A Novel AoA Positioning Solution for Wireless Ad Hoc Networks Based on Six-Port Technology

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Abstract. Mobile device positioning in ad hoc networks is a crucial issue due to the network properties and hardware limitations of particular devices (nodes). In this paper, a new conception of mobile device based on software defined radio architecture for mobile positioning in ad hoc networks is proposed. Six-port technology is implemented into our software defined radio receiver. Angle of arrival localization method as self positioning approach is implemented. The aim of the paper is to present an interaction of specific positioning method with proposed receiver conception. Moreover, we analyze various situation scenarios and their impact on the positioning accuracy, e.g., mutual position of the nodes, radio channel characteristics.

Keywords: Angle of arrival method, mobile positioning, positioning error, wire-less ad hoc networks, software defined radio receiver, six-port technology.

1 Introduction

Positioning in wireless ad hoc networks plays a major role in the development of geographic aware routing and multicasting protocols that result in new more efficient ways for routing data in multihop networks. The positioning in these net-works is specific. It is given by network properties and hardware limitations of network devices. Most of proposed positioning methods for ad hoc networks are based on actual capabilities of devices; therefore the positioning accuracy is not excellent [1], [2], [3] and [4]. The capabilities of individual devices are very limited at the present time. In the near future, the practical use of receivers based on Software Defined Radio (SDR) will increase abilities of given devices and also facilities of offered applications. Implementation of SDR is necessary in ad hoc net-works, which could work at the different frequency bands and they are based on various communication platforms. This application could contribute for improvement of particular functions, e.g. positioning of devices in the networks.

In this paper, we propose the application of SDR based on six-port technology determined for wireless ad hoc networks positioning. Our proposal is based on the Angle of Arrival (AoA) positioning method. The combination of SDR and Six-Port Technology (SPT) provides a great flexibility in system configuration, a significant reduction in system development cost, and also a high potential for soft-ware reuse. We decided to use this receiver solution because we think that SDR means future in the wireless communication. Selection of positioning method results from good ability to measure phase difference i.e. to determine angle of arrival by means of SPT. On the other hand, this method is only exemplar solution for positioning utilization. Implementation of SDR in ad hoc networks is not new idea, but conception of SDR, AoA and ad hoc network is solution of the future. Many researchers have paid an attention on the issue of angle of arrival estimation by six-port technology [13], [14] and [15]. But any of the works investigated the impact of radio channel on a node mobile positioning. It is aim of this paper, the investigation of radio channel impact on mobile positioning.

This paper depicts untraditional realization of AoA method because the pro-posed method is implemented as a self-positioning solution. In the case that localized node is realized as SDR. The AoA method is implemented as remote-positioning solution in almost previous works [5], [6], [7] and [8].

The rest of the paper is structured as follows. The following section introduces positioning by angle of arrival method. Then SDR conception and SPT is presented. Implementation of the AoA method into SDR is presented. Simulation results are presented and discussed. Conclusion concludes the paper.

2 Angle of Arrival Positioning Method

Node with the information about position coordinates is called “Reference Node (RN)” and node without this information is called “Blindfolded Node (BN)”. AoA method represents measuring the angle of arrival of a signal propagating from RN to a BN or vice versa. Single measurement produces a straight line between two mentioned nodes.

Position estimation is determined as the point of intersection of minimal two straight lines drawn from the RNs (different locations).

The information about AoA can be obtained by means of following approaches. The first fundamental approach is based on measuring of the incoming signal phase differences. Another approach is based on a beam-forming.

In our case, we decided to use the phase difference measuring approach. Mod-eled blindfolded node utilizes six-port technology because of its positive proper-ties for simple phase differences measuring and on the other hand the six-port technology can be also necessary part of SDR receiver. The principle of phase measuring by means of six-port technology will be described later.

3 Software Defined Radio

Software defined radio has been identified as one of the potential methods to enhance the flexibility of wireless communication systems. In the past, the operating speed limitation of analog digital converter and processing ability limitation of reconfigurable chips for signal processing have slowed down the development of SDR for useful commercial application. The development of re-configurable de-vices such as digital signal processors and field programmable gate arrays caused that SDR has now become practical for use in a lot of system solutions.

