Performance of a Wireless Unattended Sensor Network in a Freshwater Environment

John C. McEachen and Juan Casias
Department of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, California 93943
mceachen@nps.edu

Abstract

This effort investigated the use of wireless unattended sensor network motes in the surroundings of a freshwater lake. The network was required to organize, establish and maintain itself in or on the water. Commercial components developed by Crossbow Technologies were used in developing the experimental networks consisting of single and multiple nodes. Nodes were tested on a solid ground surface, on the surface of the water, below the surface of the water (but not submerged) and fully submerged. Performance metrics based on link quality, parent changes and formation time are presented under a variety of scenarios. It was observed that nodes operating on the surface of the water performed much better than those on a hard surface, operating at a greater inter-node spacing and experiencing fewer parent changes. Submerging one or both nodes had considerable but not overwhelming effects on network performance.

1. Introduction

As technology continues to progress at a prodigious rate the size, weight, and cost of the components necessary to realize these mandates become viable. The maturation of technologies involving integrated circuitry, wireless communications, and data networking make the systems more autonomous without sacrificing processing capability. All of this combines to provide a practical mechanism for the implementation of this type of system. Many of the risks associated with this type of technology have been alleviated, however military applications continue to present additional challenges that must be addressed. [1] Much of the previous work in the field has been accomplished for dry environments. Consequently, the focus of this work is with relation to watery environments.

The objective of this paper is to evaluate the performance of wireless, unattended sensor networks in a freshwater environment. Performance metrics of interest are network formation and organization and communication range and efficiency. These will be assessed with respect to a variety of orientations on and in the water.

Tingle [2] observed the communication and sensor ranges of the MICA2 mote at a fixed radio transmission power over four types of terrain. The four terrain types were open terrain, outdoor wooded terrain, urban outdoor terrain and indoor terrain. The tests were conducted at ground level and two heights, six and twelve inches off the ground. The study found that the radio ranges varied between five to nineteen meters. It was noted that communication at ground level was never greater than six meters and the longest connectivity recorded was nineteen meters with the mote at twelve inches off the ground in the indoor environment. The study also tested the characteristics of the different types of sensors that can be used in wireless sensor networks and the viability of their use in military applications. This information is of particular interest in comparison to similar data obtained in the experimentation performed for this work. [2]

A separate study evaluated the connectivity ranges of motes using the XMesh routing protocol for multiple power settings. XMesh proved adaptable, reliable, and stable under a variety of stressors at all power levels. The study also performed an energy efficiency study to explore various means of extending network longevity. [3]

The study in [4] provides a detailed study of the performance of mote antennas and their radiation characteristics.

A new approach for electromagnetic (EM) wave propagation through seawater was presented in [5]. Experiments were conducted in a laboratory as well as real seawater environments.

Empirical link quality analyses specific to the MICA2 platform are also presented in [6] and [7]. In [6], the MICA2 radio was observed in both indoor and outdoor conditions and under a variety of antenna polarizations with results similar to [2] above. The work presented in [7] analyzes measured MICA2 transmissions in an open-air environment for the purposes of evaluating interference range versus communication range.

Finally, in [8] a small underwater robot was designed for experiments with sensor-actuator networks. The MICA2 mote platform, which is used extensively in the sensor networking community as an experimental testbed, was the basis for the robot. Depth regulation and temperature measurement were reported and analyzed in preliminary tests.

2. Background

This section discusses the experiments undertaken and the results that they produced. The experiments were performed under a variety of conditions with several parameters of interest. Mote performance in the areas of radio reception range, signal quality, network stability, and network formation times were evaluated on the water at different proximities. After some baseline results were obtained for motes on an arbitrary hard surface, they were tested on the surface of the water and floating below the water's surface without being completely submerged. Submerged performance was not specifically evaluated, but is discussed briefly. Performance metrics were then evaluated from the data gathered during these experiments.

Partially submerged and submerged performance is of interest in this research to give an indication of performance degradation under deteriorating environmental conditions. Specifically, we desire to understand what amount of degradation will occur as the mote sinks or if the mote is in a turbulent environment.

