İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF INFORMATICS

THE EFFECTS OF WAVE HEIGHTS TO CONNECTIVITY AND COVERAGE IN SEA SURFACE FLOATING WIRELESS SENSOR NETWORKS

M.Sc. Thesis by
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Programme : Computer Science

JUNE 2009

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JUNE 2009

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ BİLİŞİM ENSTİTÜSÜ

DALGA YÜKSEKLİKLERİNİN DENİZ YÜZEYİNDE YÜZEN TELSİZ DUYARGA AĞLARINDA BAĞLANTILILIK VE KAPSAMA ALANINA ETKİLERİ

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FOREWORD

I would like to express my deep appreciation and thanks to my supervisor Prof. Dr. Sema OKTUĞ for her contribution and support. I also wish to thank Prof. Dr. Serdar BEJİ of Department of Ocean Engineering for his guidance in developing the wave models.

May 2009

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Computer Engineer

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ABBREVIATIONS

cm	: Centimeter
MEMS	: Micro-Electro-Mechanical Systems
LOS	: Line-of-Sight
m	: Meter
m^2	: Square meter
MHz	: Megahertz
OSI	: Open Systems Interconnection
RFS	: Restricted Floating Sensors
UDG	: Unit Disk Graph
WSN	: Wireless Sensor Network

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LIST OF SYMBOLS

C : Wave speed
g : Gravitational acceleration
H : Maximum wave height
h : Sea depth
k : Circular wave number
$\mathbf{k}_x$: Horizontal circular wave number
$\mathbf{k}_y$: Vertical circular wave number
L : Wave length
Π : Pi
T : Wave period
t : Time
θ : Wave angle
x : X-coordinate
ω : Circular frequency
y : Y-coordinate
z : Point height

THE EFFECTS OF WAVE HEIGHTS TO CONNECTIVITY AND COVERAGE IN SEA SURFACE FLOATING WIRELESS SENSOR NETWORKS

SUMMARY

Although acoustic communication has high range underwater, it has significant drawbacks, such as high and variable propagation, half-duplex communication capability, high bit error rate, and high energy consumption, which make radio based communication solutions usable for aquatic applications. Sea surface floating sensor networks with underwater sensing units and oversea communication units, formed either by bottom-anchored or floating sensor nodes, have many scientific, commercial, military, and industrial applications. In these networks, waves constitute significant obstacles for radio communication over the sea surface.

When a wave enters into a shallow water area, it becomes a shallow water wave and the speed of the wave is controlled only by the water depth. Utilizing this fact, a shallow water wave height model is proposed and used in the simulation program developed. Via numerous simulations, the effects of wave heights to communication and network connectivity are analyzed under various sea states, in order to determine the number of wireless sensor nodes to provide necessary connectivity and coverage for a region. Simulation results show that, as the waves get higher, communication is affected severely and the number of nodes required to provide appropriate coverage redundancy increases. Using the shallow water wave model developed, the number of extra nodes required to provide the application-specific redundancy can be determined. Moreover, the extra number of nodes needed to overcome the obstructive characteristics of the waves can be deployed as gateway nodes with communicating units only in order to decrease equipment and energy costs.

DALGA YÜKSEKLİKLERİNİN DENİZ YÜZEYİNDE YÜZEN TELSİZ DUYARGA AĞLARINDA BAĞLANTILILIK VE KAPSAMA ALANINA ETKİLERİ

ÖZET

Akustik haberleşme, su altında yüksek menzile sahip olmasına rağmen, yüksek ve değişken yayılım gecikmesi, yarı-çift yönlü iletişim yeteneği, yüksek bit hata oranı ve yüksek enerji tüketimi gibi zorluklarından dolayı, radyo tabanlı haberleşme çözümlerini suyla ilgili alanlardaki uygulamalarda kullanılabilir kılmaktadır. Dipten çapayla bağlı veya serbest yüzen, sualtı duyargalı, su üstü haberleşme birimli düğümlerden oluşan deniz yüzeyinde yüzen telsiz duyarga ağlarının bilimsel, ticari, askeri ve sanayi birçok uygulamaları vardır. Dalgalar, bu ağlarda, su yüzeyindeki radyo haberleşmesi için ciddi engeller oluşturmaktadır.

