ON ACCURATE, LOW-COMPLEXITY QUASI DOPPLER BASED LOCALIZATION

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ABSTRACT

The aim of this paper is to discuss the Quasi Doppler or Pseudo Doppler bearing estimation method and show how contemporary digital signal processing and some minimal a priori knowledge of the signal can improve the method and make it relevant even today for low complexity localization purposes. The basic idea is that non-uniform switching of antennas on the transmitter side, and careful examination of phase jumps can mitigate or even completely cancel out the adverse effects of phase changes (due to modulation, clock mismatch, clock jitter) on the bearing estimation process.

KEYWORDS

Localization, Quasi Doppler, Pseudo Doppler, Digital Signal Processing

1 INTRODUCTION

Since the first use of directional antennas [11] accurate direction estimation and localization have always been features widely needed. Contemporary research is dominated by high-resolution, multi-channel algorithms like ESPRIT, MUSIC, and SAGE that deliver accurate and reliable bearing results at the cost of complexity and resource requirements [14]. Small, power constrained devices need a different approach. One simple, single-channel method that promises better accuracy than a directional antenna is the Doppler bearing estimation method. It involves a single, omnidirectional antenna rotating around a center superimposing a periodic Doppler shift on the measured signal, which is the function of the Angle of Arrival (AoA). Extracting this information can be a simple, analog process, which is not surprising given it was developed in an era of purely analog signal processing with newer applications still carrying this legacy. The next evolutionary step was the replacement of antenna rotation by subsequential switching among antennas equally distributed around a circle [4, 11] forming a uniform circular array (UCA). This is the Quasi Doppler (or Pseudo Doppler) bearing estimation method with the advantage of not requiring moving parts, and thus can form the basis of a complete localization solution.

The simplicity of the method and the fact that it only requires rudimentary RF hardware, has led to its popularity and wide adoption. Use cases include the traditional Doppler method for indoor sensor networks [3], a plethora of ham radio projects [7, 8], even setups with moving vehicles [1, 13]. Yet as with all simple principles the devil is in the details, and straightforward implementations tend to overlook opportunities and the complexity of important aspects. For example, the presence of a central, antenna mounting mast can introduce reflections and scattering [5]. Individual antenna elements have to be carefully matched so that they don't introduce additional phase shifts. Also individual antenna distances should be less than the wavelength to avoid phase ambiguity, even though there are methods to handle situations where that is not true [5]. Phase shift measurement in itself is not trivial and besides the phase ambiguity there is also a sine fitting issue [6], which is explained in a later section. Abrupt switching can introduce signal deterioration if the signal is not a simple sine wave but a modulated one carrying information [9],

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and the goal is not only the bearing estimation but the extraction of said information as well. Over the years much effort went into addressing the shortcomings of the method. To counter the adverse effect of hard switching on information content, smooth switching functions were investigated [2]. An adaptive approach was proposed [10] to completely remove switching related signal changes in the output signal. To address issues associated with noisy radio channel, PLLs locked on each antenna were suggested [6]. The application of directional antennas promises higher signal to noise ratio and thus longer effective radius for the system at the expense of periodically losing the signal [14]. Interferometric approach made it possible among others to operate the system at lower frequencies [12]. Each suggestion improved the Quasi Doppler approach, but kept the legacy of the analog signal processing concept. State of the art signal processing technology, however, makes it possible to utilize other opportunities not addressed until now.

The main contributions of this paper are (1) identifying important problems and issues involved in the Quasi Doppler signal processing and describing solutions, (2) introduction of an implementation based on the solutions, and (3) providing experimental results. The paper shows how with carefully selected antenna switching and phase jump detection the Quasi Doppler method can be updated to become a modulation, clock mismatch, and clock jitter resistant, accurate bearing estimation without altering or adversely affecting signal information content.