2.1 Experimental Procedure

All experiments were performed using MICA2 motes manufactured by Crossbow Technologies utilizing the high transmit power level of +5 dBm (1.64 mW). The specific data gathered for each of the following sections was gathered for a variety of different situational conditions. In order to gather a baseline of dry performance data, mote performance was evaluated on a hard solid surface with little possibility for multi-path reception. A tennis court was chosen as these conditions most closely approach those of the open watery surface used for the remainder of the experiments. A number of other dry implementation scenarios were evaluated in the study by [2]. In [2], the communication and sensor ranges of the MICA2 mote at a fixed radio transmission power over four types of terrain were tested. The four terrain types were open terrain, outdoor wooded terrain, urban outdoor terrain and indoor terrain, none of which were optimally suited for comparison to water in this context. Next, motes were tested floating completely on the surface of the water. Following this, tests were completed with one mote floating completely on the surface of the water with the others floating just below the surface of the water without being completely submerged. Maintaining an area above the mote open to the air was the critical element of this and the following segment of testing to prevent the futility of trying to actually transmit through the water, which will be discussed later. Finally, tests were performed with all motes floating just below the water's surface. Figure 1 depicts the difference between floating on the water and floating in the water. The easiest way to achieve neutral buoyancy was to be able to control the volume of the container. This was accomplished using Zip-lock™ sandwich bags. The bags were inflated slightly to provide positive buoyancy and weighted down with two rolls of fifty pennies each along with the mote until neutrality was achieved. When the bags were submerged, the tip of the antenna could be seen on the surface and a cavity surrounding the antenna in the water could be observed. Floating on the water the bags were completely inflated with no additional weighting added. [2]

A consistent antenna orientation was used to minimize loss due to polarization mismatch. Mote antennas were oriented perpendicular to the sensor ground plane and parallel to each other.

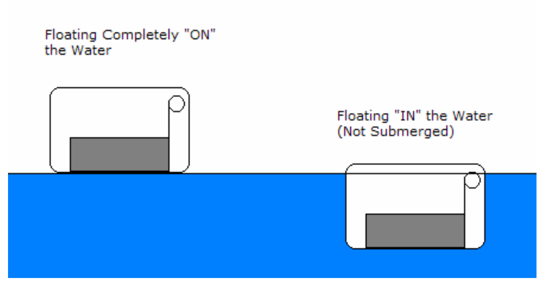

Figure 1. Mote Placement "ON" versus "IN" the Water

2.1.1 Radio Range Radio reception ranges between communicating motes was determined using a simple procedure involving Mote View software while utilizing three motes. The first mote, node zero, was established as the gateway or base station. The second mote, node one was placed such that node zero, the base station, became its parent. The final mote, node two, was positioned to establish node one as its parent. This configuration was established due to difficulties involved in attempting to float the base station and its associated connections to the PC in the water while maintaining the appropriate antenna orientation. At times it was noted that node two's parent would switch to node zero, but only at shorter ranges which had no real bearing on the range testing. Once confirmation of network communication between the nodes was verified, the motes were moved apart incrementally until the link was lost. Node two was then moved back toward node one until the link was reestablished. This process was repeated no less than four times to ensure consistent results.

2.1.2 Link Quality Link quality was also measured using Mote View software. Link quality is defined as the ratio of the number of information packets received to the total number of information packets actually sent. This value was calculated from data provided by Mote View. Mote View provides retransmission data in the form of "retries" expressed as a percentage. This represents the percentage of the time that a node had to retransmit a packet due to the lack of a link-level acknowledgement. In order to determine link quality from this quantity one hundred percent was added to the percentage of retries and that result was divided by one hundred and reciprocated. This is shown in Equation (4) and gives the fraction of sent packets that were received and acknowledged.

$$LinkQuality = \frac{1}{\left[(100\% + RetryValue\%) / 100 \right]} \quad (4)$$

As an example, if the retry value was 6.5, this means that 6.5% of the time a packet is retransmitted due to the lack of a link-level acknowledgement. Therefore, adding the extra 6.5% that were retransmitted to the 100% that were received and acknowledged results in a ratio of the total number of information packets sent to the number of information packets that were received. This is the inverse of the desired valued for link quality and reciprocating it will result in the link quality. Reciprocating the fractional representation 106.5%, which is 1.065, results in a fractional value of 0.939, which would be link quality of 93.9%. Link quality was measured incrementally during the determination of radio reception ranges at all ranges noted. [11]