Bir dalga sığ su alanına girdiği zaman, bir sığ su dalgası haline gelir ve dalga hızı sadece su derinliğine bağlı olur. Bu bilgiden yararlanarak bir sığ su dalga modeli önerilmiş ve geliştirilen simülasyon programında kullanılmıştır. Bir bölgede gerekli ağ bağlantılılığı ve kapsama alanını sağlamak için yeterli telsiz duyarga düğüm sayısını belirlemek için, birçok simülasyon aracılığıyla, dalga yüksekliklerinin, çeşitli deniz durumlarında, haberleşmeye ve ağ bağlantılılığına etkileri incelenmiştir. Simülasyon sonuçlarına göre, dalgalar yükseldikçe haberleşme şiddetli bir biçimde etkilenmekte ve uygun kapsama alanı yedekliliğini sağlamak için gerekli düğüm sayısı artmaktadır. Geliştirilen sığ su dalga modelini kullanarak uygulamaya özgü kapsama alanı yedekliliğini sağlamak için fazladan gereken düğüm sayısı belirlenebilmektedir. Bununla birlikte, dalgaların engelleyici özelliklerini aşmak için fazladan gereken düğümler, sadece haberleşme birimine sahip ağ geçidi düğümler olarak eklenerek malzeme ve enerji maliyetini düşürebilirler.

1. INTRODUCTION

Wireless sensor networks have been a major research area in the last few years with the advances in wireless communications and micro-electro-mechanical systems (MEMS) technology, which enabled development of low-cost, low-power sensor nodes [1]. Wireless sensor networks are capable of monitoring a wide variety of phenomena via many different type of sensors such as magnetic, thermal, visual, seismic, and acoustic.

1.1 Purpose of the Thesis

There are many applications of sensor networks in aquatic environments, such as tactical surveillance, oceanographic monitoring, and disaster prevention. Sensor networks have different architectural types in underwater explorations. A wide of range of these applications are designed with underwater acoustic communication capability. A detailed survey on underwater acoustic sensor networks is given in [2]. While acoustic communication has high communication range underwater, it is not always feasible, given its high and variable propagation time, high bit error probability, half-duplex communication capability, and high energy consumption. Sea surface floating sensor networks provide a viable alternative for underwater research. This thesis targets sensor networks with underwater sensing units and oversea communication units, formed either by bottom-anchored or floating sensor nodes. Hybrid networks, which include radio communication together with other communication schemes, are also in the scope of this work.

In this thesis, a sinusoidal shallow water wave height model is developed, and this model is used in the simulations under various sea states, with a range of node densities. Network connectivity is analyzed, together with sensing coverage, with the changing node density. The goal of this work is to determine the necessary number of nodes for the desired connectivity and coverage.

1.2 Background

There are several works on sea surface communicating networks. Cayirci et al. introduced a scheme, where sensors are connected to the surface buoy by cables and radio communication between the nodes is provided by antennas at the surface buoys over the sea surface [3]. This system targets maximum coverage by adjusting the depth to place the sensors, in order to provide maximum coverage, however the effect of wave height to communication is not taken into account.

In [4], bottom-anchored, restricted floating sensors (RFS) are used to measure sea depth, without any extra ranging devices, using localization data together with rope lengths. Communication is performed over the sea surface by means of radio frequency.

Voigt et al. designed a small-scale marine sensor network to monitor underwater temperature on different depths [5]. The network consists of sensor nodes placed underwater on chains, which are linked to the sea surface buoys containing oversea radio modules. Data flows from the buoys to the sink buoy that transfers data to the shore.

In [6], surface gateways with radio communication capability are used together with underwater acoustic communication, in order to mitigate high propagation delay through acoustic medium, for faster and less energy-consuming communication with the control station.

OceanSense [7] is developed to collect real-time ocean environmental data. The system consists of sensor nodes lifted up a meter above the sea surface to avoid signal-obstructing characteristics of the waves.

Marin-Perianu et al. uses non-connected node pairs due to waves in the sensor network, in order to compute wave heights [8]. This work targets computing wave heights within an area, rather than utilizing the wave characteristics for better communication.

Most of the work in the literature does not take effect of wave heights into account or uses higher antennas in order to neutralize the obstructive nature of the sea surface. This work deals with the effect of wave heights to communication for predefined sea states and the necessary node density in order to meet the application requirements.