The essence of an SDR is the ability, without introducing new hardware, to change operating characteristics such as operating frequency range, modulation type, bandwidth, maximum radiated or conducted output power and network protocols by changing the software programs executing in processing resources [8]. Operating parameters in SDR are determined by software [9]. This enables a single wireless device to be reprogrammed to use different modulation, access proto-cols etc. An ability of programming could also enhance interoperability between different radio services.

3.1 Six-port Technology (SPT)

An SPT enters a progress lately, promising its mass application in the SDR and mobile multimedia networks. SPT can be applied as a broadband input equipment of receivers, performing direct baseband conversion without demodulation [11].

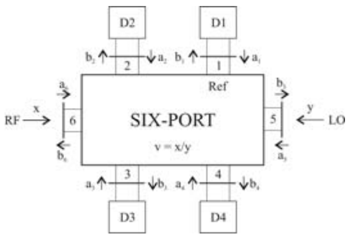


Fig. 1. Principle of the SPR [10].

The linear six-port is a basis of the Six-Port Reflectometer (SPR) (see Fig. 1). Port No. 5 is connected to the Local Oscillator (LO), port No. 6 is connected to the signal source (RF signal from an antenna) and the remaining four ports are connected to power detectors (D_1 to D_4).

Power detector (diode) D1 is used only for the power changes detection at the received travelling wave. Diodes $D_2 \div D_4$ detect the state of standing wave, which is created due to interference of two waves (*x(t)* - from the port No. 6 and *y(t)* - from the local oscillator). The detailed principle of SPR can be seen in [10].

Finally, outgoing signal from SPR is defined as a complex ratio of input RF signal phasor *x(t)*and LO signal phasor *y(t)*

$$v(t) = x(t)/\,y(t) = (X_0 / Y_0)e^{j\psi_0} M(t)\,. \tag{1}$$

The RF signal received by the antenna elements is amplified by low noise amplifier and mixed with a LO to convert the incoming RF signal to a suitable intermediate frequency or directly to baseband. To remove other intermodulation products, this signal is low pass filtered and sampled by an analog to digital converter. The baseband signal is extracted and processed [8].

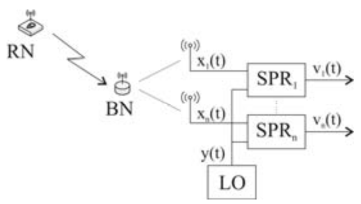


Fig. 2. Antenna array with SPRs.

In our case, the signal is especially processed for AoA estimation. In our proposal is used SDR receiver model without baseband conversion, without any training sequence, and without demodulation system. Important part of principle regarding SDR receiver based on SPRs is shown in the Fig. 2.

Each receiving antenna is connected to the input of each SPR (port No. 6). The signal received from antenna (x_i) and the signal from the local oscillator (y) are supplied to SPR_i and the signal received from antenna (x_j) and the signal from the local oscillator (y) are supplied to SPR_j. Receiving antennas form a uniform linear array with the defined distance between individual elements of antenna array. The final signal (after SPRs processing) is given by combination of particular signals from each SPR. The particular equations result from equation (1)

$$v_n(t) = x_n(t)/\,y(t) = (X_{0_n} / Y_0)e^{j\psi_0} M(t) = \alpha_n M(t)\,, \tag{2}$$

where n is the number of SPR, $M(t) = I(t) + \mathrm{j}Q(t)$ is a modulation signal in the baseband and α is complex constant resulting from state in the six-port. Positioning information *AOA* is obtained from equations (2).

SPR output signal is directly proportional to modulation signal and represent processing result. The receiver is tuned by local oscillator, i.e. the frequency of the received signal is equivalent to the frequency of the local oscillator [10].

