Exploitation of a Special Case in RIPS Q-Range Ambiguity

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***Abstract*—The Radio Interferometric Positioning System (RIPS) was developed for the purpose of node localization in wireless sensor networks. In RIPS measurements a value called a Q-range is determined. This Q-range is a linear combination of all distances between all the nodes and can be used to determine the relative positions of the nodes involved in the RIPS measurement. Ambiguity occurs in the Q-range when measurements are made using nodes that are separated by a distance greater than a carrier wavelength. This paper presents possible solutions for Q-range ambiguity based on a special case in Q-range ambiguity.**

***Index Terms*—Localization, Wireless Sensor Networks, RIPS.**
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I. Introduction

In the last decade wireless sensor nodes have received a lot of attention from both academia and the industry. Wireless sensor networks have many useful applications in areas such as environmental monitoring, surveillance and industrial process control [1]. In many of these applications data recorded by sensor nodes could be even more useful when associated with a node's position. Nodes in wireless sensor networks do not always have predetermined positions, therefore methods for localization of nodes are needed. The Radio Interferometric Positioning system (RIPS) is such a method developed for the localization of nodes in wireless sensor networks [2].

Various ways of localizing nodes in a network have been developed. Radio signals are most commonly used in localization, but solutions that make use of ultrasonic sound and infrared have also been developed [3]. Most localization methods use one or more of the following measurement techiques: RSS (Received Signal Strength), where the uniform fading of a signal over distance is used to calculate a distance. TOF (Time of Flight), where the propagation time of a signal is used to determine a distance. And AOA (Angle of Arrival), where the angle of an incoming signal is determined in order to determine the direction of a node [4]. All of the methods mentioned have their own strengths and limitations in terms of accuracy and hardware requirements. RIPS is interesting because it offers accuracy typically associated with TOF while making use of RSS which has typically has low hardware requirements.

One problem encountered when using RIPS is Q-range ambiguity. This occurs when nodes used in measurements are separated by a distance which is greater than the wavelength of the carrier signal used. This places limitations on the use of higher frequencies, since the wavelength then becomes too short to allow for practical distances between nodes [5]. A solution for this problem has been given in [5] but this requires as many as 16 RIPS measurements to be made in order to determine a single Q-range [6]. In [7] the identification of a special case of Q-range ambiguity provides an opportunity for alternative methods of solving Q-range ambiguity. This paper carries on from work presented in [7] and contributes by exploring how such alternative ambiguity solutions would function. The different solutions are also simulated in order to indicate viability of the solution.

The remainder of this paper is structured as follows: In section II a background of RIPS is given. The Special Case in Q-range Ambiguity is explained in section III. Proposed solutions for q-range ambiguity that exploit this special case are presented in section IV. These proposed solutions are then implemented in MATLAB in section V. Finally conclusions are made and future work is discussed in section VI.

II. RIPS Background

RIPS was first presented in [2]. Unlike conventional methods of localization that use pairwise measurements, RIPS makes use of sets of four nodes in its measurements as is shown in figure 1. This is done by having two of the four nodes acting as transmitters and the remaining two acting as receivers. Measurements are made by having each of the transmitter nodes transmit pure sine waves simultaneously at slightly different frequencies. This small difference in frequencies is key to how RIPS functions as it creates an interference

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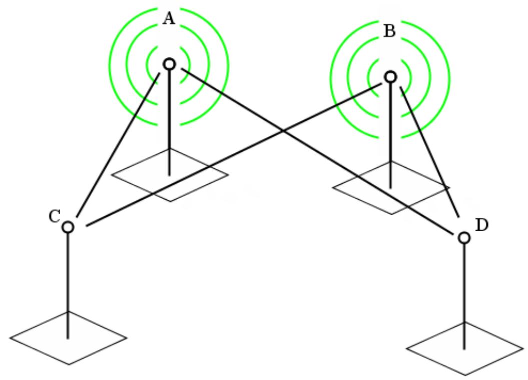

Fig. 1. Illustration of a RIPS measurement with nodes A and B transmitting and nodes C and D receiving.

signal that has a frequency that is defined in (1).

$$f_e = f_A - f_B \tag{1}$$

Where f_A and f_B are the frequencies of the signals transmitted by the two transmitter nodes. This frequency is called an envelope frequency. If the difference between the two transmitter frequencies is small enough it will be possible to measure this interference signal with low cost hardware. The two receivers then each measure the phase of the interference signal that they receive. The phase measured at each node is equal to the phase difference between the two transmitter frequencies. As is shown in equations (2) and (3).

$$\varphi_{AC} = -2\pi \left(\frac{d_{AC}}{\lambda_A} \right) \tag{2}$$

$$\varphi_{BC} = -2\pi \left(\frac{d_{BC}}{\lambda_B} \right) \tag{3}$$

$$\varphi_C = \varphi_{AC} - \varphi_{BC} \tag{4}$$

Where φ_{AC} and φ_{BC} are the phases of the signals from transmitters A and B at receiver node C. λ_A and λ_B are the wavelengths of the the transmitted frequencies and d_{AC} and d_{BC} are the distances from nodes A and B to node C. The phase of the interference signal is then φ_C. The equations for node D are similar.