1.3 Structure of the Thesis

The remainder of this thesis is organized as follows. Chapter 2 gives brief information wireless communication, wireless sensor networks, network connectivity and coverage. Chapter 3 describes the target system model, which consists of node and network architectures, and communication and sensing models. The sinusoidal wave model is explained in Chapter 4, which also introduces the water wave characteristics and sea states. Chapter 5 presents the simulation environment and gives the results obtained through simulations. Chapter 6 concludes the thesis mentioning future work.

2. WIRELESS SENSOR NETWORKS

2.1 Wireless Communication

2.1.1 Wireless channel

Wireless communication means transport of the electromagnetic waves over a wireless channel. Wireless channel is an unguided medium [9], i.e. it transmits the signals but do not guide them. In wireless channel, transmitting antenna, itself, is generally more influential on the transmission characteristics than the channel bandwidth.

Wireless transmission is performed by radio waves, microwave or infrared over the electromagnetic spectrum. Figure 2.1 depicts the electromagnetic spectrum [10].

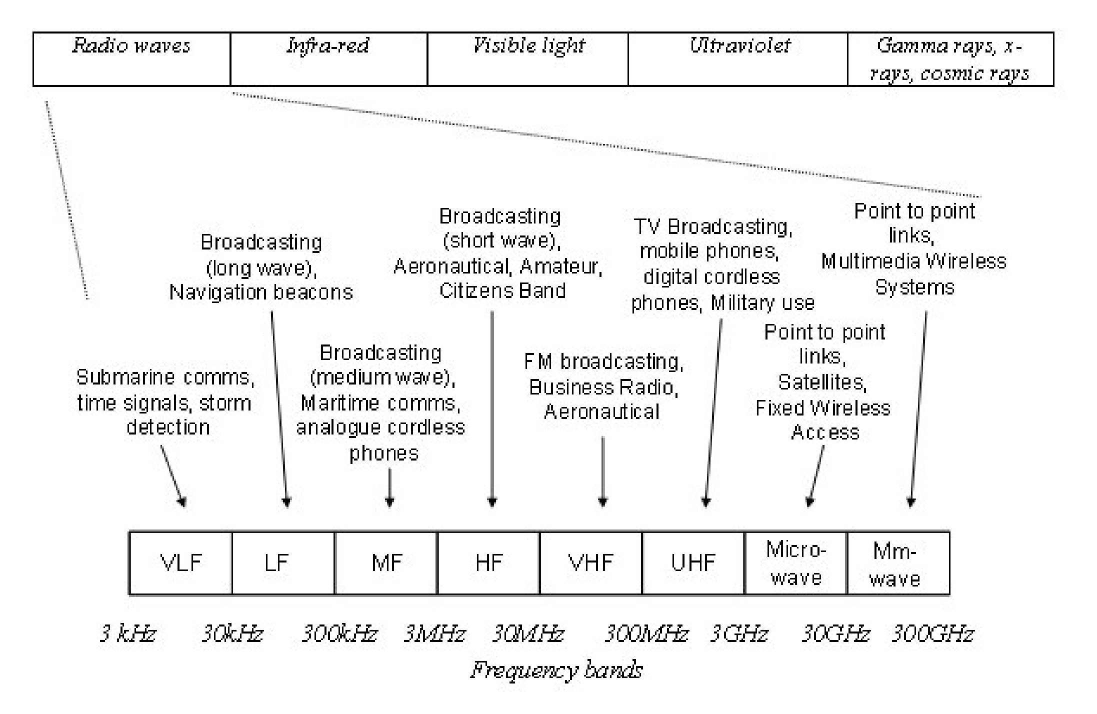

Figure 2.1 : The electromagnetic spectrum

2.1.2 Wireless transmission impairments

Radio signals are impaired by many factors, such as:

- Attenuation
- Shadowing
- Reflection
- Refraction
- Scattering
- Diffraction
- Multipath

Although some of the listed impairments are also applicable for wired communication, wireless transmission is affected by the environmental conditions much more than the wired transmission, which forms the necessity of wireless-specific communication schemes.