3.2 Angle of Arrival Estimation by Antenna Array with Six-Port Technology

The principle of angle of arrival estimation consists of phase difference determination of the signal impinging to elements of antenna array.

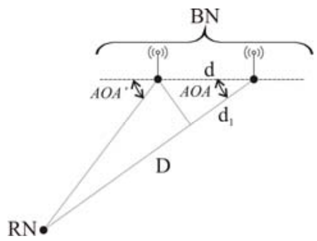


Fig. 3. Illustration of AOA.

The distance of antenna elements d is known (see Fig. 3). The received signal $x(t)$ impinges on antenna elements in a different time, i.e. modulation signal from SPR_i will be delayed, or forwarded against the modulation signal from SPR_j. A phase shift (φ_{ij} in degrees) of carriers will be calculated by following equation

$$\varphi_{ij} = phasor(v_i) - phasor(v_j) \, , \tag{3}$$

where v_1, v_2 – are complex variables obtained from eq. (2).

Since the SPR can assign the shift phase of the carrier frequency in a real time, we need to calculate equation (3). The *AOA* of signal traveling from RN to BN can be calculated

$$AOA = \cos^{-1}(d_1/d) = \cos^{-1}(\varphi_{ij} c / 2\pi f_n d) \tag{4}$$

where f_n is the carrier frequency in Hz, c is speed of light and d represents distance of antenna elements.

The equation (4) is valid under the condition that the distance D between observed nodes is much longer comparing with the distance d.

After this step, estimated angle of RN and BN is known with respect to reference direction. The estimated angle produces straight line. The next estimation provides a second straight line. The position estimation of the BN is determined as the point of intersection of minimal two straight lines drawn from the different reference nodes.

4 System Model

WANs consist of peer-to-peer links between nodes (devices). Pairwise measurements can be done from any of these links, but only a small number of nodes have coordinate knowledge. Thus measurements are made between pairs of nodes. The coordinates of one node are known.

Precise *AOA* measurement by means of SDR defines fundamental limitations on the performance of proposed positioning systems. This ability depends on a correct calibration of the SPR. We will assume that the SPR does not add any noise to the positioning process in our model.

4.1 Channel Model

We consider three different channels in our simulation:

- Additive White Gaussian Noise (AWGN) channel - absolute LoS propagation,
- Ricean channel - dominant LoS propagation,
- Rayleigh channel - NLoS, multipath propagation.

These three channels were chosen purposely because of their different properties. The channels have absolutely different signal propagation conditions. Therefore it can be said that performance of the method was validated in the representative samples of environment. Basic assumptions of the model have to be defined: perfect spherical radio propagation and identical transmission power for all nodes.

In case of AWGN channel various values of Signal to Noise Ratio (SNR) in [dB] has been used during the simulation. In cases of Ricean and Rayleigh channel also the signal fading was generated in addition. The fading was generated by Ricean distribution with different value of *K*-factor for particular channel. In terms of the Ricean *K*-factor, the envelope probability density function (pdf) of the amplitude can be expressed

$$p(r) = \frac{r}{\sigma^2} e^{-K} e^{-\frac{r^2}{2\sigma^2} I_0(2rK)}, \tag{5}$$

where $I_0(.)$ is the modified Bessel function of order zero, σ^2 is variance. The Ricean *K*-factor is the relation between the power of the LoS component and the power of the Rayleigh NLoS. When $K \to 0$ the envelope pdf approaches the Rayleigh pdf, it is case of our simulated Rayleigh channel. Ricean channel was simulated with $K = 5$.

4.2 Simulation Environment

Proposed simulation model takes into consideration a network of two RNs and one BN. The relative location problem corresponds to the estimation of BN coordinates. For simplification we consider the location in 2D plane. Let $[x_i; y_i]^T$ $i = 1,2$ are coordinates of RNs and $[x_j; y_j]^T$ $j = 1$ are coordinates of BNs. Pairwise measurements $\{AOA_{i,j}\}$ are done, where $AOA_{i,j}$ is an angle of arrival measurement between nodes i and j. Other conditions of the system model are following:

- signals from RNs are measured at a BN,
- received signal from each node is independent to each other,
- all RNs in the system are deployed with omni directional antennas,
- the BN is realized as a SDR receiver and calculate its position,
- position of RNs is based on relevant experiment in the specified area.

