

Node Position Discovery in Wireless Sensor Networks

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Abstract—Wireless sensor networks (WSN) have gained a significant attention in research and carry the promise to be helpful in numerous aspects of life. For many applications, the location information of the nodes needs to be known. As this information is not necessarily available, there is a huge interest in algorithms estimating the positions of individual nodes. The precision and computational complexity of such “localization” algorithms is still a big issue. However, there are cases where the nodes are placed in one of a few possible predetermined positions. In those cases, computing the relative positions of nodes in relation to each other might be sufficient to determine their real positions. In this study, we introduce a methodology for discovering the sequence of nodes in a unidimensional configuration using the measured Received Signal Strength (RSS) values and allowance of frequency diversity of high frequency radio (CC2420) that is frequently used in wireless sensor networks. In the reported experimental tests, we were able to determine the node sequence correctly for the nodes that are as close as 50cm to each other, using the developed methodology.

I. INTRODUCTION

Wireless Sensor Networks (WSN) are composed of tiny devices, that are often called sensor nodes, and have a broad range of application areas. These areas include security and safety, environmental monitoring, target tracking, inventory tracking, smart living environments and more. For many of them, the location information is important, if not crucial.

Some applications, like target tracking, require very precise location information. For others, like outdoor environmental monitoring, less precise location information is sufficient. Different systems and technologies are used to detect the relative or absolute positions of the sensor nodes, such as radio frequency (RF) ranging, acoustic ranging, ultra-wide band signal ranging or global positioning system (GPS) [1]. In general, however, precise determination of the position, especially in the indoors scenarios, is recognized to be a complex problem, for which better solutions are needed.

There are applications in which the positions of the nodes are limited. In fact, a node can be located in one of the predetermined positions. We will assume further on that the positions are defined by a regular grid. In those cases highly accurate calculations for node localization is not needed. Instead; mapping the nodes to the set of potential positions will give us the exact locations of each node deployed. We call this; *position discovery*. We claim that position discovery can be done pretty accurately with low computational complexity,

and less energy consumption. Here, we demonstrate this for a unidimensional grid.

An example for the application areas that can benefit from this work is inventory tracking where wireless sensor nodes can be attached to the items of interest in a storage environment. However, locating them (or finding the correct place in the storage area) is difficult. Solutions supporting such applications exist, e.g. using *RFID* technology [2] but they come with extra complexity, cost and restrictions on locating the inventory. It is also not usable for sensing related communication. Other indoor *non-RFID* solutions can only provide information about joining to or leaving the network. We are specifically interested in discovering the location of the nodes indoors, using only the easily available signal strength information (RSS). However, due to multipath, this is considered a complex issue.

Difficulty of precisely assessing the location of a sensor node by using just simple RSS information is well known. In this paper, we will demonstrate that combining the frequency diversity and simple RSS measurements, it is possible to discover the position of a sensor node (equipped with CC2420 radio) within a set of possible locations with high accuracy. The experiment results have shown that we can achieve correct results under the case that the nodes are positioned indoors as close as 50cm to each other on a single dimensional plane.

This paper is structured as follows: we give an overview to the existing studies in Section II. The problem and the system model is defined in Section III. The explanation of our approach is in Section IV, followed by the experiments and results in Section V. Finally, we conclude and refer to the future work in Section VI.

II. RELATED WORK

To discover the positions of WSN nodes, a number of approaches have been considered. Multiple studies, such as [3], show that RSS data by itself does not provide practical use for range estimation. The studies that rely on RSS information often require an intensive calibration process or a database for mapping the RSS values to actual distances or positions. Those computations are environment specific and not reusable in different locations without precalibrating. In [5], a calibration method that promises to reduce the error in localization has been described. A good comparison of some of the best

known RSS based localization algorithms is given in [6], with conclusions that the relative positioning error is between 50% and 100% in most cases.

Another valuable result is given in [7], focusing on indoor applications. It is shown that even when the nodes are located between 1 to 2 meters apart in a grid, the error is more than 2 meters with a probability of 0.5 or higher.

In the current wireless sensor network literature, there is a gap for indoor node sequence discovery. In this study, we propose a cost effective solution to fill this gap.