The rest of the paper is organized as follows: Section 2 summarizes the traditional Doppler method, introduces the Quasi Doppler approach, and finally explains the concept of a complete localization system based around the Quasi Doppler bearing estimation. Section 3 shows a

2 OVERVIEW

2.1 Doppler method summary

Assume that a single, omnidirectional ant[…] sensing a simple sine wave emitted by a […] omnidirectional antenna in free space w[…] multipath propagation. For the sake of sim[…] both the transmitter and the receiver shal[…] pletely reside in the $z = 0$ plane at all tim[…] receiver shall be at (x, y), and signal am[…] (A), carrier frequency (f_c), and phase (ϕ) s[…] constant. Assume also that the transmitte[…] away, thus the signal reaching the receiv[…] safely be considered to be a plane wave. […] simple scalar projection the received sign[…] be written as (1), where $\beta = \frac{2\pi}{\lambda}$ and λ is the wavelength for a wave with f_c frequency and θ is the azimuth or AoA of the plane wave.

$$f(x,y,t) = A\cos\left(2\pi f_c t + \phi + \beta(x\cos\theta + y\sin\theta)\right) \quad (1)$$

With this equation in mind, let us look at the traditional Doppler method for direction finding that is based on the Doppler effect: the measured frequency (and thus the phase) changes as the signal source or the receiver starts moving with regards to each other. Let us equip the receiver with an antenna that can be moved around clockwise or counterclockwise on a circle as shown in Figure1.

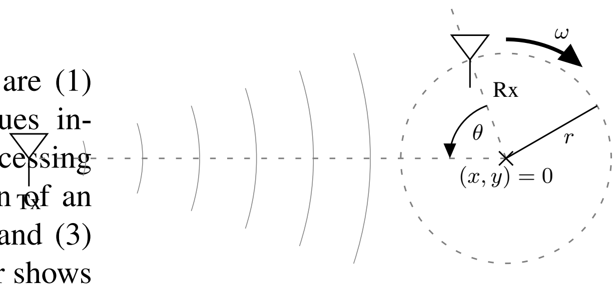

Figure 1: Doppler method with a receiver antenna orbiting with a constant angular frequency ω on a circle with radius r receiving the signal from the transmitter at time $t = 0$.

The heading of such an antenna system shall be defined as the azimuth where the actual antenna resides at $t = 0$. As the receiver antenna is rotating with constant angular velocity it alternates between moving away from and moving towards the source. In both cases frequency shifts can be observed, based on which the actual signal AoA can be calculated. If the receiver is moving on a circle with a radius of r with an angular frequency of ω we can write (2).

$$\begin{aligned} & x\cos\theta + y\sin\theta \\ & = r\cos(\omega t)\cos\theta + r\sin(\omega t)\sin\theta \\ & = r\cos(\omega t - \theta) \end{aligned} \qquad (2)$$

Substituting this result into (1) yields the fundamental equation for the Doppler method.

$$\begin{aligned} & f(r,\theta,t) = \\ & A\cos\left(2\pi f_c t + \phi + \beta r\cos(\omega t - \theta)\right) \end{aligned} \qquad (3)$$

Eq. (3) means that the signal suffers a phase modulation because of the circular motion. Important here is that the modulating signal $\beta r\cos(\omega t - \theta)$ contains the AoA as a simple phase shift, thus comparing it with the reference $\cos(\omega t)$ gives the AoA. A received signal is shown on Figure2. Note that in this case the phase changed between $-180°$ and $180°$, however, this is the result of the particular measurement setup and is not characteristic. With different setups the phase change may be less or even more, in latter case the phase will wrap around.

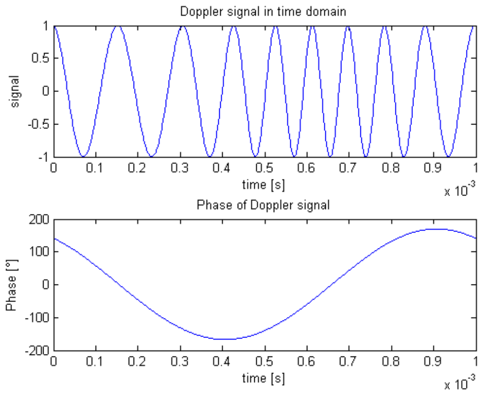

Figure 2: Upper part is the phase modulated signal, lower part is the modulating signal or phase change due to antenna rotation.

