Dual Tone Approach for Unambiguous Six-Port Based Interferometric Distance Measurements

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***Abstract*— This publication shows an approach for absolute, unambiguous distance measurements with a Six-Port radar at 24 GHz. Such an interferometric radar has the drawback of ambiguity problem concerning phase, limiting the measuring distance to half of the used wavelength. This can be solved with the presented dual tone system using the resulting beat frequency between two tones to determine an absolute position within even several wavelengths. In the following, this system will be presented along with simulations and measurements proving the concept.**

***Index Terms*— Distance measurement, Interferometry, Phase measurement, Radar, Six-Port**

I. INTRODUCTION

High accuracy distance measurement is a topic of high interest to industrial, as well as biomedical sector to distinguish not only the correct position, but also parameters like vibrations and slow movements of huge machines [1]. In the medical sector further applications are heart beat monitoring and respiration rate detection [2].

There are not many contactless measuring strategies to achieve the often required accuracies down to 1 µm. In common systems usually Laser based devices are used [3], but they have the drawback of a small measuring range, or high costs.

Other concepts for remote distance measuring are radar based methods. Usually *Frequency Modulated Continuous Wave* (FMCW) systems are used [4], but their accuracy is bandwidth limited and at least within the lower ISM-Bands the bandwidth, i.e. the achievable accuracy, will not be high enough. Therefore, you have to evaluate the phase with high computational effort as well.

For a low-cost system it is also possible to choose a CW strategy and to analyze only the phase to distinguish the distance of the target, which results in low system complexity. This publication will describe a Six-Port [5]–[7] based CW receiver, because of the known excellent phase measuring capabilities [8] and therefore a high precision distance evaluation. The only problem of CW radar systems with phase evaluation is the given ambiguity shorten the measuring range to only half of the used wavelength. However, this drawback can be eliminated by using two frequencies, which will be shown and discussed in this publication.

II. DISTANCE EVALUATION WITH SIX-PORT

Measuring distances with a Six-Port receiver is an interferometric method, comparing the phases of a transmitted signal with the one reflected by the target. This principle is shown in Fig. 1. A VCO is used to generate a radio frequency (RF) signal, from which a small portion is fed into the Six-Port as the reference signal. The main part of the signal is radiated by the antenna. The scattered signal is decoupled from the sent one by a radar coupling structure and fed into the second Six-Port input.

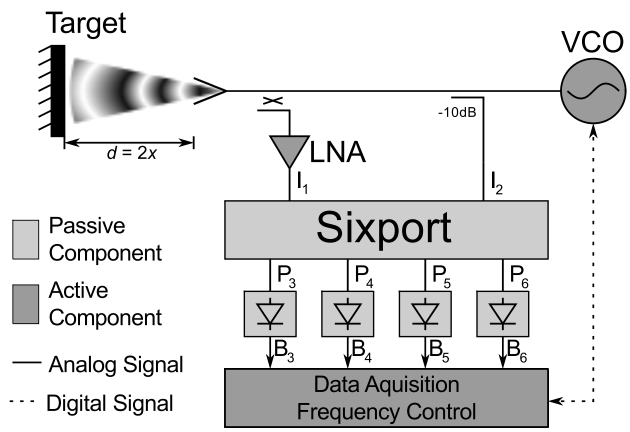

Fig. 1. Overview of a Six-Port radar front-end for distance measurements.

The Six-Port structure itself can be understood as an homodyne concept, transferring the two input signals I_1 and I_2, superimposed with discrete phase shifts of 90 °, 180 °, 270 ° and 360 °, into baseband by diode detectors [9]. These detectors measure the power at the four ports (P_3 to P_6) producing four DC-voltages (B_3 to B_6), from which the complex vector z can be calculated:

$$\underline{z} = (B_3 - B_4) + j(B_5 - B_6). \quad (1)$$

The phase and amplitude of this vector exhibit the information of the input signal amplitudes, as well as the difference phase $\Delta\sigma$ between them. In this scenario we are only interested in the phase, because it includes the information of the distance to the target. This phase can be calculated by building the argument of the complex vector, for example using the *atan2* function:

$$\Delta\sigma = \arg\{\underline{z}\} = \text{atan2}\left(\Im\{\underline{z}\}, \Re\{\underline{z}\}\right). \quad (2)$$