2.1.3 Network Formation Network formation was timed from the initiation of the network with motes at various ranges. The network was considered to be initiated for this portion of the experiment when the motes were activated and moved into position as quickly as possible. This was done to simulate a mass dispersion of motes into an inaccessible area where the motes would be activated en masse and inserted to perform their function. In this instance, activated means that power was applied to the motes or that they were switched on. The network was considered formed and time stopped when all of the nodes set in place and activated were accounted for by the base station with their data being received. This part of the experiment was performed with nine motes, including the base station, situated in a relatively uniform distribution that would allow great flexibility in parent selection. The nodes of the network were configured into rows that layered away from the base station with three in the first row, two in the second, and three in the last. The base station is node zero with all of the other nodes being one through eight as they get further away. Figure 2 depicts the formation and gives an example of the parents selected. The procedure was performed at three ranges for each situational condition except the both "IN" the water situation. The first range is one meter, one half meter for the both "IN" situation, well within the most reliable region. The next was at the far edge of the reliable region, one meter for the both "IN" situation. The last was at the maximum radio reception range as a representative case for the transition region. The procedure was repeated four times at each range.

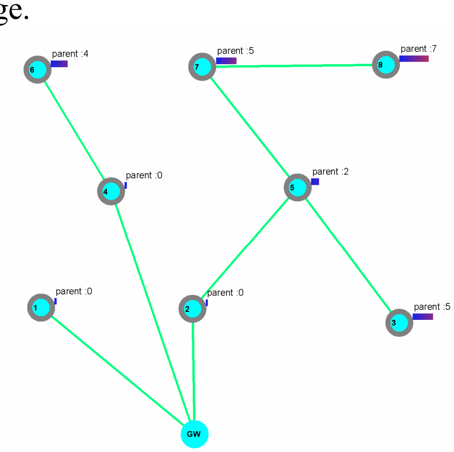

Figure 2. Communication Topology Example for Node Formation and Parent Selection Experiments

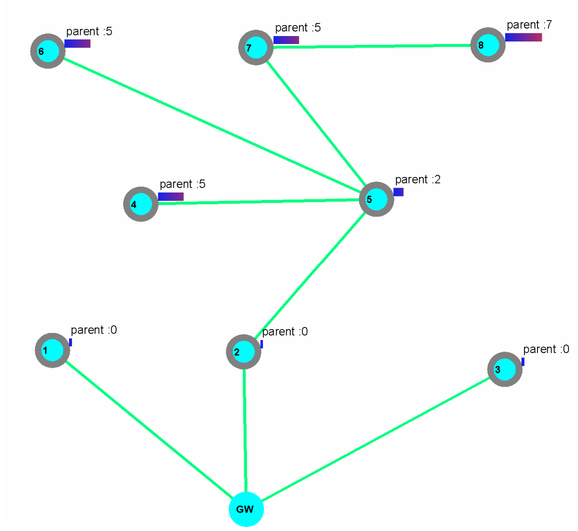

Figure 3. Alternate Communication Topology Example for Node Formation and Parent Selection Experiments

3. Experimental Results

3.1 Radio Range

Propagated ground waves take three separate paths to the receiver, the direct wave, the ground-reflected wave, and the surface wave. A ground wave's effectiveness of depends on a number of factors. These factors include the radio frequency, transmitter power, transmitting antenna characteristics, electrical characteristics of the terrain, and electrical noise at the receiver site. All of these factors remained constant for the purposes of these experiments save one, the electrical characteristics of the terrain. Specifically, these are the conductivity and dielectric constants of the terrain. The direct path component of the ground-wave travels from the transmitting antenna to the receiving antenna directly, while the ground-reflected path is reflected off the ground or sea en route to the receiving antenna. Once reflected off of the terrain's surface, the phase of the ground wave shifts 180 degrees. The ground-reflected path traveling a longer distance in reaching its destination, the overall phase shift is somewhat greater than the 180 degrees caused as a result of the reflection. The net result near the ground is a weakening of the direct wave that is roughly equal to the strength of the reflected wave. The surface path component of the ground-wave component is affected primarily by the conductivity and the dielectric constant of the terrain. When both the transmitting antenna and the receiving antenna are close to the ground, the direct path and ground-reflected path tend to cancel each other. The surface path is not confined to the earth's surface and extends up to considerable heights. Diminishing in strength with increased height its intensity becomes negligible at about one wavelength above the ground and five to ten wavelengths above sea water. The ground absorbs part of the surface path's energy attenuating the electric intensity of the surface wave. This attenuation is dependent on the conductivity of the terrain over which the wave travels, sea water being the best type of surface for surface-wave transmission. [10]