2.2 Quasi Doppler method summary

The Quasi Doppler method omits the moving antenna concept in favor of switching between stationary antennas of a UCA. Figure3 shows one possible setup with three antennas, other setups may include more antennas. The heading of such an antenna system shall be defined as the azimuth where the first antenna resides. The antennas are numbered in the order they get switched to.

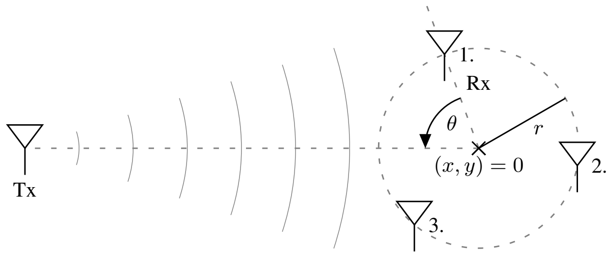

Figure 3: Quasi Doppler method with UCA antenna arrangement.

To better understand the relationship between the Doppler and the Quasi Doppler method picture the following: start with the Doppler method, an antenna emitting a sine wave while the receiver antenna is rotating. Stop the antenna at three points, e.g. at an azimuth of $60°$, $180°$, and finally $300°$. Initially the time spent standing still at one position shall be low compared to the time moving. By gradually increasing the time standing still and decreasing the time while moving we'll end up with a Quasi Doppler signal, see Figure4. The continuous curve without abrupt changes results from the Doppler method, the one with abrupt changes from the Quasi Doppler method.

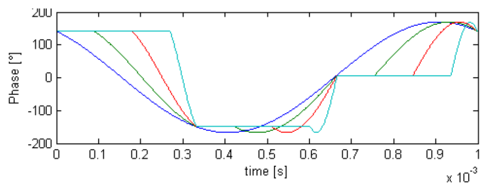

Figure 4: Modulating signal of an antenna alternatively rotating and standing still. Time standing still is increased in four steps.

We see that the Quasi Doppler method is the sampling of the Doppler method's modulating signal. Phase jumps similar to the ones seen on Figure4 will occur probably everytime the receiver switches antennas. Phase jumps are extensively discussed in [12].

To be perfectly precise we should assume that the first switch from the last antenna to the first antenna took place at $t = 0$, but without time synchronization any observer will only see it with regards to its own time scale τ. Note that even so the original analog reference $\cos(\omega t)$ can be reconstructed (4) given we know the times when switched to the first antenna: $\tau_1, \tau_2, ...$

$$\begin{aligned}\cos(\omega t) &= \cos(\omega t - 2\pi k) = \\ &= \cos(2\pi\frac{t}{T} - 2\pi\frac{t_n}{T}) = \\ = \cos(2\pi\frac{\tau - \tau_1}{T} &- 2\pi\frac{\tau_n - \tau_1}{T}) = \\ &= \cos(2\pi\frac{\tau - \tau_n}{T}) = \\ &= \cos(2\pi\frac{\tau - \tau_n}{\tau_{n+1} - \tau_n}) \end{aligned} \quad (4)$$

2.3 Localization concept based on the Quasi Doppler method

Given a method for bearing estimation a complete localization system can be built. However, it seems that neither of the previous methods are directly applicable, since receivers usually have to be small and simple, thus complex antenna rotating mechanisms or even stationary but large UCAs are out of question. One fact not mentioned until now is that the concepts discussed are symmetrical. The rotating antenna or UCA can be placed on the receiver side to measure AoA from the receiver's point of view (as introduced), or it can be placed on the transmitter side to inform the receiver at which azimuth it resides from the transmitters point of view. For either approach the measured signals will look like the ones in Figure2 and 4, thus the Doppler and Quasi Doppler method are still applicable, but the receiver can become a small, single antenna system. Figure5 shows a setup with two transmitters and one receiver, where simple triangulation can calculate position given the transmitters' location and orientation are known.