III. PROBLEM STATEMENT AND SYSTEM MODEL

We consider a set of N nodes deployed indoors in relatively smaller areas with all nodes being in the transmission range of each other. In other words, we cannot divide the network by neighborhood information. The nodes are assumed to be located along a line with equal distances apart from their immediate neighbors. We are specifically interested in dense placement of non-mobile nodes, at distances that are known and in the order of tens of centimeters. The position of the first node in the sequence is assumed to be known (we call this node 'reference node'), while the sequence of the remaining nodes is to be determined.

We assume all nodes to be equipped with high frequency (2.4GHz), low power radios chips, which provide the signal strength (RSS) information upon packet reception. Using the available RSS information, we will discover the geographically closest node to the reference node and iterate for all nodes in the sequence.

IV. APPROACH

A. Principles of the suggested approach

Received signal strength (RSS) is widely used as an indicator of the signal quality at the receiver side. However, signal quality does not always correlate with the actual geographic distance. Due to many reasons like signal attenuation and multipath propagation, it does not always change relatively with the distance. Even under stationary conditions, RSS varies in time; therefore it is not suitable for indoor ranging [3]. However, we claim that it is possible to recognize the closeness of the nodes in regards to each other by using available RSS information.

We start our considerations with a simplified model of line-of-sight transmissions. In such a case, the power of transmitted radio signal attenuates with the distance. This means; the farther node will measure a lower RSS than a closer node to the source of the signal in line of sight settings, under ideal conditions. So signal attenuation is a function of distance. The derivative of this function is negative and the absolute value of this derivative decreases as the distance to the transmitter grows. Ergo, the node that measures the highest RSS value, from a particular instance of transmission, is the closest node to the transmitter. In sequence discovery, it is intuitional to sort the nodes by iterating the sequence by discovering the closest node to the previously sorted node until all nodes are added to the sequence.

We assume that all transmissions are done at a constant power level Tx . Then let us assume that Rx_{AB} be the expected RSS value at node B for the transmission of node A in the ideal case of having no external effects, but only distance correlated attenuation. Similarly, Rx_{AC} is the ideal RSS value of the reception at node C . If node B is closer to node A than node C , then the inequality of $Rx_{AB} > Rx_{AC}$ is true. This phenomenon, however, is severely affected by multipath distortion in reality.

Multipath distortion can be defined as a combination of multipath propagation (multiple paths caused by reflection or refraction of the transmitted signal) and RF interference (constructive or destructive). In this context, we refer this shortly as *multipath*. Multipath can corrupt or destroy the signal, as well as increase or decrease its amplitude at the receiver antenna.

Inevitably, there is a magnitude of multipath effects that will add to the Rx value, which we show by Ψ as a normally distributed random variable. So the measured signal strength at node B will be $RSS_{AB} = Rx_{AB} + \Psi_{AB}$, and it will be $RSS_{AC} = Rx_{AC} + \Psi_{AC}$ at node C .

Assuming this three node sequence discovery case, in Figure 1, node A wants to determine whether node B or node C is closer, where all of them are placed d distance apart from each other. For the sake of simplicity we take this three node scenario. For more nodes, the suggested approach can be iterated as far as desired.

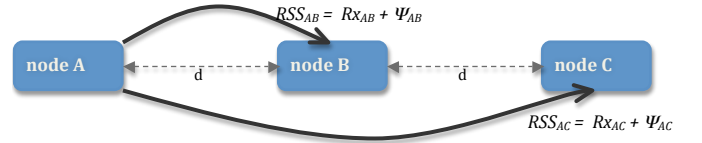


Fig. 1. Three nodes (A,B,C) and effective multipath (Ψ)

We would be able to recognize the sequence correctly, if $RSS_{AB} \gg RSS_{AC}$ was always correct. So we desire to achieve the inequality given in Equation 1.

$$\begin{aligned} RSS_{AB} &\gg^? RSS_{AC} \\ \Rightarrow Rx_{AB} + \Psi_{AB} &\gg^? Rx_{AC} + \Psi_{AC} \\ \Rightarrow Rx_{AB} - Rx_{AC} &\gg^? \Psi_{AC} - \Psi_{AB} \end{aligned} \quad (1)$$

To make this equation hold, we can either increase the left side, or decrease the right side of the inequality, and we do both. We increase the difference on the left side by assuring to operate on the steep part of the attenuation curve. This is the case when we select node A to be close to both node B and node C . On the other hand, node B and node C are not allowed to be excessively close to each other. So, the derivative of the signal attenuation curve remains bigger. Concurrently, we want to reduce the difference on the right side of the inequality by finding proper values of Ψ for both of the receivers.