3.1.1 Hard Surface

In continuing a portion of the research conducted by [2] study some expectations were made based on his results. During his research he observed radio reception ranges did not exceed four meters with motes on the ground in open outdoor terrain that consisted of a grassy field with little opportunity for multi-path reception. Moving the experiment to a hard solid surface with more favorable conductivity and dielectric characteristics, still little opportunity for multi-path reception and motes on the ground produced radio ranges out to seven meters. Motes were moved incrementally one meter at a time beginning at one meter. When moved beyond seven meters to eight meters reception was lost and regained when returned to seven meters. An increase in radio range was expected, but the magnitude of the change being 75% demonstrates the significance of terrain with respect to mote performance. These results were consistent over four repetitions of this cycle and are graphically depicted in Figure 4 which follows in the section covering link quality. [2, 8]

3.1.2 On Water Surface While sea water possesses the best conductivity and dielectric characteristics for surface wave propagation, a fresh water lake was used for the purposes of these experiments. Even so, moving the experiment from a hard solid surface to fresh water with even more favorable conductivity and dielectric characteristics, little opportunity for multi-path reception, and motes on the surface of the terrain produced radio ranges out to nine meters. Again motes were moved incrementally one meter at a time beginning at one meter. When moved beyond nine meters to ten meters reception was lost and regained when returned to nine meters. While the 29% increase in radio range is not as dramatic as the increase from the previous section, it is nevertheless significant and further demonstrates the importance of the terrain and its effects on mote performance. These results were consistent over four repetitions of this cycle and are graphically depicted in Figure 4 which follows in the section covering link quality. [10]

3.1.3 Submerged Water is a poor medium for the propagation of RF signals. In anything besides free space an RF signal becomes compressed, slows down, and is attenuated more rapidly. This is especially true in salt water. The experiments documented here were performed using fresh water which, while not having as great an effect on signal losses as salt water, still causes severely detrimental signal losses. [11]

The fully submerged radio reception range between two communicating motes was on the order of centimeters for which no foreseeable purpose can be determined. No further experimentation under these conditions was performed.

3.1.4 Below Water Surface This portion of the experiment took place in two stages demonstrating more of the detrimental aspects of water as part of the communication environment. In the first stage, data was collected with one of the nodes "ON" the water, completely above the surface of the water as before while the other node was "IN" the water, floating completely below the surface, but not completely submerged, as discussed above. In the second stage, data was collected with both of the nodes "IN" the water, floating just below the surface. With this geometry the advantages provided by water with respect to surface wave propagation are never fully realized. The water between the motes acts as a barrier until the signal radiates clear of it. At this point only a portion of the signal, which is weaker in magnitude, is allowed to propagate along the surface. [4, 8]

(1) One Node "IN" the Water/One Node "ON" the Water. Once placed in this configuration, motes were moved incrementally one meter at a time beginning at one meter. When moved beyond four meters to five meters reception was lost and regained when returned to four meters. With the shorter range the mote was then moved away only another half meter when again the link was broken. This decrease of just over 55% from the open water trial is very significant. It begins to delineate the serious shortcomings involved with using this technology with respect to water.

These results were consistent over four repetitions of this cycle and are graphically depicted in Figure 4 which follows in the section covering link quality.

(2) Both Nodes "IN" Water. In this final configuration, motes were again moved incrementally beginning at one meter, but this time only one half meter at a time. When moved beyond one meter to one and a half meters reception was lost and regained when returned to one meter. This result, with another 75% decrease in radio range from the previous case, clearly demonstrates that compelling issues remain for these systems in this environment. These results were consistent over four repetitions of this cycle and are graphically depicted in Figure 4 which follows in the section covering link quality.

3.2 Link Quality

The data measured for link quality was recorded incrementally in conjunction with the radio reception range data. The retransmission percentage was averaged over a five minute period at each range increment and used to calculate the corresponding link quality as previously described in the procedure section.

Figure 4 depicts the qualities of the links at the various ranges. This figure clearly demonstrates three distinct performance regions for each situation except the last which only shows two. The first three trials have distinct regions where the performance is very reliable, averaging in the middle to high nineties for link quality expressed as a percentage. This region for the hard surface, water surface, and one "ON"/one "IN" trials extends out to ranges of five meters, seven meters, and three meters respectively. The trial with both motes "IN" the water exhibited no such region as link quality improved only marginally inside of one half meter where the chart stops.