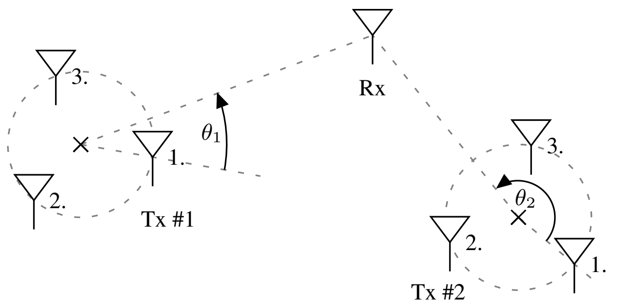

Figure 5: Quasi Doppler based localization system.

3 SIGNAL PROCESSING

In this section increasingly improved Quasi Doppler signal processing approaches are discussed. We start with a simple and general solution, and work our way through more and more complex concepts with the goal to arrive at a processing approach that can be utilized by the receiver node described previously in the localization system section. The concept is straightforward: extract the phase change associated with antenna rotation/switching and compare it with the reference $\cos(\omega t)$ to get AoA result. There are of course plenty of other choices and processing methods not presented here, but the goal is not to give an exhaustive list but rather to point out important aspects and issues that need to be considered.

3.1 Doppler and Quasi Doppler method

Figure6 shows a setup, where first a phase demodulator (PM dem) extracts and unwraps the phase, which includes Doppler and carrier frequency related phase shifts alike. This latter results in a DC offset in the derivative signal, and can be removed at that point with a High Pass Filter (HPF). Subsequent integration yields the modulating signal, and a very narrow Band Pass Filter (BPF) then takes care of noise or harmonics filtering in the switched antenna case. Comparing the output to the reference gives the AoA. To be perfectly precise the BPF in the diagram introduces delay, so in order to get the true AoA some correction is required. For the sake of simplicity the end result correction/calibration block will not be included on the figures.

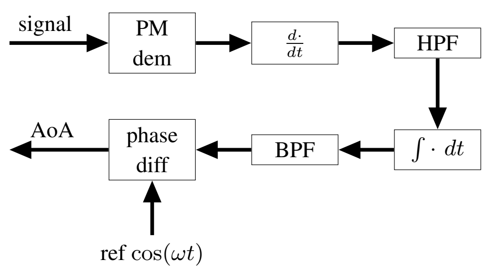

Figure 6: Signal processing for the Doppler and Quasi Doppler method.

Two main problems arise with this simplistic approach. The more serious are **other phase**

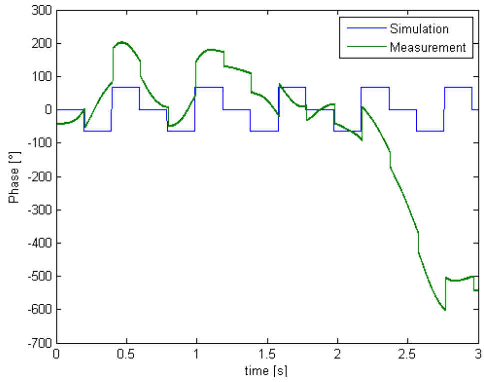

Figure 7: Simulated modulating signal compared to actual measurements suffering clock instability.

changing factors like modulation, clock mismatch, clock jitter, and frequency instability. See Figure7 for a situation where phase changes due to frequency instability are in the order of the phase jumps. One solution for this problem is to increase frequency stability and/or decrease antenna switching time period so that frequencies stay constant with greater probability during the observed time window.

The other solution is to carefully pick phase jumps from the modulating signal, however, a minor issue here is that **phase jumps are not instantaneous** so we cannot possibly pinpoint one sample that carries all the information, and thus a small time window has to be integrated. This means that some noise will end up in the integration as well, but if the time window is sufficiently small, noisy samples do not have a significant effect.

3.2 Quasi Doppler method: fine time window selector

If we have access to the antenna switching signal, (the UCA is on the receiver side) switching times can be utilized to pick phase jumps. See Figure8 for the setup. A side effect of introducing discrete time windows around switching times is that we no longer constantly provide the modulating signal, we only have results available when a switch happened, as indicated by the dashed, gray arrows on the diagram. Also recall (4), we don't have to have access to the full $\cos(\omega t)$ reference, we can deduce it.