Knowing the used transmission frequency and measured phase $\Delta\sigma$, the distance d can be calculated using the following equation:

$$d = \frac{x}{2} = \Delta\sigma \cdot \frac{c}{2 \cdot 2\pi \cdot f_{RF}}. \quad (3)$$

III. Solving the Ambiguity

It has been shown in previous publications that this setup is capable of the needed 1 µm accuracies, but has the disadvantage of an unambiguity range of only $\frac{\lambda}{2}$, where λ corresponds to the used signal frequency [1]. This means a limited measurement range or the constraint of only relative measurements of a target.

Nevertheless, there are possibilities to perform an absolute distance measurement. A simple method is to count the phase jumps and add the appropriate offset. Unfortunately, for this procedure at least one absolute reference position has to be known. Furthermore, the movements in the system have to be slow and continuous to safely detect each of those jumps.

The approach adopted to the Six-Port system in this paper is to use two different frequencies having a spacing of $f_B = f_2 - f_1$ between them and measuring the phase difference $\Delta\sigma$ at both frequencies.

$$\sigma_1(t) = 2\pi f_1 t + \varphi_{10} \quad (4)$$

$$\sigma_2(t) = 2\pi f_2 t + \varphi_{20} \quad (5)$$

$$\Delta\sigma_B = 2\pi \cdot (f_2 - f_1)t + \varphi_{20} - \varphi_{10} \quad (6)$$

Because of the different wavelengths of both signals, this leads to two different relative phases σ_1, σ_2. These two phase measurements are ambiguous, but subtracting the phases at each measuring point a difference phase $\Delta\sigma_B$, i.e. the phase of the so called beat frequency, can be calculated (4)-(6). This beat frequency is the same as f_B and can be in the range of a few ten Megahertz up to the bandwidth of the radar front-end.

Using the relationship $t = \frac{x}{c}$ between time and velocity of the RF signal, (7) obviously shows, that a distance calculation can also be performed on the difference phase, and therefore based on the beat frequency. The term σ_0 combines the two possible static phase offsets $\varphi_{10}, \varphi_{20}$ and has to be measured and eliminated once by determine a known target distance. This offset includes the phase delay caused by the traveling wave through microstrip lines, LNA, antenna feed as well as imperfections inside the Six-Port structure.

$$\Delta\sigma_B = 2\pi \cdot (f_2 - f_1)\frac{x}{c} + \sigma_0 \quad (7)$$

This coarse distance, i.e. the unambiguous one based on the difference phase, can now be calculated to:

$$d_{\text{coarse}} = \frac{x_{\text{coarse}}}{2} = \Delta\sigma_B \cdot \frac{c}{2 \cdot 2\pi \cdot B}. \quad (8)$$

This means, the phase of 0 to 2π is mapped onto the wavelength of the beat frequency leading to an unambiguous region of d_{max}.

$$d_{\text{max}} = \frac{c}{2 \cdot f_B} = \frac{c}{2 \cdot (f_2 - f_1)} \quad (9)$$

This extends the unambiguous range up to several meters, without influencing the sub-wavelength accuracy of system at each single frequency.

To prove the shown equations and determine the influence of system parameters a simulation was performed. The parameters for the evaluation were a center frequency of 24 GHz and a frequency span of 2.4 GHz generating the two frequencies at f_1 and f_2, respectively (10)-(11). This span is quite high and not within the allowed ISM-Band, but is chosen for illustrating the concept of this paper, as for lower bandwidths it is hard to see the different phase relations. Furthermore, the resulting unambiguous range of $d_{max} \approx 60$ mm can be achieved with the available reference measuring system to verify the simulation results.