We were running 1000 independent trials. The first step of every trial was generating the positions of BN and RNs. In the next step were calculated *AOAs* between each RNs and BN on the base of equation (4). Then were calculated mutual intersections of mentioned lines.

The accuracy of position estimation is evaluated by means of *RMSE* (Root Mean Square Error)

$$RMSE = \sqrt{(x_r - x_{est})^2 + (y_r - y_{est})^2} \ \text{[m]} \tag{6}$$

where $[x_r; y_r]$ are coordinates of real (precise) position and $[x_{est}; y_{est}]$ are coordinates of estimated position.

5 Simulation Results

In this section, we discuss simulation results. The main goal of simulations is to evaluate the performance of AoA method implemented in SDR receiver. The simulations are realized for different nodes deployment scenarios. This condition is very important from optimization of RNs selection for positioning point of view. The following criterions were investigated:

- impact of SNR on the *AOA* estimation,
- impact of distance between nodes on the *AOA* estimation,
- impact of BN and RNs positions on the location accuracy,
- impact of radio channel on the location accuracy.

In the first experiment was investigated an influence of propagation conditions (channel quality) on the accuracy of *AOA*, i.e. influence of SNR on the *AOA* estimation. This dependency is very important for the next processing. In this model, the channel parameters means only one direct error source in the positioning process. Therefore it is necessary to observe the *AOA* positioning error vs. SNR dependency. This experiment was realized for two nodes (one RN and one BN) and *AOA* was estimated in BN. Distances between nodes were 100 and 250 m.

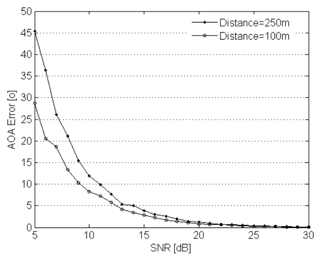


Fig. 4. *AOA* positioning error [°] versus SNR [dB].

Fig. 4 depicts error of *AOA* estimation versus SNR. On the basis of simulation results, it can be concluded that the error of *AOA* is an exponential function of SNR. Ascending value of SNR means decreased *AOA* estimation error.

In the following experiments will be used only AWGN channel, because the basic dependencies between nodes position, its distances and location accuracy is more clear for understanding with additional fading. The following values of SNR: 6, 9, 15, and 24 dB were used for simulation. Moreover, we can say that the increasing distance between nodes means the *AOA* error increase. This fact is significant by reason of selection of nodes for positioning. Nearer RNs to BN will be preferred for positioning.

The goal of the following simulation is observe relation between mutual position of nodes and positioning accuracy. Hence, we decided to use minimum RNs for BN positioning, i.e. only two RNs. The number of RNs is sufficient for verification of defined goal.

Two different scenarios were used (Fig. 5). The deployment of RNs was the same for both scenarios, the coordinates of RNs were [0; 125] and [0; 375]. The scenarios are different from trajectory of BN point of view. In scenario a), the BN positions were generated in the following way: the x coordinate was varying from 0 to 500 m and y coordinate was permanently 250 m, i.e. BN was moved along a horizontal line (see left part of Fig. 5).