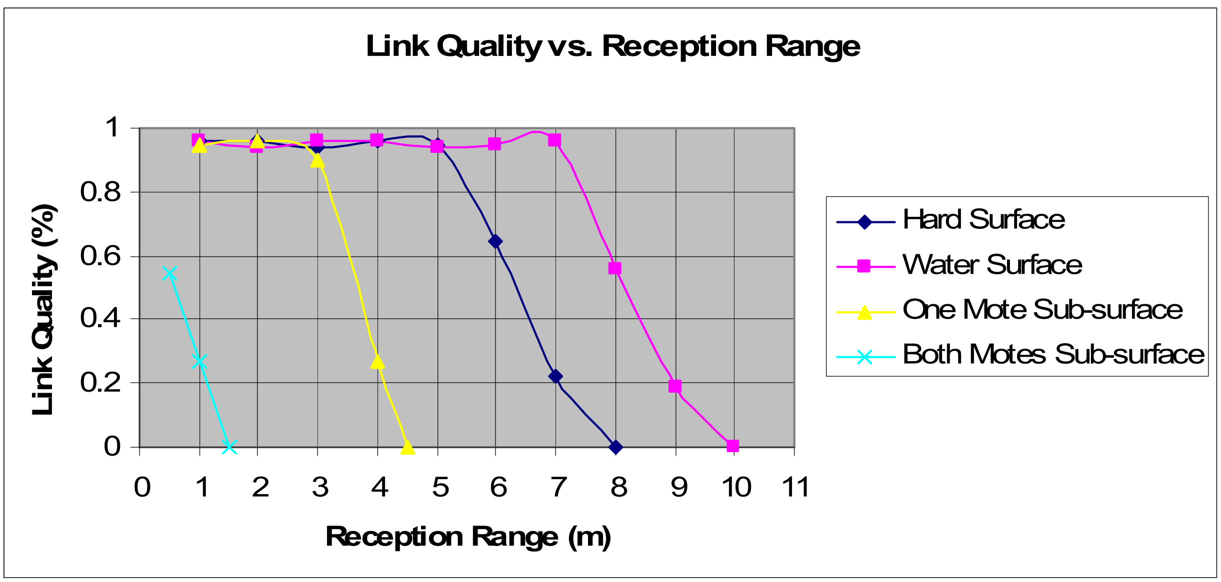

Figure 4. Link Quality versus Radio Reception Range

All trials displayed attributes that fall into a transitional region where reception was possible, but link quality was not as high. This region for the hard surface, water surface, one "ON"/one "IN", and both "IN" trials extends from the reliable region, except in the case of the both "IN" trial, out to the maximum radio range of seven meters, nine meters, four meters, and one meter respectively. Beyond this maximum radio reception range is the unusable region beyond which no communication is possible. This behavior was predictable and similar from case to case.

3.3 Network Formation

Network formation times were recorded as described in the procedure section and were equally as predictable and similar across all cases. With motes operating anywhere in their respective reliable regions as discussed in the previous section, network formation was completed in one to two minutes. With motes operating at maximum radio reception range, as a representative case for the transition region, network formation was completed on average in four to five minutes. This was the case for all situations except for the both “IN” the water scenario which were on average a full minute longer than all of the other situations. This geometry poses significant problems for mote to operate in. Figure 5 depicts the specific results of the hard surface and both “ON” the water network formation times while Figure 6 depicts the one “ON”/one “IN” the water and both “IN” the water network formation times. These results made sense as they paralleled the overall communications difficulties demonstrated by the link quality measurements discussed in the previous section.