$$f_1 = f_m - \frac{f_B}{2} = 22.8\,\text{GHz} \quad (10)$$

$$f_2 = f_m + \frac{f_B}{2} = 25.2\,\text{GHz} \quad (11)$$

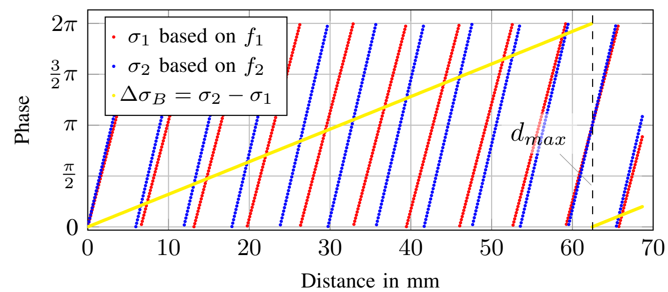

Fig. 2. Phase responses for two different frequencies (blue, red) at the same distance and corresponding beat frequency phase (yellow).

Fig. 2 illustrates the system simulation of the shown procedure with the mentioned frequencies. The ambiguity and the resulting jumps in the phase σ_1 are clearly visible. To eliminate this ambiguity, the second frequency f_2 is used on the same measuring channel. The corresponding second phase σ_2 has a similar ambiguity behavior, but by building the difference of these two measured phases, a linear relationship between the difference phase $\Delta\sigma_B$ and the simulated distance can be observed. As you can see at the right side of the measuring range, this resulting phase of the beat frequency becomes also ambiguous if the measured distance gets greater than d_{max}. This basic concept is also known as *nonius* for measurement application.

IV. Measurement Results

The used measuring setup was previously well described in [10]. For this setup shown in Fig. 1 an *Agilent E8267D* signal generator was used as VCO to obtain the two accurate frequencies. The system was tested with different frequency spacings between 100 MHz and 6 GHz. For demonstration, only the results for a long range capable and ISM-Band specific spacing of 250 MHz and a second measurement at 2.4 GHz to verify the simulation results are shown here.

Fig. 3 shows the measurement-based proof of the shown simulation. In the upper plot you can see the raw measured phases as well as the calculated difference. It obvious that linearization techniques have to be implemented for this raw

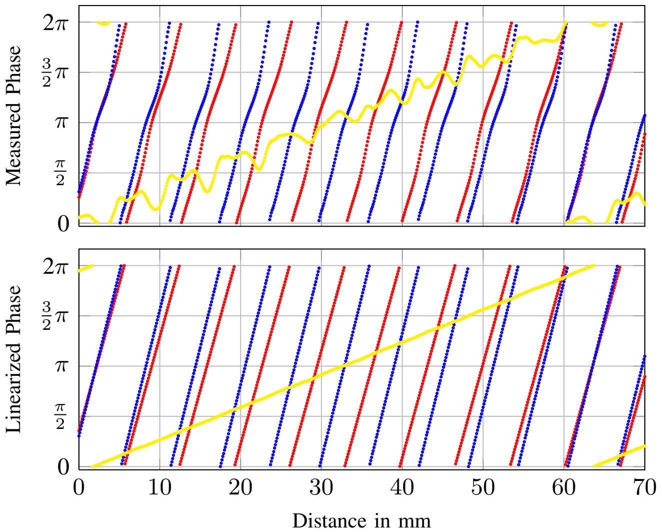

Fig. 3. Raw measured phases (top) in RAD with the dual tone system for a frequency spacing of 2.4 GHz and linearized phases of the same signal (bottom).

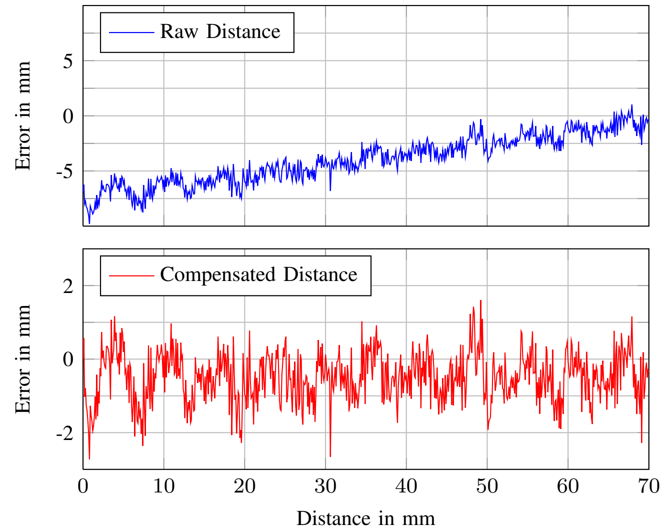

Fig. 5. Calculated distance error at 250 MHz frequency spacing without compensation (top) and compensated for the beat frequency shift (bottom).

phase response. The lower plot shows the same measurement with additional linearizing which achieves an excellent matching to the simulation compared to Fig. 9.