2.2 Wireless Sensor Networks

Wireless sensor networks (WSNs) are separated from other infrastructural or ad hoc networks by equipment differences, node density, scalability, energy needs, configurability, and data centric behavior [11]. Therefore, wireless sensor networks need their own protocols to be implemented for efficiency.

2.2.1 Sensor node architecture

A typical sensor node consists of sensing unit, communication unit, processing unit, and power unit. Figure 2.2 illustrates components of a wireless sensor node [1].

2.2.2 Protocol stack for WSNs

Wireless sensor networks have a similar protocol stack to OSI (Open Systems Interconnection) model [12], but also have a management plane dimension. Figure 2.3 illustrates the protocol stack for wireless sensor networks containing physical, data link, network, transport and application layers together with power management, mobility management and task management planes [13].

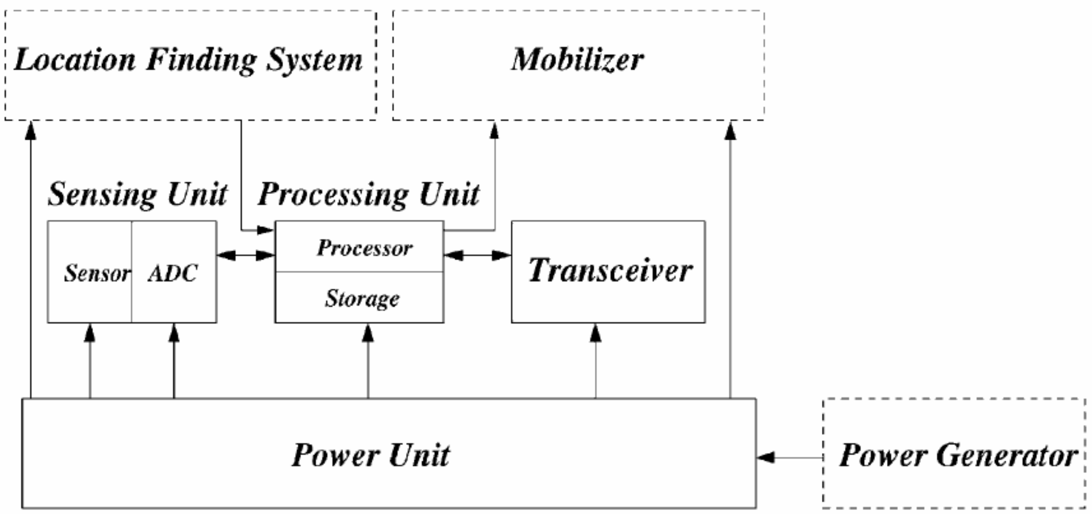

Figure 2.2 : Components of a wireless sensor node

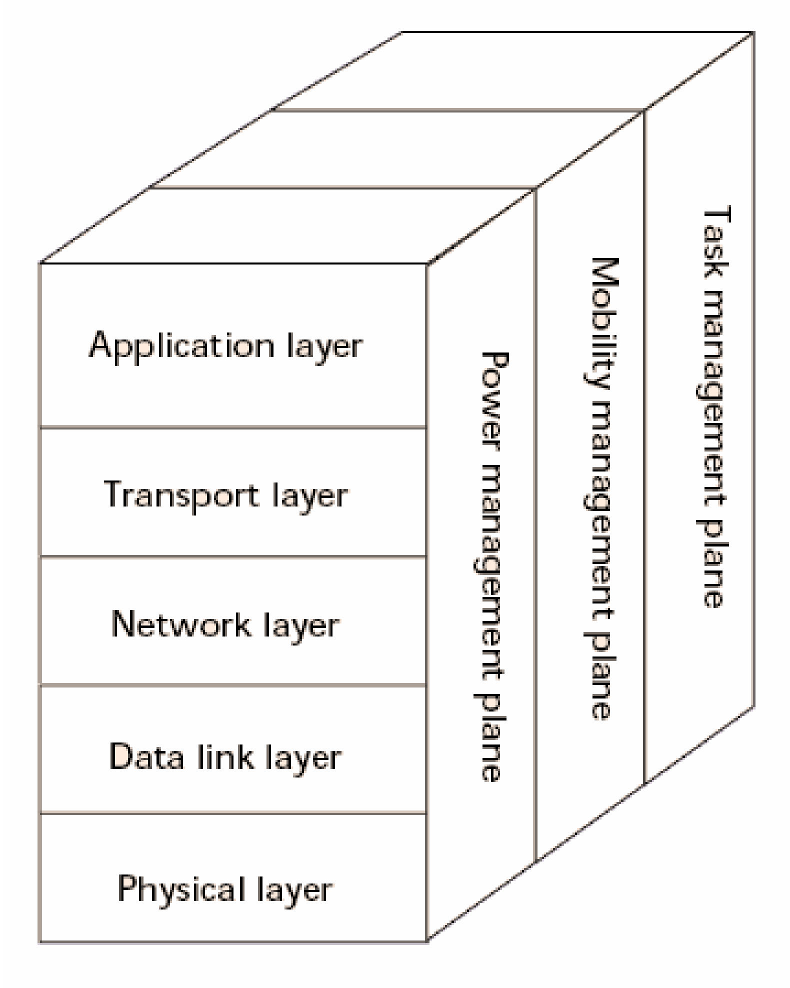