The problem here is the **phase ambiguity** inherent in phase demodulation. Phase calculations of any kind can suffer a $\pm N360°$ error, which

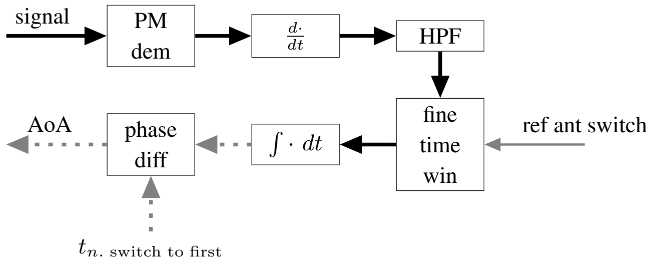

Figure 8: Quasi Doppler method processing with fine time window selector.

can render this approach useless introducing the sine fitting problem: distortion of the modulating signal to a point where it does not resemble a sine wave anymore. Since phase calculations are more likely to give smaller results, decreasing the magnitude of phase jumps may solve the issue. Thus distance between antennas could be decreased or (if the antennas allow it) the wavelength increased.

3.3 Quasi Doppler method: fine time window selector, phase ambiguity correction.

A so far unpublished approach for phase ambiguity correction stems from the following realization: Summing phase jumps is practically integrating a sampled sine wave, thus if adding complete periods (as many phase jumps as number of antennas) the result should be very close to zero. If we correct the measurements with $\pm 360°$ in a consistent manner then the result that gives the value closest to zero when summed and the highest value when absolute summed is likely the valid one. There might be cases this step does not give a single solution. Figure9 shows a setup, where phase ambiguity is corrected so that the output resembles the modulating sine wave.

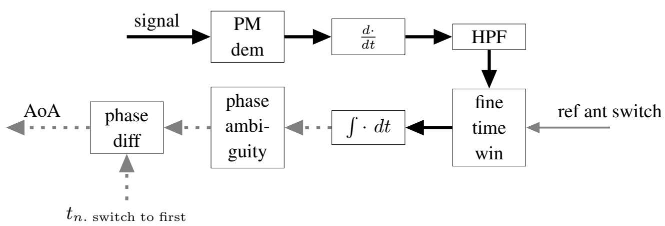

Figure 9: Quasi Doppler method processing with fine time window selector, phase ambiguity correction.

The problem here arises when the receiver has **no access to the switching reference**, and there is no precise timing synchronization between transmitter and receiver.

3.4 Quasi Doppler method: fine time window selector, phase ambiguity correction, coarse time slot

With no switching reference we can still find phase jumps in the measurement. Assume that we know which phase jump resulted from switching to the first antenna. One approach is to look for the maximum value in coarse time slots, and to dynamically adjust said time slots based on the position of a previous couple phase jumps. See Figure10 for details.

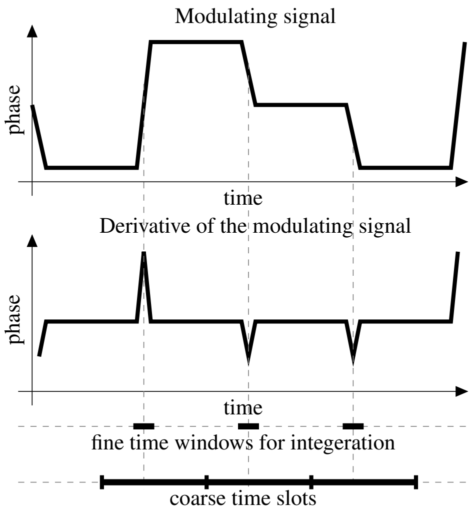

Figure 10: The fine time windows and coarse time slots for phase jump selection in relation to the modulating signal and its derivative.

A diagram is shown on Figure11 and the result on Figure12, here the phase jumps in actual measurements were found and colored red by the described method.

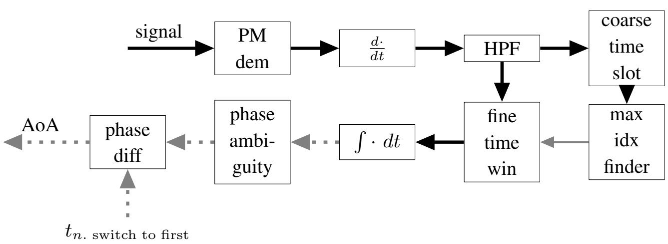

Figure 11: Quasi Doppler method processing with fine time window selector, phase ambiguity correction, coarse time slot.