There is always a chance, that the farther away node can be affected by a bigger constructive multipath than the

closer node, or the closer node can be affected by a greater destructive multipath. Yet, *the peak* of the multipath for a transmission by node *A* is expected to be close when received by neighboring nodes *B* and *C* due to their closeness to each other, as $\Psi_{AB}^{max} \approx \Psi_{AC}^{max}$. Let this peak value of multipath be Ψ^{max} . Therefore, we are trying to find the peak magnitude of the received signal strength at the receiver (RSS^{max}), which is transmitted signal power with attenuation plus multipath effect, to use in our comparisons (Equation 2).

$$\begin{aligned} Rx_{AB} - Rx_{AC} &\gg? \Psi_{AC}^{max} - \Psi_{AB}^{max} \\ \Rightarrow RSS_{AB}^{max} &\gg? RSS_{AC}^{max} \end{aligned} \quad (2)$$

To assure that we will measure something close to the Ψ_{AB}^{max} and Ψ_{AC}^{max} , we will use both time diversity and frequency diversity, as shown in the following section.

B. Frequency diversity

If a node(*A*) is transmitting to another node(*B*), the measured signal strength(RSS_{AB}) varies, in principle, with the change of distance between the nodes. However, as we discussed above, this difference is not always comparable due to multipath. In [8], the signal strength as a function of distance has been shown. It is stated that the replacement of receiver antenna in factors of the wavelength, causes a big change in RSS gain.

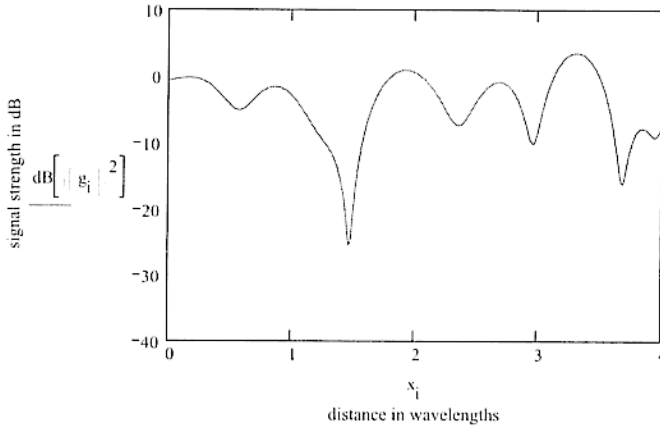


Fig. 2. Signal Strength as Function of Position [8]

Figure 2 shows that some positional displacement of the radio antenna can lead us to the Ψ^{max} within a wavelength distance. However, it is not possible to reposition the nodes in a network to find the best positions separately. At this point, we want to benefit from the high frequency multichannel radio for displacing the propagation path of the signal. The displacement of disseminated signal in fractions of a wavelength in higher frequencies can have a big effect on aggregate gain, which we examine below.

While moving the node antenna by fraction of a wavelength is not possible, because the nodes are fixed, a similar effect can be achieved by changing the wavelength of the radio

output. The above figure shows that there is a rough periodicity in the amplitude of the received signal strength that equals to half of a wavelength. Unfortunately, even that movement would not assure achieving Ψ^{max} ; in some cases movement for several wavelengths would be needed. When using the CC2420 radio chip, which operates on 2.4Ghz frequency, we need roughly 1.2Ghz bandwidth for observing the whole change in RSS. But we have only 80Mhz bandwidth spread across 16 channels(11 to 26) that are 5Mhz apart [4]. Our hypothesis is to combine this limited *frequency diversity* with *time diversity* in order to achieve an acceptably good approximation of RSS^{max} , therefore Ψ^{max} .

In order to find RSS^{max} , we spread the transmissions both in time and frequency. Among all samples, we choose the highest measured RSS being the $(Rx + \Psi^{max})$. Since multipath (Ψ) is a random variable, we want to find the maximum that it takes within a certain time for all nodes that are in comparison. Therefore we claim that, if we collect a number of samples over time, we have a better chance in reaching (or getting sufficiently close) to one of the peaks that are illustrated in Figure 2.