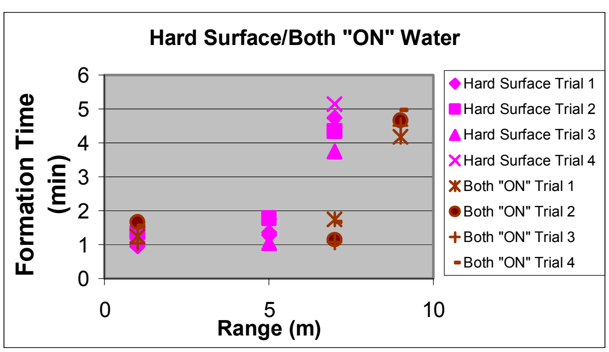

Figure 5. Hard Surface and Both “ON” Water Network Formation Times

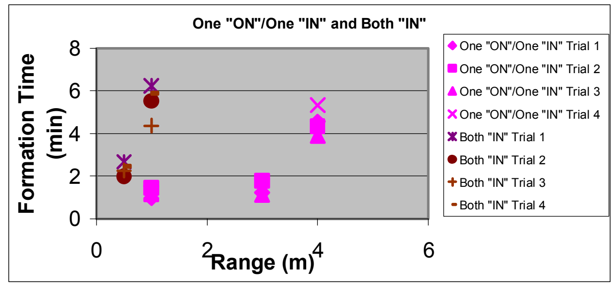

Figure 6. One “ON”/One “IN” and Both “IN” Water Network Formation Times

3.4 Network Stability

Network stability was evaluated as described in the procedure section and was similar across all cases except the both “IN” cases. The hard surface and both “ON” the water cases were nearly identical. The one “ON”/one “IN” case had one minor difference from these cases due to its configuration. In the one “ON”/one “IN” case the base station is “ON” the water with the closest row of three motes “IN” the water. The next layer of two motes was also “ON” the water with the last row “IN” the water. The both “IN” case in particular further demonstrated the difficulties associated with this geometry with its results standing apart from the other situational trials completely.

Through all of the experiments the network exhibited great stability once network formation was complete. Most parent changes occurred during network formation. While operating within their respective reliable regions established in the radio range section, each node underwent a parent change on average just over once in a thirty minute period. While operating at maximum radio reception range, again as a representative case for the transition region, each node underwent a parent change on average less than three times in a thirty minute period. On only a couple of occasions did a node change parents a maximum observed five times in the thirty minute period while in the reliable range. These could be attributed in part to the mobility of the network during the cases in which the motes were in the water as they drifted in place. The lone exception to this was the both "IN" the water situation which has no reliable region. On the lone occasion that a node was lost, all routing was redirected and the network reorganized in less than one minute. Figure 5 depicts the results from the hard surface situation while Figure 6 depicts the results from the both "ON" the water situation. The results of the hard surface were nearly identical.

3.4.1 One "ON/One "IN" Network Stability Trial In all of the other trial cases, the nodes closest to the base station established and maintained the most stable links directly with the base station with the fewest number of parent changes, if any parent changes were made at all. However, in this trial the other nodes that were "ON" the water established and maintained the most stable links. This is due to the geometry of the links that were involved in order to even make this trial possible. With the ranges set in order to allow one "ON"/one "IN" links to be established, all motes that were "ON" the water were well within the reliable ranges established for both being "ON" the water. It came as no surprise then that nodes four and five in the second row away from the base station established and maintained the most stable and reliable links directly with the base station. There was a greater than 500% increase in parent changes between the closest nodes and the rest of the nodes in general.