A relative phase difference is then determined by subtracting the phase differences measured at the receiver nodes from each other in (5) .

$$\varphi_{ABCD} = \varphi_C - \varphi_D \tag{5}$$

Once the relative phase difference has been determined a special value called the Q-range can be determined.

$$d_{ABCD} = \varphi_{ABCD} \frac{\lambda_C}{2\pi} \tag{6}$$

Where λ_C is the wavelength of the carrier frequency f_c.

$$f_c = \frac{f_A + f_B}{2} \tag{7}$$

The Q-range is a linear combination of the distances between each transmitter and receiver.

$$d_{ABCD} = d_{AC} - d_{AD} - d_{BC} + d_{BD} \tag{8}$$

In order to determine the values of the individual distances that make up a Q-range, multiple measurements must be made using different combinations of nodes. Combinations of nodes must be chosen in such a way that they provide Q-ranges that are linearly independent and therefore solvable. This aspect of RIPS is outside the scope of this paper and is further discussed in [8]. Once the individual distances have been determined the positions of the nodes can be determined.

This paper is concerned with what happens when measurements are made where at least one pair of the four nodes participating are separated by more that a carrier wavelength. In such a case the actual value for the Q-range is no longer defined by equation 6 but by the following:

$$d_{ABCD} = \varphi_{ABCD} \frac{\lambda_C}{2\pi} + n\lambda_C \quad n\epsilon Z \tag{9}$$

This is a problem because the value provided by measurements would differ from the true Q-range value.

III. Special Case in Q-range ambiguity

In [7], a special case in Q-range ambiguity was identified. When the two transmitters in a RIPS measurement are separated by less than a carrier wavelength Q-range ambiguity only has a meaningful effect in circular bands around the transmitter pair. These bands occur at distances equal to multiples of the carrier wavelength and have a width that is equal to the difference in the distances from each transmitter to a receiver node.

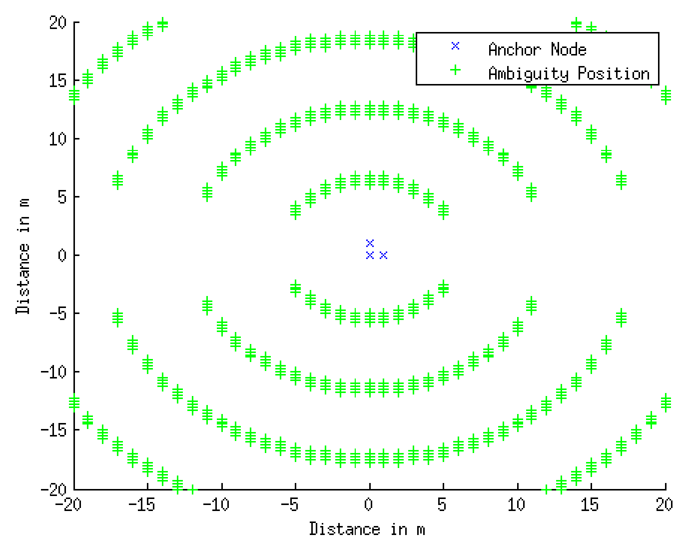

Fig. 2. A two dimensional map showing where ambiguity occurs (Green dots). This was done by moving one of the four nodes all around the map using fixed intervals. The static nodes are represented with blue dots.

This effect can be explained by taking a look at the mathematics behind RIPS. Q-range ambiguity occurs when the number of wavelengths completed before a phase measurement is unknown. Therefore we need to look at the equations defining measured and true phase offsets.

$$\varphi_{true} = -2\pi \left(n\lambda + \frac{Res}{\lambda} \right) \tag{10}$$

$$\varphi_{measured} = -2\pi \left(\frac{Res}{\lambda} \right) \tag{11}$$

Where Res is a distance measured from the position of the last completed period to the receiver and n represents the number of complete cycles the signal has completed before reaching the receiver. The number of complete cycles is omitted from the measured equation because only the phase of the a signal is measured.

