mobile stations. In this operational mode, the BSs do not need to exchange positioning information within the infrastructure. At least one BS needs control signals from the HPLS server to broadcast a periodic timing reference signal, which we will call a beacon hereafter, to synchronize local clocks. More information is available in the protocol section.

- Mobile stations (STA): Our solution provides the mobile STAs with both WLAN and HPLS functionality. Precision location information is available in the STAs only. This is to support those applications with fast moving objects such as automated forklifts or cranes.

- HPLS server: A central server is needed to enable a smooth operation of the entire system under varying conditions. The HPLS server needs access to the APs for administrative purposes such as the registration of STAs that become visible in the system space.

The synchronization of the BSs is a challenging task since the BSs might be placed at positions without line of sight (LOS) contact. One BS plays the role of a synchronization reference. The position of this reference BS has to be chosen with the aim of minimizing the multipath propagation in the direction of the BSs to be synchronized. Both synchronization of stations and measurements are performed using ramp sequences. A ramp sequence begins with an FSK header of the reference BS for pre-synchronization. An attached CW-signal will be received by the BSs and the mobile STAs in order to calibrate the individual clock frequency offsets, as shown in Figure 2 and Figure 3. Now the reference BS emits a frequency ramp that equally serves as synchronization ramp for the BSs and as a measurement ramp for the STAs. The hereby synchronized BSs emit a frequency ramp with their specific delay.

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A comprehensive simulation chain, for analysis and evaluation of various signal properties of the HPLS system is presented in Figure 4.

An FMCW transmit signal of the form
\[ s_{TX}(t) = \cos(\omega(t) \cdot t) \]

is generated by an idealized transmitter. Here, the parameter \( \mu \) describes the slope of the frequency ramp, and is determined by the ratio of bandwidth \( B \) to ramp period \( T \).

After passing through a channel block, which includes a static multipath model obtained through measurement as well as additive white noise, the signal is mixed with a frequency ramp identical to the original transmit signal. In the simple case of rectangular windowing, Fourier analysis yields a receive signal of the form
\[ s_{RX}(f) = \sum_{n=1}^{N_c} a_n \cdot \text{sinc}(\pi T (f - \mu n)) + N(f) \]

Here, \( N_c \) is the total number of path components; \( a_n \) is the modified amplitude of the \( n \)-th component; \( T \) is the observation length; \( \tau_n \) the path runtime; and \( N(f) \) is a white noise term. The signal is downsampled and the peak of the line of sight path lobe is obtained by the DSP in Figure 4, as only this peak translates directly into the runtime of the signal. Simulations have shown that it is advantageous to measure on the flank of the LOS pulse rather than at the peak, which can be impacted by temporally close multipath signals.

The optimal relative measurement level is strongly dependent on the channel scenario, i.e. channel impulse response (CIR) and noise level. The elliptical geometrical channel has been chosen for modelling and simulation since the system will be used in indoor environments where the multipath components arrive with bounded delays [2]. Using the aforementioned model we are able to simulate both LOS environments and obstructed-LOS environments by controlling the relative power of the first arriving multipath component (MPC) which is the LOS component of the channel. This is shown in Figure 4. The values of excess delay, Angle of Departure (AoD), Angle of Arrival (AoA) and path loss coefficients for each MPC are stored in matrices for future processing using the AAC algorithms described in the following section. In order to better simulate the environment in this case, we have extended the aforementioned model to 2-bounce model. The angle dependent complex impulse response of the two bounce geometric wireless communication channel can be divided into three parts as
\[ h(t, \tau, \phi) = h_{LOS}(t, \tau, \phi_0) + h_{S1}(t, \tau, \phi_1) + h_{S2}(t, \tau, \phi_2) \]

where \( t \) is the absolute time, \( \tau \) is the excess delay and \( \phi_0, \phi_1, \phi_2 \) are the AoD and AoA respectively, essential for systems with smart antennas. \( h_{LOS} \) represents the impulse response associated with the LOS path, \( h_{S1} \) represents the contributions of single bounce MPCs and \( h_{S2} \) represents the contributions of two bounce MPCs.

The following assumptions were made in the development of the proposed model:
- All scatterers lie in the same plane as the transmitter and the receiver, considered roughly parallel with the ground. Hence calculations concerning the AoD and AoA include only azimuthal coordinates.
- The scatterers are assigned Gaussian random loss coefficients with uniformly random phase shifts.
- The nodes of the model are assumed to be stationary.
- Each scatterer is assumed to be an omnidirectional reradiating [3] element whereby the impinging signal is reflected to the receiver antenna or to other scatterers.

The total number of multipath components (including LOS) arriving at the receiver is
\[ L = 1 + n_s + n_s \cdot (n_s - 1) = 1 + n_s^2 \]

where \( n_s \) is the number of scattering points. Although in [2] to [3] only single bounce scattering is taken into account, in our model we adopt two bounce scattering and the number of multipath components increases by a factor of \( n_s \), compared to that of single bounce models.