We verify this hypothesis by experiment.

In one experiment, node A is positioned 100cm away from node B at its line-of-sight and node A transmitted a bulk of IEEE 802.15.4 packets starting from the lowest available channel to the highest at a constant transmit power. The plotted values in Figure 3 are the averages (over 100 measurements) of RSS_{AB} values at each channel. Here we observe, that the difference in the strength of the received signal on different channels can be as big as 25dbm. This change very much achieve the whole scope of the changes of Ψ as theoretically predicted in Figure 2. In our experiments, we observed that sampling 40 times with 20ms intervals is just as good as sampling 100 times at the same speed and having 200 samples did not improve results. Hence combining the frequency diversity with time diversity is promising for measuring close Ψ magnitudes of nearby nodes, therefore we can reduce the right side of Equation 1.

Thus, we come to the understanding that, if the maximum RSS value that we measure over time and frequency by Node A to Node B is greater than that to Node C, it is highly probable that Node B is closer to Node A than Node C. So we implement this comparison in our algorithms starting from a known reference node, which is placed in the first place in the sequence. Then the roles are changed and every node in the sequence becomes the transmitter (in turns) while others, as well as the previous transmitters, remain as receivers. This procedure is shown in Algorithms 1, 2 and 3.

Algorithm 1 for node A (reference node)

```

for ch = 1 to endChannel do
  for i = 1 to N do
    Radio.Send(Packeti)
  end for
end for

```

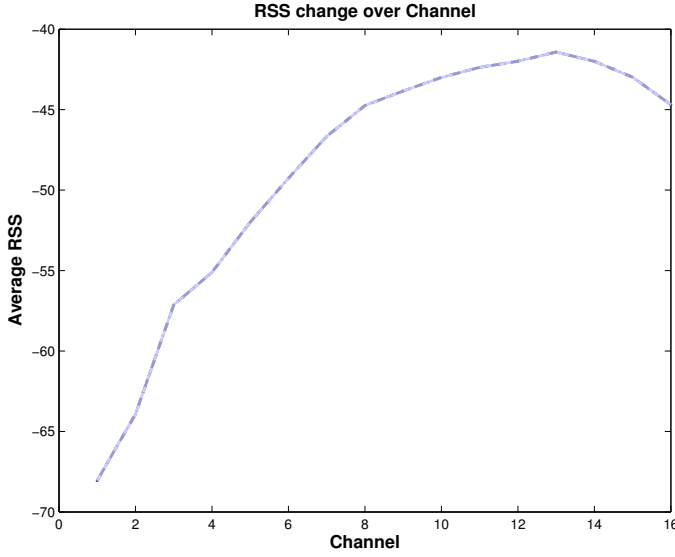


Fig. 3. Change in RSS between two nodes over 16 channels at 2.4Ghz using CC2420

Algorithm 2 for nodes B and C (receiver nodes)

```

Y ← THIS_NODE_ID
for ch = 1 to endChannel do
  i ← 0
  while i < N do
    Packet pkt ← Radio.Receive()
    i ← getOrder(pkt)
    X ← getSenderId(pkt)
    rss ← getRss(pkt)
    if rss > RSSXYmax = (RxXY + Ψmax) then
      RSSXYmax ← rss
    end if
  end while
end for

```

Algorithm 3 Decision algorithm

```

if RSSABmax > RSSACmax then
  CloserNode ← B
else
  if RSSACmax > RSSABmax then
    CloserNode ← C
  end if
end if

```

C. Position Computation

In a network of m nodes, we can extend the above procedure to compute the sequence of nodes, therefore their positions.

After having each node $N_i (1 \leq i \leq m)$ collected the maximum RSS values from each of its neighbors, a sequence of neighborhood S is created by using these measured RSS values in Algorithm 3.

$S_i = [N_i, N_j, \dots, N_k, \dots, N_m]$, where

$$RSS_{N_i N_j}^{max} > RSS_{N_i N_k}^{max} > RSS_{N_i N_m}^{max}$$

In this sequence, the nodes that are closer to the head node (N_i) are more likely to be geographically closer as well, since they measured a higher RSS^{max} than the nodes that are farther from the head node in the sequence.