Figure 2.3 : Protocol stack for WSNs

The physical layer deals with the modulation, transmission and receiving techniques. Data link layer handles medium access control issues in a power-aware manner. Routing is provided by the network layer, while transport layer supplies the necessary data for the application layer.

Power management plane regulates the power usage of sensors both for communication sensing needs. Mobility management plane maintains neighbor information for the sensors during movement. The task management plane deals with the scheduling of sensing tasks across the field.

2.2.3 Applications of WSNs

Wireless sensor networks have many applications in science industry, and military. Figure 2.4 shows the application areas of WSNs [14].

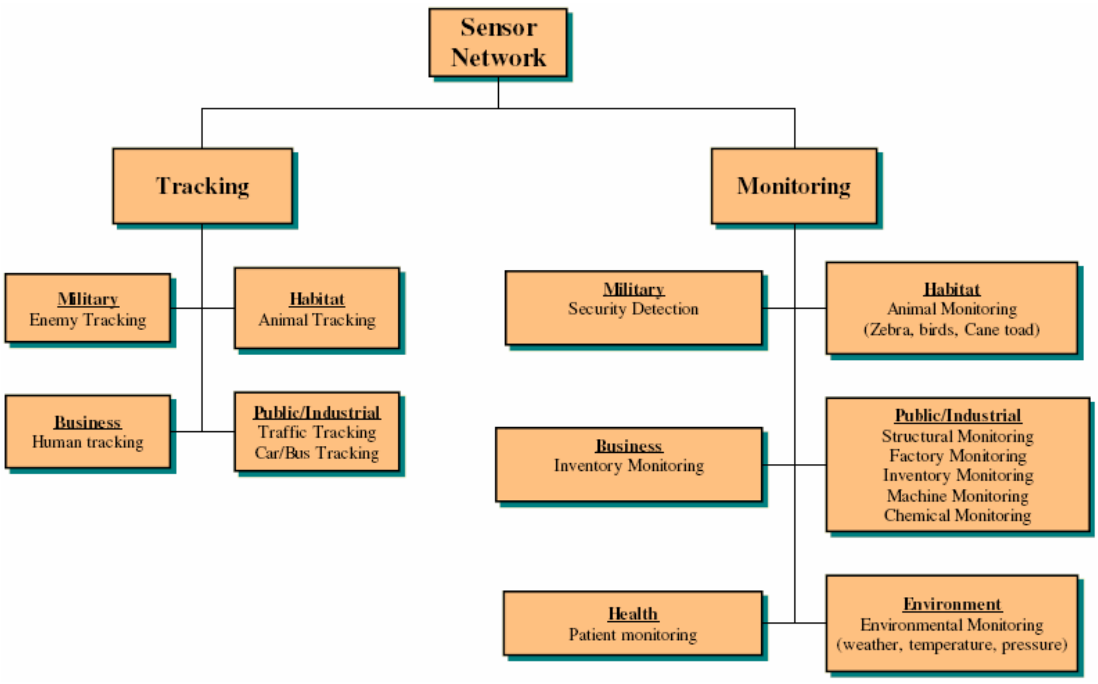

Figure 2.4 : Applications of WSNs

2.3 Connectivity

Number of edges or vertices needed to remove in order to disconnect a graph gives the degree of connectivity in a graph [15]. Figure 2.5 shows a 3-connected and a disconnected graph [16].