When (10) and (11) are each substituted into (5) it can be seen that if signals sent from the two transmitter nodes are in the same nth wavelength and the transmitter frequencies are close enough, as is usually the case in RIPS, the values of the measured and true phase offsets will be close to each other. In the mathematical proof of the RIPS concept [2], it is assumed that the difference between the two transmitter frequencies is smaller or equal to 1 KHz.

$$\begin{aligned} \varphi_C &= -2\pi \left(\left(n_A\lambda_A + \frac{Res_A}{\lambda_A} \right) - \left(n_B\lambda_B + \frac{Res_B}{\lambda_B} \right) \right) \\ \varphi_C &= -2\pi \left(\left(\frac{Res_A}{\lambda_A} - \frac{Res_B}{\lambda_B} \right) + ((n_A\lambda_A - n_B\lambda_B) \right) \\ \varphi_{C_{measured}} &\approx -2\pi \left(\frac{Res_A}{\lambda_A} - \frac{Res_B}{\lambda_B} \right) \end{aligned} \tag{12}$$

So in summary, this effect is caused by the signals sent by the two receivers still being in the same nth wavelength. The areas where Q-range ambiguity has a meaningful effect are caused by one signal being in the next n'th wavelength and the other still being in the previous.

IV. Proposed Solutions

In the previous section a special case in Q-range ambiguity was shown. This effect can be exploited to provide alternative methods for solving Q-range ambiguity. In this section two such possible methods are presented.

A. *Single Measurement Method*

This method uses a single RIPS Q-range method to determine a Q-range. The idea behind this can be best explained by referring to figure 2. As previously mentioned, large ambiguity only occurs in circular bands around the transmitter pair in this special case of Q-range ambiguity. Therefore for most of the surrounding area the nodes will be able to determine Q-ranges with a single measurement.

Complications occur when the node to be localized henceforth referred to as the NOI (node of interest) is located in an ambiguity band. In such a case the Q-range determined from a measurement would result in incorrect positioning. Therefore a way of identifying such cases is needed. This can be done by taking a look at all the possible values for a Q-range. With three stationary anchor nodes the Q-range has maximum and minimum values that are dependent on how close these three nodes are to each other. The limits for the Q-range are given in (13).

$$d_{AC} - d_{BC} - d_{ADBD} < Q - range < d_{AC} - d_{BC} + d_{ADBD} \tag{13}$$

$$d_{ADBD} = Max(d_{BD} - d_{AD}) \tag{14}$$

This is useful because when nodes are in ambiguity bands, Q-ranges are produced that have values that are larger or smaller than the maximum or minimum Q-range values. This large change in value can be explained by referring to (12). When a node is in an ambiguity band it means that the signals sent by transmitters are in different nth wavelengths. Therefore the values of Q-ranges will have a value defined in (16) added or a value defined in (15) subtracted , depending on which of the transmitter nodes is closest to the node to be localized. These values are very close in size to the wavelength of the carrier frequency.

$$C \left(\frac{-f_{diff}n - f_A}{f_A - f_{diff}f_A} \right) \tag{15}$$

$$C \left(\frac{-f_{diff}(n+1) + f_A}{f_A - f_{diff}f_A} \right) \tag{16}$$

$$f_{diff} = f_A - f_B \tag{17}$$

If transmitter node A is closest then (15) is added to the Q-range value. If transmitter node B is closest then (16) is subtracted from the Q-range value. Equations (15) and (16) can easily be derived from (12).

This is the case as long as the frequencies used in measurements have wavelengths that are larger than the maximum or minimum Q-range values. Now it is possible to separate useful Q-ranges from ambiguous ones. But it is also possible to go one step further. Since the Q-range values jump by know values, it could be possible to repair ambiguous Q-ranges by adding or subtracting this value to the measured Q-range. The choice between addition or subtraction can be made by looking at the value ambiguous Q-range itself. A Q-range with a large negative value can be repaired with addition and a Q-range with a large positive value can be repaired with subtraction.

Although this seems to be intuitively right it can also be be proven by referring to (12). When transmitter B is closer to the node to be localized large negative Q-ranges are produced. Conversely when transmitter A is closer positive values are produced. This splits the two dimensional plain into two halves. One with large positive ambiguity values and one with large negative ambiguity values.This alone already confines the possible positions of the node to be localized to one half of the two dimensional plain.

B. *Multiple Measurement Method*

The second proposed method makes use of multiple measurements at different frequencies that have ambiguity bands that mostly do not overlap as shown in figure 3. At the very least such a method would require two measurements at different frequencies. The difference between these frequencies must be large enough to create a difference in wavelength that is large relative to the distance between the anchor nodes. In this method ambiguity is resolved by using Q-ranges obtained from other measurements made at different frequencies.