From the linearized phase difference the absolute distance can be calculated and the error, that means the difference to the actual moved position, can be calculated. This error, presented only in the unambiguous range up to d_{max}, is shown in Fig. 4. It is clear to see that there is a linear error in the measurement. This means, that the wavelength of the beat frequency is not exactly determined through the used bandwidth f_B. Thus, the phase offset σ_0 in (7) is frequency-dependent.

The source for this error has to be distinguished in future evaluations. Possible reasons are the moving of the phase center of the horn antenna, dispersion of the waveguide or

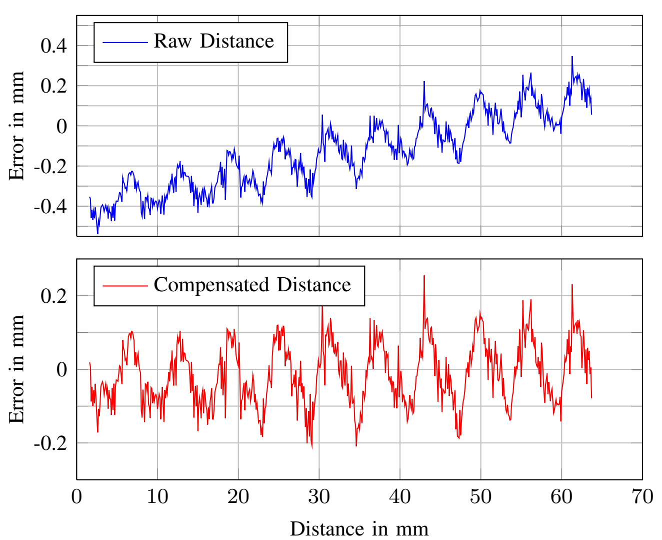

Fig. 4. Calculated distance error at 2.4 GHz frequency spacing without compensation (top) and compensated for the beat frequency shift (bottom).

a frequency dependent phase shift inside the LNA.

Nevertheless, this error is very reproducible and hence easy to remove. The lower plot shows the linear corrected distance and the error, which is inside the band of $\pm 200\,\mu m$.

These measurements are for a frequency spacing of 2.4 GHz, which is not allowed in the 24 GHz ISM-Bands. To prove the concept also for smaller and ISM-conform bandwidth, another measurement was performed with an frequency spacing of only 250 MHz. The results are shown in Fig. 5. Here the error is slightly higher, but still small enough to identify the ambiguity region, needed for the following high accuracy measurements examining the both native phase responses.

The announced errors refer only to the calculation of the coarse distance using the beat frequency. Hence, this is not the system accuracy, because the overall error depends on the evaluation of the two single RF phases, as documented in [10]: After determining the actual period by the shown nonius calculation a static offset, representing the period of interest, is added to the highly accurate phase value, e.g. σ_2.

V. Conclusion

In this paper a concept for solving the ambiguity issue of Six-Port based interferometric radar systems is presented. By the help of two CW signals at different frequencies the ambiguity free area can be enhanced from original half wavelength to several wavelengths. This paper also compares simulation to measured results that show good agreement and deals with the effect of linearizing techniques. For a frequency span of 2.4 GHz an unambiguous range of about 60 mm can be ensured. The nonius-like two-tone concept is only used to determine the actual period of one of the signals and delivers an offset value that is added to the highly accurate phase. By the help of the presented concept a system for measuring absolute distances of a target with micrometer accuracy is feasible, featuring low-cost one-dimensional positioning devices, e.g. for industrial applications.

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