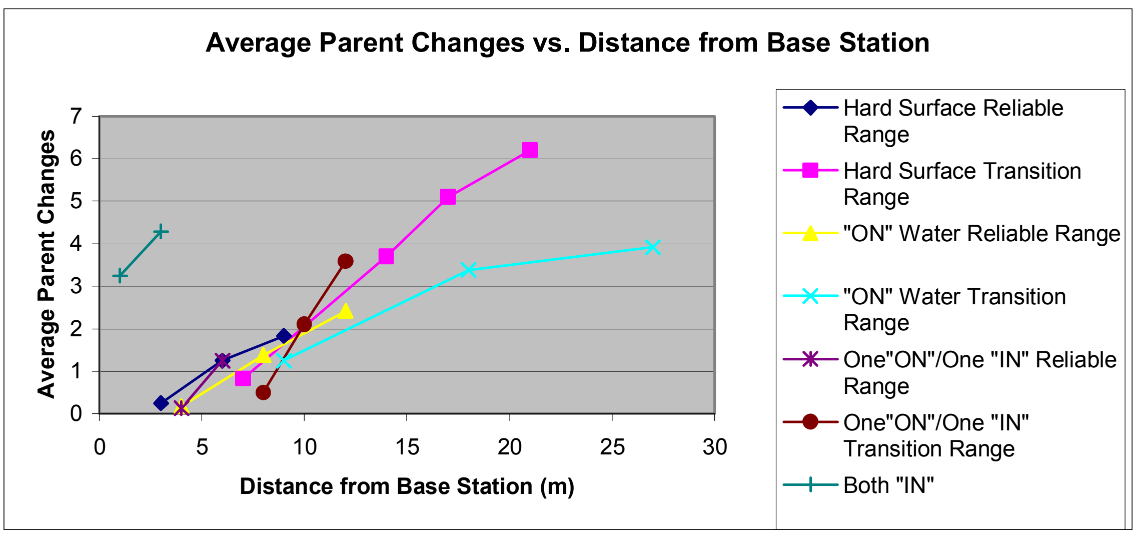

Figure 7. Average Parent Changes versus Average Distance from the Base Station

3.4.2 Both "IN" Network Stability Trial This last case stood apart from the other trials in that all nodes demonstrated a higher degree of instability throughout its transition region including the three nodes closest to the base station. The nodes in general changed parents on average just fewer than three times, almost one full parent change more. A difference between the nodes closest to the base station and the rest of the nodes was noted, but to a lesser degree than in previous situations, only about a 33% increase in parent changes.

As a final consolidation of data Figure 7 is presented to demonstrate the effect of distance from the base station on overall network stability.

4. Conclusions

The wireless, unattended sensor network performed admirably in situations where calm surface water conditions could be assured. With motes resting atop the surface of the water the performance even exceeded the dry land results. Surface path propagation over water allowed radio reception ranges out to a distance of nine meters whereas the radio range on a hard dry surface was only seven meters. However, this increase in range was undone by the very medium that provided it. A problem not as readily experienced on dry land, but very commonly associated with floating on the water is mobility. For the purposes of all of the experiments that took place in the water, a certain amount of herding was necessary to keep the motes in positions appropriate for the gathering of data.

Mobility notwithstanding, water precipitates other difficulties. Any water between two motes that are attempting to communicate greatly decreases their communication range to the point of futility. Completely submerged, motes have a communication range of a few centimeters and limited practical use. The transmission geometries for situations where one mote is below the surface of the water reduce this capability by more than half to four meters. Twice as many motes would be required to cover the same area. With the potential for motes to be on opposite sides of a wave or temporarily submerged and constantly moving in a variety of directions additional research with more dynamic situations will be necessary and is currently being pursued.

10. References

[1] C. Chong and S. Kumar, "Sensor Networks: Evolution, Opportunities, and Challenges," Proc. of the IEEE, vol. 91, no. 8, pp. 1247-1256, August 2003.

[2] M. Tingle, "Performance Evaluation of Prototyped Wireless Ground Sensor Network," Master's Thesis, Naval Postgraduate Sch., Monterey, CA, March 2005.

[3] A. Teo, and G. Singh, "Evaluation of the XMesh Routing Protocol in Wireless Sensor Networks," 49th IEEE Intl. Midwest Symp. on Circuits and Systems (MWSCAS '06), San Juan, Puerto Rico, August 7 – 10, 2006

[4] S.J. Koh, and G. Singh, "RF Characteristics of Mica-Z Wireless Sensor Network Motes," 49th IEEE Intl. Midwest Symp. on Circuits and Systems (MWSCAS '06), San Juan, Puerto Rico, August 7 – 10, 2006

[5] A. I. Al-Shamma'a, A. Shaw, and S. Saman, "Propagation of Electromagnetic Waves at MHz Frequencies Through Seawater," IEEE Transactions on Antennas and Propagation, Vol. 52, No. 11, November 2004.

[6] C. Alippi and G. Vanini, "Wireless Sensor Networks and Radio Localization: a Metrological Analysis of the MICA2 received signal strength indicator," Proc. of the 29th IEEE Conf on Local Computer Networks (LCN '04), Tampa, November 2004.

[7] G. Zhou, T. He, J. A. Stankovic,and T. Abdelzaher, "RID: Radio Interference Detection in Wireless Sensor Networks," Proc. of 2005 IEEE Infocom, Miami, March, 2005, pp. 891 - 901.

[8] V. Bokser, C. Oberg, G. S. Sukhatme, and A. Requicha, "A Small Submarine Robot for Experiments in Underwater Sensor Networks," Technical Report, Univ. of Southern California, 2003.

[9] "Mote View Users Manual," Rev. C, November 2006, Document 7430-0008-04. Crossbow Technology, Inc., San Jose, California.

[10] Air Force Weather Agency Doctrine, CDC 1W051A (A Course), Vol.3, Tactical and Radio-Communications Equipment, Unit 3, Radio-Frequency Communication, http://www.fas.org/spp/military/docops/afwa/U3.htm

[11] Rodney Vaughan, http://www.science.ca/askascientist/viewquestion.php?qID=1767