The existing solution for Q-range ambiguity also makes use of multiple measurements at different frequencies. But our proposed method differs from the existing solution in that it does not calculate all of the possible values for each Q-range. In this method each measurement supplies a single value. When a value is incorrect due to ambiguity a value from another measurement is simply used.

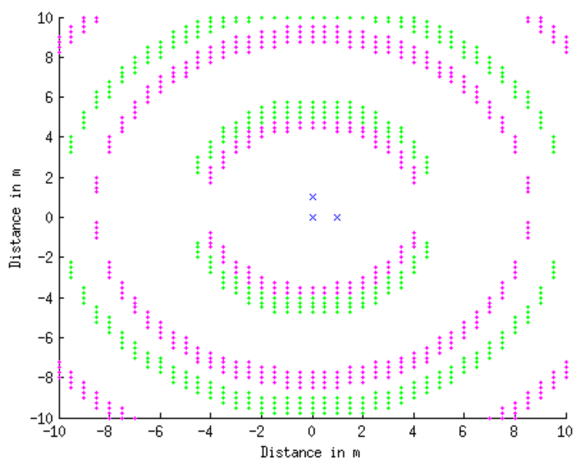

Fig. 3. A two dimensional map showing the ambiguity areas of two measurements.

V. MATLAB IMPLEMENTATION

In this section the methods discussed in the previous section are implemented in MATLAB in order to gain an understanding of how they would function. For this implementation the hyperbolic trilateration method is used to determine positions from Q-range values. Hyperbolic trilateration makes use of three stationary anchor nodes. These nodes are used to determine the position of a single NOI. This is done by making two RIPS measurements. In RIPS hyperbolic trilateration, three anchor nodes are denoted as nodes A, B and C while the NOI is denoted as node D. The two RIPS measurements then produce two Q-ranges, d_{ABCD} and d_{ACBD}. Thus the transmitter nodes are always among the anchor nodes and the NOI node D is always a receiver node. This subject is further discussed in [9]. In the special Q-range case the ambiguity bands created by such two measurements are illustrated in figure 4. It should be noted that these implementations are only theoretical and for the this paper, only the use of the basic mathematics behind RIPS are considered. Channel models are not used.

A. Single Measurement Method

In this example the anchor nodes B and C are separated from anchor node A by one meter, as can be seen in figure 5. A carrier frequency of 60 MHz is used with a frequency separation of 1 KHz between the transmitter nodes. Hyperbolic

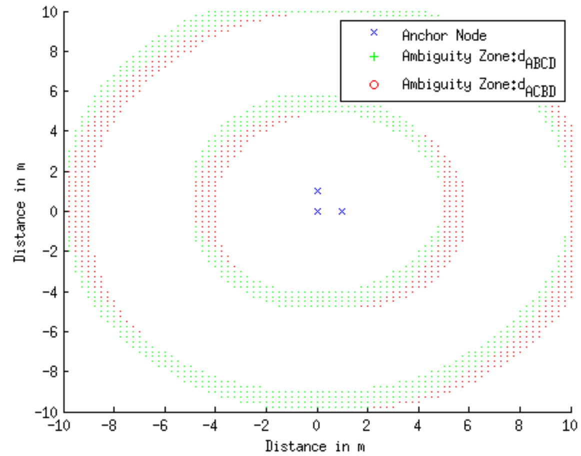

Fig. 4. A two dimensional map showing the ambiguity areas caused by two measurements made using two different transmitter pairs as is done in hyperbolic trilateration

trilateration is used to determine positions from the measured Q-ranges. According to (13) the maximum and minimum values for Q-ranges are defined as:

$$-0.5857 < q - range < 1.414 \quad (18)$$

In figure 5 the true NOI positions are shown in red markers and the corresponding positions determined by use of RIPS are marked with black markers.

The first measurement was made with the NOI having a position outside the ambiguity bands. The position of the NOI is marked with a red dot and the position determined with the single measurement method in RIPS is marked as a black dot. It can easily be seen that the position was determined correctly. The exact position of the NOI was (5,6) and the exact position determined by RIPS was (5.0125,6,0153).

The second measurement shown was made with the NOI inside an ambiguity band, in figure 5 as a red diamond. The measured Q-ranges where not corrected using (15) or (16). The position determined from these faulty Q-ranges is shown as a black diamond. It can be seen that the position determined in such a case is completely wrong. The exact position of the NOI was (2.5,4.5) and the exact postion determined by RIPS was (-1.171,-0.586).