For the final decision, we take the reference node (N_R) and assign it to the first place in the sequence and flag it. Then starting from S_R , we take the first unflagged node from its sequence (N_t) and iterate from the sequence of that node (S_t). This procedure is given in Algorithm 4.

Algorithm 4 Sequence algorithm

```

S ← Set of Sequences
N ← All Nodes
P ← {} // Empty Positions Set
NR ← N.getReferenceNode()
Nt ← NR
while UnflaggedExists(N) do
  P.add(Nt)
  Nt.setFlag(true)
  Nt ← firstUnflaggedIn(Si)
end while
return P

```

V. EXPERIMENTS AND PERFORMANCE RESULTS

In our experiments, using the algorithms that are described in Section IV, we chose the closest node for each node. The first node in the node sequence has been taken as the reference node. Then, iteratively, we sorted the remaining nodes into a single dimensional sequence. All experiments were done indoors with severe observed multipath.

In one experiment, we placed 3 TelosB nodes in a single dimensional space that were about 100cm apart from each other. We collected RSS^{max} values in all available 16 channels that the CC2420 radio operates at. Each transmission is repeated 100 times. The nodes were given IDs 5, 6, 7 and they were positioned in the order 5–7–6. The reference node was Node 5 at the first place in the node sequence. Hence node 5 was the transmitter while the nodes 6 and 7 were the receivers at the first iteration. For each proceeding iteration, nodes 6 and 7 have become the transmitters in turns. After collecting the RSS data from the measurements, we iteratively sorted them and found the correct ordering as being 5–7–6. The experiment output is shown in the Figure 4.

We extended the same experiment to 4 nodes, having a sequence of nodes with IDs 5–7–6–8 relatively and having the Node 5 as the reference node. In these experiments, the node placement was done intentionally irrespective of node IDs to prevent any false positive verdicts due to software error. Applying the same computations, we were again able to find the correct ordering with the data shown in Figure 5.