III. SYSTEM ARCHITECTURE

A. Antennas and Adaptive Antenna Combining (AAC)

The goal of the AAC is process the received signal that will be used by the HPLS algorithm so that the effect of multipath propagation is minimized. Two different approaches for the implementation of the AAC have been investigated. The first approach includes the adaptive beam forming algorithms based on minimum mean square error (MMSE) processing. These algorithms are: Sample Matrix Inverse (SMI), Recursive Least Squares (RLS), Least Mean Squares (LMS) and Constant Modulus Algorithm (CMA). The second approach is the Direction of Arrival (DoA) estimation technique which include the following algorithms: Multiple Signal Classification (MUSIC), Power Pattern Cross-Correlation (PPCC), Minimum Norm Method, Estimation of
Signal Parameters using Rational Invariance Techniques (ESPRIT) and Matrix Pencil Method. The DoA estimation techniques are robust only in the presence of spatially spread signals. In cases where both methods are used the DoA estimation techniques take place before the adaptive beam forming algorithms.

All the above algorithms require as many front-ends as the number of antenna elements on the antenna array. In order to reduce complexity, the ESPAR (Electronically Steerable Parasitic Array Radiator) antenna is proposed, which allows steering the beam to a desired direction electronically. The ESPAR antenna consists of one active radiator and some parasitic elements loaded with reactance devices [4]-[5]. The elements used for the antenna are monopoles or dipoles and the space is typically a quarter wavelength. It provides a lower-cost solution to system needs, since it needs a single receiver circuit only. The ESPAR antenna changes its radiation pattern not with RF switches but with variable reactors loaded on the parasitic elements. The reactors are usually variable capacitance (varicap) diodes that cost less than GaAs FET RF switches. ESPAR antennas can be applied to adaptive beam forming with deepest descent methods, diversity reception, and DoA estimation. To implement a given set of beam forming weights on an ESPAR antenna, a special mapping design is required and performed in RESOLUTION.

B. VCO Architecture

The VCO is the most important subcomponent of the CMOS systems. Its phase-noise performance is directly correlated to the achievable precision of the whole system.

The most common used LC oscillator topologies in radio frequency integrated circuits are the Colpitts- and the cross-coupled-oscillator. A drawback of the Colpitts-VCO compared to the cross-coupled VCO is the lower loop gain. This can be compensated with a higher tail current, but this increases the power consumption, which is not desired in mobile applications. The cross-coupled oscillator on the other hand has a higher loop gain and therefore has a lower power consumption, but the phase-noise performance is worse. To overcome the drawbacks of both architectures a new topology published by Xiaoyong Li et al [6], [7] has been used. This topology is based on a Colpitts-VCO in common-gate configuration. The gates of the transistors are not connected to a constant biasing voltage like in the case of a conventional Colpitts-oscillator. Instead at the gate a voltage that has a phase shift of 180° to the voltage at the LC-tank is applied. If the transistor is switched off, the non-constant biasing voltage has no effect on the circuit operation. But when the transistor is switched on to compensate the losses in the LC-tank the gate-source voltage is twice as high as it would be with constant biasing. Therefore the effective transconductance is increased. The required effective transconductance is given by the quality factor of the LC-tank. Thus for the same LC-tank the tail current of the gm-boosted-VCO, which is shown in Figure 5, can be reduced compared to the classical Colpitts-oscillator.

In analog radio frequency integrated circuits the VCO is usually built with a differential architecture to reduce the effect of substrate noise coupling. This is a substantial advantage for the gm-boosted-VCO. A voltage with the necessary phase-shift and an amplitude that is sufficiently large is available at the other path of the VCO. The gate can either be connected to the source or the drain of the other transistor. It is advantageous to connect it to the drain as no further biasing is necessary then. In Figure 6 a microphotograph of the fabricated test chip is shown.

C. Measurements Results

1) Tuning range

The tuning range describes the output frequencies that the oscillator is able to generate. The derivative of the tuning range is the tuning sensitivity KVCO. It is defined as the frequency change per voltage change. Ideally the tuning sensitivity would be a constant but in practice, especially when the output frequency is close to the minimal or maximal possible frequency, this is not the case.

The presented VCO is tuneable from 4.9 GHz to 6.0 GHz which can be concluded from Figure 7.
2) Phase-noise performance

Phase noise is the most important metric for an oscillator. It is a random variation in the phase of the output signal of the oscillator. Usually the phase noise close to the carrier is dominated by the flicker noise of the oscillator components. In this region the phase noise is proportional to $1/f^3$. Above the cut-off frequency the phase noise is mainly composed of the thermal noise of the oscillator devices. The noise is proportional to $1/f^2$ in this region. Phase noise is defined as the ratio of the output power at the oscillation frequency divided by the noise power in a 1 Hz bandwidth. The phase-noise performance of this VCO is -99 dBc/Hz at an offset frequency of 1 MHz and its phase noise performance is shown in Figure 8.

![Figure 8: phase-noise performance of VCO](image)

IV. CONCLUSION

RESOLUTION aims at achieving the highest positioning resolution in local environments through the integration of HPLS, WLAN and AAC. The localisation system is based on FMCW frequency ramps. The modelling and the simulation model of the indoor environment play a crucial role in the implementation of the system. The amelioration of the geometrical elliptical model so as to meet the actual conditions measured, as far as the multipath components are concerned, has to be conducted. In this improved model, the time difference between the LOS and the first multipath component has to be less than 5 ns and the AoA bigger than the 15° so as to distinguish the LOS with the use of AAC. All the AAC algorithms perform well in narrowband signals, thus the challenge to overcome is to make them operating for wideband signals as are the signals of the HPLS system. Furthermore, the optimization of the VCO in terms of tuning range and phase-noise performance has to be conducted. An error of about 1 ns in the peak detection will introduce an error of about 30 cm, so the need for all the components to work perfectly is imperative.

REFERENCES