The third measurement was once again made with the NOI in an ambiguity band but this time the Q-ranges involved were corrected with (15) or (16). It could easily be seen that the one of the two Q-ranges produced was ambiguous as it had a value of -3.7126. This is far outside the limit of possible Q-range values for this case as defined in (18). Thus this Q-range was corrected and the position of the NOI was determined. In this case the NOI is shown as a red square and the position determined by RIPS is shown as a black square. The exact position of the NOI was (-2.5,5) and the exact position determined by RIPS was (-2,481,4969).

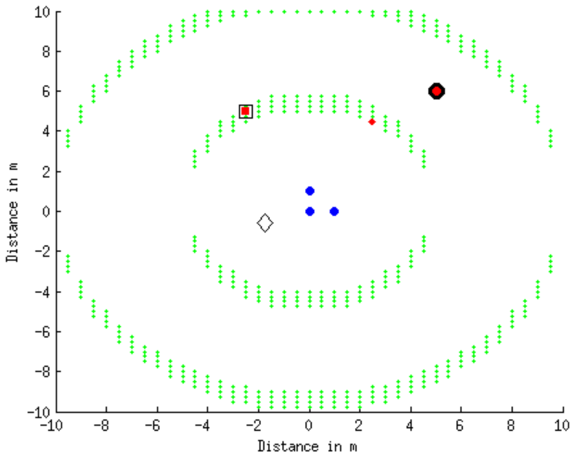

Fig. 5. A two dimensional map showing results obtained with the single measurement method

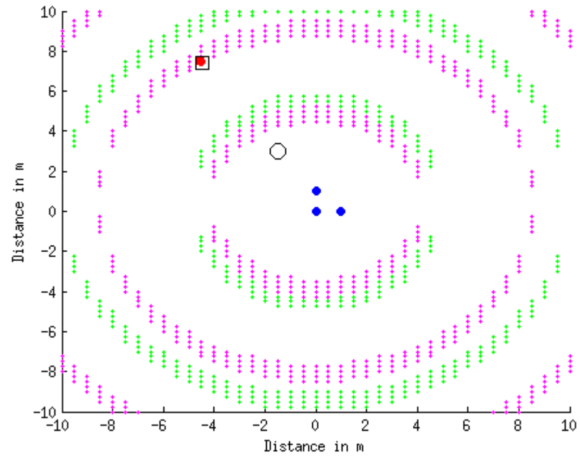

Fig. 6. A two dimensional map showing results obtained with the multiple measurement method

B. Multiple Measurement Method

In this scenario only two measurements are made, one at 60MHz and one at 70MHz. The distances between the nodes are the same as in the previous scenario as well as the frequency separated of the two transmitter nodes.

In this case the position of the NOI interest is determined twice. This is done using two different frequencies and using hyperbolic trilateration. This means that two sets of Q-ranges will be produced. Each set contains two Q-ranges, so four Q-ranges in total are produced. The NOI is placed inside an ambiguity band at (-4.5,7.5). The results of this implementation are shown in figure 6. The 60MHz measurement produces a position of (-1.507,2.987) as indicated by the circle. The Q-ranges produced have values of 6.2551 and -0.1398. One of which is beyond the possible limits of Q-range values so the position is disregarded. The 70MHz measurement produces a position of (-4.452,7.431) as indicated by the square. The Q-ranges produced have values of 1.2551 and -0.1398. These Q-range values are within the possible limits so the position can be accepted as correct.

VI. Conclusions and Future Work

In this paper we showed how we can exploit the special case of RIPS Q-range ambiguity as identified in our previous work [7]. Two methods to solve the Q-range ambiguity under the given usage case were proposed and shown to provide the correct Q-range values when required to do so. The MATLAB implementation showed that theoretically these methods will work. The inaccuracies experienced can be explained by the fact that the NOI was placed outside the triangle formed by the three anchor nodes, this was shown to have an effect how sensitive RIPS is to differences in the Q-range [10]. Due to this the proposed methods might not be well suited as a single solution but may be better suited when used in conjunction with existing methods.

The main benefit to the two proposed methods is that far less RIPS measurements are required to determine a Q-range when compared to existing methods. Existing methods require multiple RIPS measurements regardless of where the NOI is placed. When these measurements have been made all the possible Q-range values for each measurement have to be calculated and then a common value must be found between all measurements to determine the correct Q-range. While the single measurement method only requires a single measurement and does not need to compute a list of possible values for the Q-range. This will lower the load on network and processing resources.

Future work on this topic entails the incorporation of a channel model in the simulations used as well as further practical testing.

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