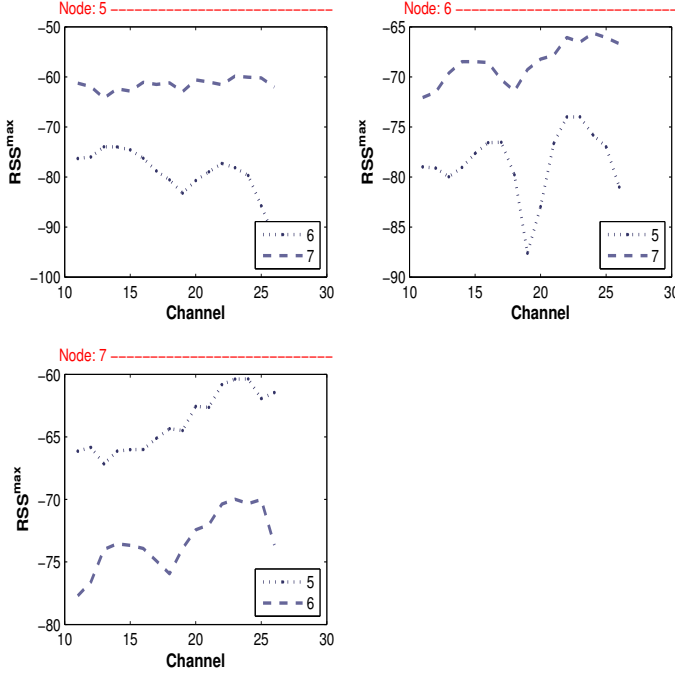


Fig. 4. Experiment output gives the correct ordering: 5-7-6

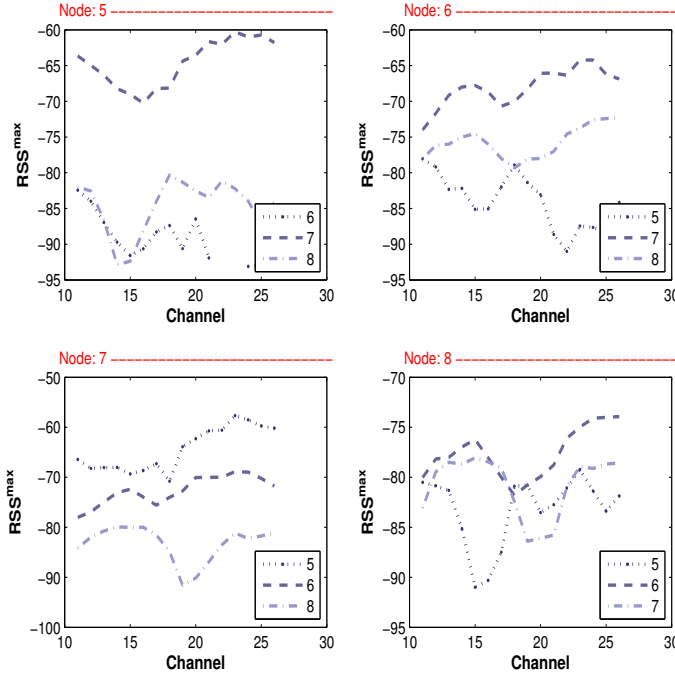


Fig. 5. Experiment output gives the correct ordering: 5-7-6-8

In another experiment we used 5 nodes with IDs 5, 6, 7, 8, 9 and placed them in the sequence 5-6-7-8-9 while decreasing the distance in between nodes to 50cm, again having the reference node as Node 5. After following the suggested methodology, the outcome of this experiment has again been the correct sequence, which is shown in Figure 6.

Even though in most cases the suggested method performed

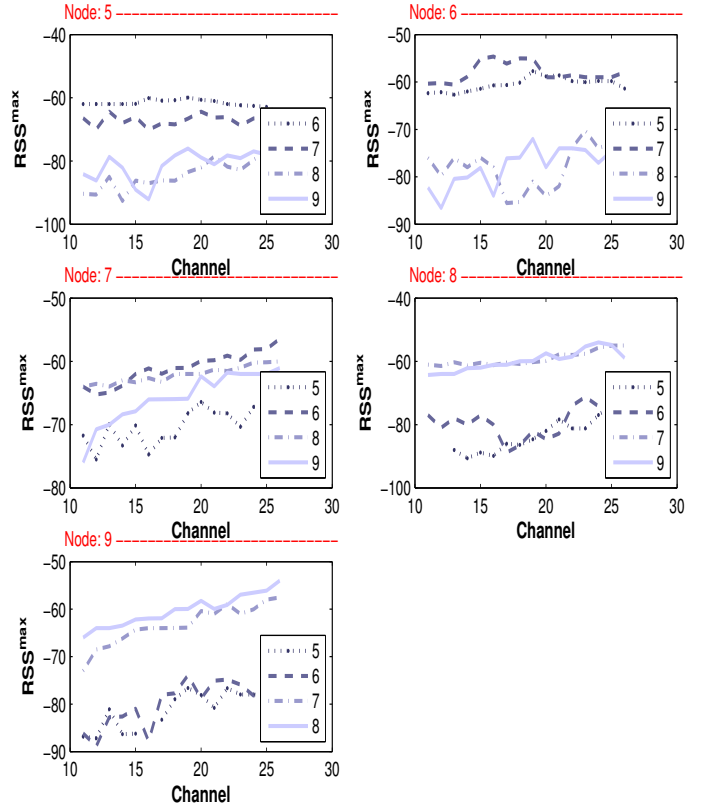


Fig. 6. Experiment output gives the correct ordering: 5-6-7-8-9

very well, letting us to discover the correct sequence of nodes, there has been few cases in which the sequence of two of the neighboring nodes were swapped. Such as, the data illustrated in Figure 7 has given us the ordering as 5-7-6-8-9 with Node 5 being the reference node, while the correct ordering was 5-6-7-8-9. This experiment was done with the same settings and at the location as the other experiments and the internode distance was 100cm. However, when we took the reference node as Node 9, we could find the correct ordering as 5-6-7-8-9.

A. Verification of the concept

To verify the effectiveness of frequency diversity on closeness information, we performed two other sets of experiments. We placed 5 nodes 50cm apart from each other in a small, multipath-prone room. Each node transmitted 40 packets with 20ms intervals, only on channel 11(2405Mhz) and we sorted the nodes according to the methodology in subsection IV-C. We repeated this experiment 10 times. Later, we repeated the same set of experiments for the whole bandwidth case, which is 16 channels.