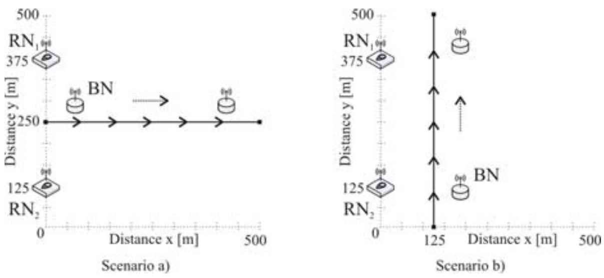
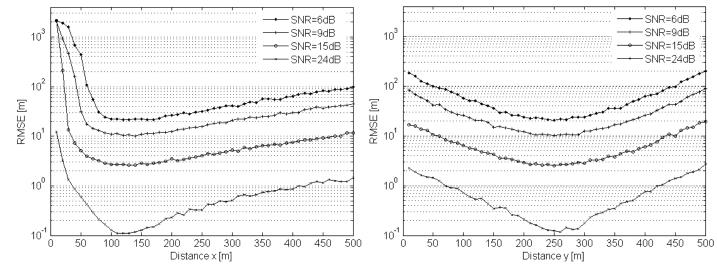


Fig. 5. Deployment of reference nodes and trajectory of blindfolded node.

In scenario b), the BN positions were generated similarly compare to previous scenario, but the y coordinate was changed and x coordinate was constant during simulation. It was done in the following way: the x coordinate was permanently 250 m and y coordinate was changing from 0 to 500 m, i.e. BN was moved along a vertical line (see right part of Fig. 5).

Fig. 6 shows the dependency of positioning error on horizontal distance (*distance x*) and vertical distance (*distance y*) between reference and blindfolded nodes. It is scenario a).



Scenario a) Scenario b)

Fig. 6. RMSE [m] versus distance between nodes.

The simulation was done for various SNR values. In the Fig. 6-Scenario a) can be seen that the change of distance and SNR plays an important role in positioning accuracy or error (RMSE). The most accurate results were obtained with the biggest SNR (24 dB). We consider that the real environment approximately correspond to the 9 dB SNR. In this case, the minimal positioning error is about 10 m.

The minimum RMSE has been achieved approximately at the coordinate [125; 250] for all values of SNR, i.e. *distance x* represents one half of the distance between RNs. Positioning error was the biggest in the case that *x* coordinate was small. It means the case when the BN is located in the middle of RNs. These differences are caused by mutual configuration of RNs and BN. Hence, the suitable geometric configuration of RNs and BN is very important for the positioning error elimination.

Fig. 6-Scenario b) depicts dependency of positioning error on vertical distance (*distance y*) between RNs and BN. The simulation was again realized for the same SNR values.

The minimal positioning error was obtained in the area between RNs (coordinate *y* is about 250 m), i.e. the distances from both RNs are similar. The biggest error was achieved at the borders of the observed area. This is caused by relatively long distance between BN and further RN. A further RN has brought bigger positioning error comparing with closer RN (see Fig. 4). The best results were again achieved for SNR = 24 dB. In the case of SNR = 9 dB, the minimal positioning error is approximately 10 m.

Finally, Fig. 7 shows a complex view on the observed area and depicts the RMSE dependence on a BN position. These simulations were done for SNR = 9 dB and two distances between RNs, 100 m and 250 m, respectively. First, it is necessary to note that the RMSE value bigger than 100 m was depicted with white color, because positioning error is very high in that case. On the other hand, black color defines the most accurate results. The achieved results for both cases are similar. These results demonstrate the fact that the increasing of distance between RNs means increasing of the positioning error. The more accurate results were in the case of smaller distance between RNs. The highest RMSE has been observed at the border of the area (especially close to RNs). The smallest error has been achieved at about one half of RNs distance. These facts confirm results from previous simulations.

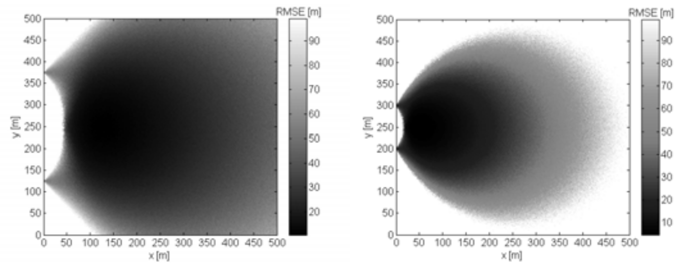


Fig. 7. RMSE [m] versus BN position.