The still remaining problem is that the system is completely symmetrical with regard to switching, there is no way to tell when switched to the first antenna, thus there is no reference. This results in an **azimuth ambiguity**, which in the case of three antennas will give three potential AoAs each of them $\frac{360°}{\text{number of antennas}} = \frac{360°}{3} = 120°$ apart.

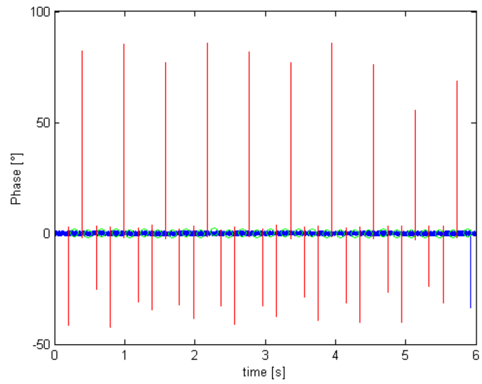

Figure 12: Derivative of the modulating signal for a three antenna measurement. Coarse time slot borders marked with green circles, phase jumps samples colored red.

3.5 Quasi Doppler method: fine time window selector, phase ambiguity correction, sliding time windows, no reference

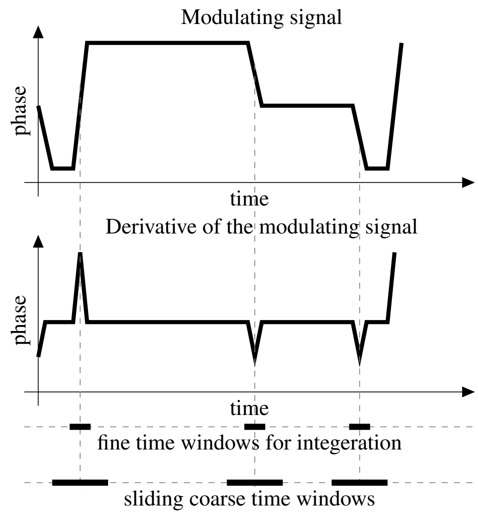

Figure 13: The fine time windows and sliding coarse time windows for phase jump selection in relation to the modulating signal and its derivative.

One novel solution to address the lack of reference issue is to have non-uniform time distances between switching times. That way we can have for a e.g. three antenna system three coarse time windows always at the proper, non-uniform time distances apart corresponding to the three switch events. We can then "slide" these three windows together along the signal and if we find a time when the contents give good results (value close to zero if summed, value high if absolute summed), then we know the onset time of the first antenna switching and simultaneously have all the other switching times as well. See Figure13 for details.

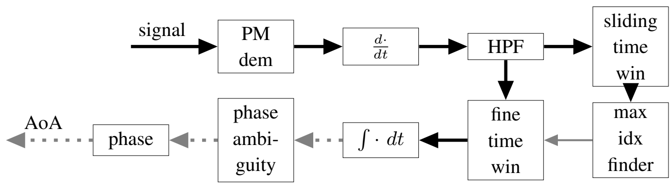

Figure 14: Quasi Doppler method processing with fine time window selector, phase ambiguity correction, sliding time windows, and no reference

Figure14 shows a diagram for such a setup. After the PM demodulator extracted the phase and the derivative was calculated, the HPF removes DC content associated with the carrier frequency. At this point the signal is split in two directions. One direction includes the sliding time windows which will pick coarse time windows around the switches. A maximum finder then will look for the indexes of maximal phase changes in the coarse time windows assuming that it is an antenna switching phase jump. The fine time window picker then will use the position of the maximums and the output of the HPF to provide samples around the phase jump, which are then integrated. The phase ambiguity correction tries to find the best solution for the sine-fitting problem, but it can also help the sliding time window block decide whether the current results are valid or not. The subsequential phase calculation gives AoA, which may require some correction/calibration. With this approach it is possible to give bearing estimation without reference. Furthermore, once a good result is found the onset time and the results of the fine time window can be used to remove the phase jumps from the signal and reconstruct the original without the Doppler shifts.