In these experiments, we positioned Node 0 as the first node (reference node) in the sequence and positioned nodes 1, 2, 3, 4 next to it respectively, each node 50cm farther than the previous one. Hence, if the output of our algorithm is {0 1 2 3 4}, then the verdict is true(T), otherwise false(F).

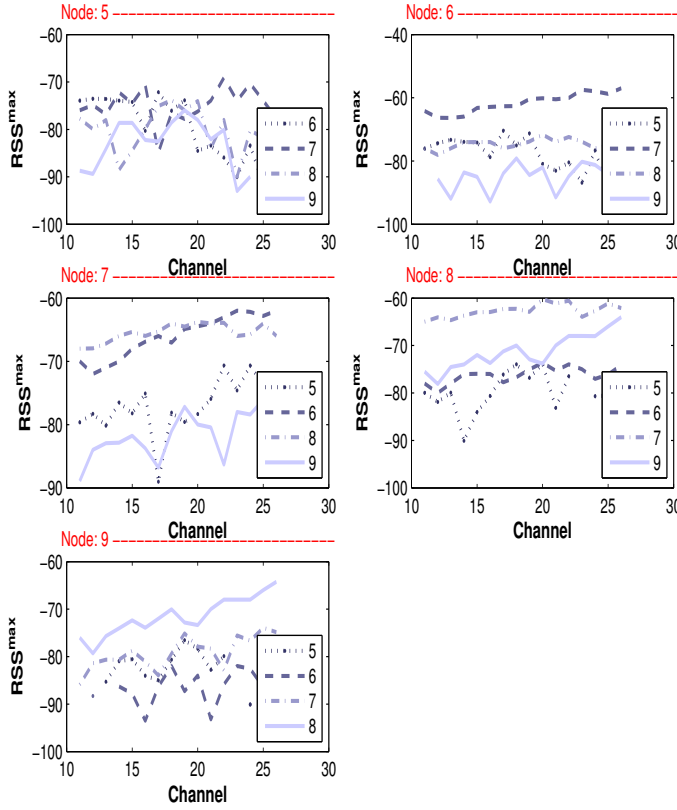


Fig. 7. Experiment output gives the ordering slightly wrong as: 5-7-6-8-9

Exp. No:	Single Channel		Multiple Channel	
1	0 2 1 4 3	F	0 2 3 4 1	F
2	0 2 1 3 4	F	0 1 2 3 4	T
3	0 2 1 3 4	F	0 1 2 3 4	T
4	0 2 1 3 4	F	0 1 2 3 4	T
5	0 2 1 3 4	F	0 1 2 3 4	T
6	0 2 3 4 1	F	0 1 2 3 4	T
7	0 2 1 3 4	F	0 1 2 3 4	T
8	0 2 1 3 4	F	0 1 2 3 4	T
9	0 2 1 4 3	F	0 1 2 3 4	T
10	0 2 1 3 4	F	0 1 2 3 4	T
Result:	0/10 Success		9/10 Success	

TABLE I
VERIFICATION: SINGLE CHANNEL VS MULTIPLE CHANNEL

In Table I, each row is the result of a single experiment. We see that in single channel case none of the 10 experiments resulted in correct sequence, while in multiple channel experiments 9 out of 10 verdicts have been correct. It is also noticeable that in the incorrect verdict of multiple channel experiments, only one node was not found in its respective position.

VI. CONCLUSION

In this paper, we suggested an approach for discovering the node sequence in wireless sensor networks in a single dimensional space. In our methodology we take Received Signal Strength (RSS) as our input parameter. We sample the

RSS from transmissions in all available channels that the radio chip allows us to operate at. For decision criterion, we take the highest measured RSS among all channels between a node pair and by comparing these values with all other pairs we give a binary decision to choose the closest node. Starting from one known reference node, we iterate sorting the nodes in the sequence until positions of all nodes are computed. In our experiments we have high success in sequence discovery with occasional error of swapped adjacent nodes, while the overall sequence is still being correct.

As for future work, we will extend the experiments to an increased number of nodes and we will use non-line-of-sight settings, which will bring us more challenge in discovering the node sequence. The step after this will be extending the position computations for two-dimensional setups for discovering $2 \times M$ and $N \times M$ setups. With increased experiment scale, we will develop a methodology to rank the reliability of the computed sequence.

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