On the basis of obtained results we can conclude that the distance between RNs affects positioning accuracy and range of positioning. The range of positioning means a range with the satisfactory positioning accuracy. These facts are important for development of an algorithm dedicated to the RNs selection. An additional measurement or central information about positions of all RNs should be added to the mentioned algorithm.

In the next simulations, we would like to investigate impact of various channels on location accuracy, i.e. impact of fading on accuracy. Therefore, there was performed only one trial. The average value of more trials could eliminate the immediate fading, we need to know immediate situation in this case. The deployment of RNs and trajectory of BN was same as is shown in Fig. 5-Section a). The BN position estimation was done each 1 meter.

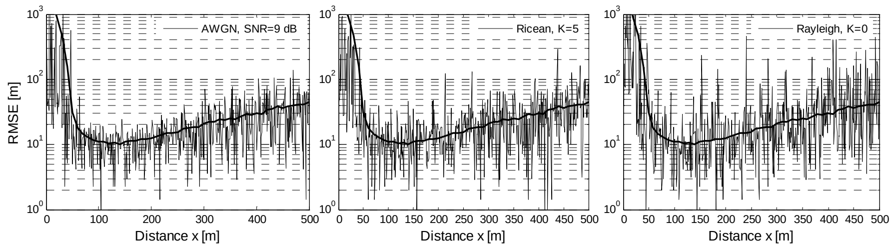


Fig. 8. RMSE [m] versus BN position for different channels.

Fig. 8 depicts dependency of positioning error on horizontal distance between RNs and BN. The simulation was again realized for AWGN channel (SNR = 9 dB), Ricean channel ($K = 5$) and Rayleigh channel ($K = 0$), see eq. (5). In the Fig. 8 dependency from Fig. 6-Scenario a) is shown for comparison of the immediate and reference value (AWGN, SNR = 9 dB). From the figure can be seen immediate change of amplitude envelope and their impact on location accuracy. The changes are the smallest in the AWGN channel. In case of the Ricean channel the propagation properties are worse compare to AWGN. It results to bigger influence on the location accuracy. According assumption, the Rayleigh channel causes the most unstable situation. The biggest problem occurs in the presence of deep fading. It results in sudden change of trajectory, but this error can be eliminated by prediction of the node motion. This phenomenon is evident especially in case of Rayleigh channel.

6 Conclusions

The goal of this paper is a suggestion of a modern positioning solution for wireless ad hoc networks. Proposed solution combines technology of future - software defined radio receiver and well-known angle of arrival positioning method. Software defined radio receiver is based on the six-port technology in this proposal. Angle of arrival of incoming signal is obtained by means of SPT antenna array. Proposed positioning solution is implemented as self-positioning, i.e. measurements and calculation of position is done in a mobile node implemented as SDR. Practical implementation of the SPT based receiver is possible and it will be feasible in the near future.

We analyzed an influence of radio channel properties (specified by varying value of SNR and type of channel), spatial deployment of reference and blindfolded nodes and impact of these parameters on the positioning accuracy.

According to the reached results we can conclude that the performance of proposed method depends on spatial arrangement of the nodes. It seems necessary to make a proper selection of the reference nodes used for positioning. This selection should result from immediate parameters as a distance between reference nodes and particular distance between reference nodes and blindfolded node. The channel parameters are also very important for positioning accuracy. There is an assumption that the mobile positioning is more precise in outdoor environment in comparison with indoor conditions. It results from a nature of radio signal propagation in this frequency band. In case of multipath propagation there is necessary to compensate impact of signal fading. For example, it could by done with Kalman filter.

Available positioning accuracy is high due to very precise calibration of six-port reflectometer. An advantage of software defined radio receiver is an ability to compensate errors from six-port calibration. These errors of scattering parameters are compensated by means of software processing. Proposed solution maybe seems unrealistic, but we believe that it can provide an effective mobile positioning in heterogeneous wireless networks.

Our future work consists of a proposal dealing with complex optimized algorithm for selection of reference nodes for localization. A new algorithm should be based on results presented in this paper.

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