4 MEASUREMENT RESULTS

In this section our initial measurement results are presented. All the measurements were taken in an urban outdoor environment with surrounding buildings and trees. We have placed a three antenna Quasi Doppler transmitter at the center of a circle with a radius of 9 m, the single antenna receiver moved on the circle perimeter. Measurements were taken at several measurement points each roughly $30°$ apart.

The carrier frequency was chosen 430 MHz giving a wavelength of 69.72 cm, the setup had antennas 22 cm apart. Two different monopole antennas were tested: the SMA703 and the ANT-433-CW-HWR-SMA. The latter proved to emit more efficiently, but otherwise had no effect on the bearing estimation process. Metal plates under the monopole antennas were the substitute for the ground plane and were essential for accurate measurements. Without the plates the measurements from each antenna would suffer a random but permanent phase shift due to line mismatching that would render the method useless. For the antenna switching we had a custom built hardware component, which would switch between the three antennas at every 200 ms. Measurements were conducted with the Software Defined Radio (SDR) concept in mind using x86 PCs and USRPs on the receiver and transmitter sides alike. GNUradio was used to record and transmit. The sampling frequency was 1 MHz, the number of samples recorded 6,000,000 at every measurement point. Samples were complex, consisting of In-Phase and Quadrature parts. Results are shown on Figure15 and Figure16.

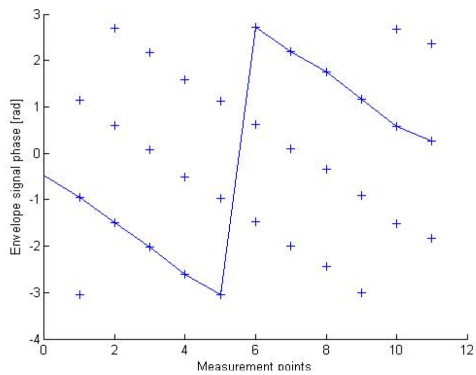

Figure 15: AoA measurement results at different azimuth positions for a three antenna setup with $120°$ azimuth ambiguity.

For Figure15 the x axes shows the different measurement points on the circle, the y axes shows the AoA in radians. Around 20 to 30 consecutive phase jumps were utilized to estimate the modulating signal's phase and thus the AoA for every point on the figure. Even with uniform antenna switching periods resulting in azimuth ambiguity the anticipated linear trend is clearly visible. Note that the break in the line is the result of the phase wrapping around.

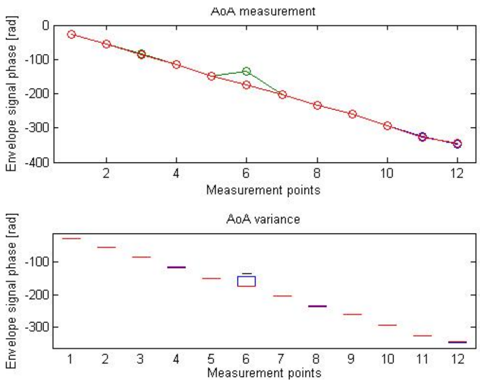

Figure 16: Summary of results for a three antenna setup for three independent measurement runs.

Figure16 shows the summary of three measurement runs without the azimuth ambiguity. The results indicate an accuracy in the order of degrees, which means an accuracy of around 20 cm at a distance of 10 m. Note that this resulted instantly from only a few seconds of observation. With increased number of phase jumps and thus with more measurements to average the accuracy further improves.

5 CONCLUSION

The paper gave an overview of the Doppler theory, and has shown a step by step guide to address the problems involved in using the concept for a localization system. The paper has also shown that using the buffering, maximum search, and accumulation capabilities of contemporary digital systems it becomes possible to revisit and improve on the Quasi Doppler method. Promising measurement results showed that phase difference detection in urban environment is not only possible but can be quite accurate as well using the above described solutions, thus a complete positioning system may very well operate on the Quasi Doppler basis.

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