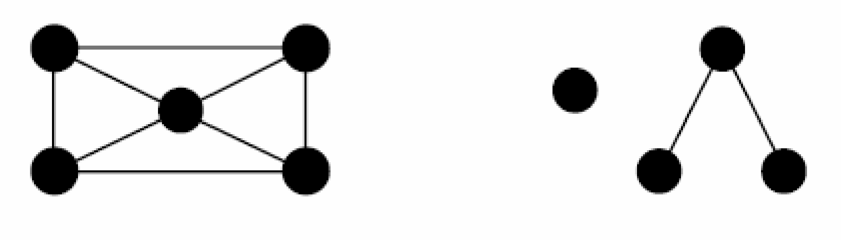

Figure 2.5 : A 3-connected and a disconnected graph

Connectivity is dependant on the communication ranges, the locations, and the environment of the wireless sensor nodes. Disconnection of one node due to communication or power issues may lead to disconnection of the network; therefore, sensor network design should consider the failure possibilities to form a redundant network.

An optimal wireless sensor deployment strategy should aim a fully connected network, while maintaining the coverage. Therefore, connectivity should be studied together with coverage [16].

2.4 Coverage

Coverage area of a wireless sensor node is determined by the sensing range of the sensor unit attached. Sensing coverage can refer to either area coverage or node coverage. Area coverage is the ratio of covered area to total area interested, while the node coverage is the ratio of redundant nodes to the total number of sensor nodes [17].

2.5 Aquatic Wireless Sensor Network Applications

Wireless sensor networks have many applications in aquatic environments. Aquatic environments include sea shores, sea surface, and underwater. Typical applications are oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications.

These applications are realized by means of either radio communication over the surface or acoustic modems underwater. The communication scheme usually depends on the application type.

2.6 Challenges of Underwater Communication

Underwater communication is usually handled by acoustic modems. Acoustic modems provide high range data communication underwater. Figure 2.6 illustrates the component diagram of an acoustic sensor node.

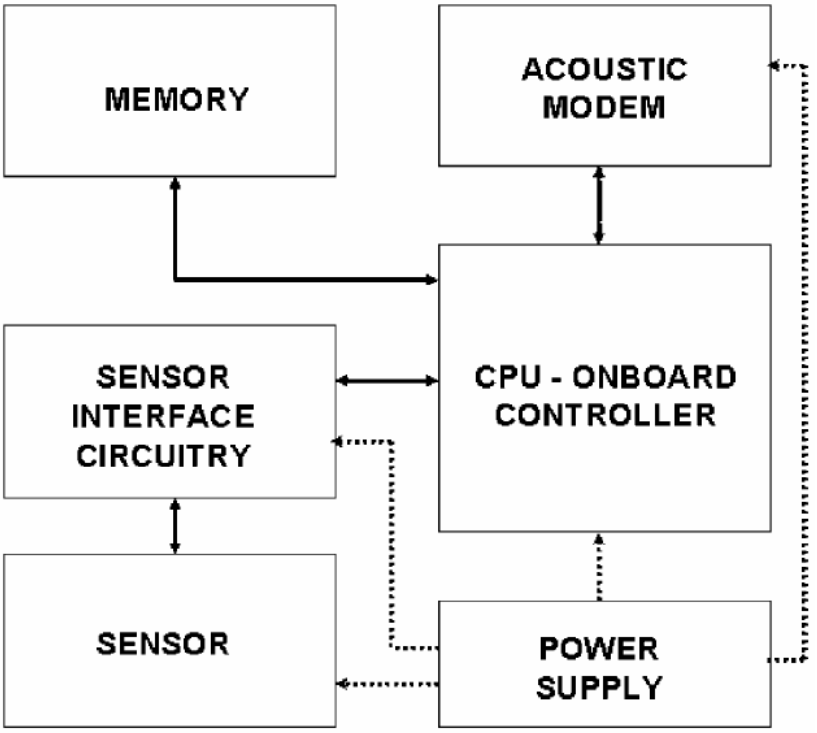

Figure 2.6 : Component diagram of an acoustic sensor node

Despite the superiority of acoustic communication to radio communication in underwater transmission range, acoustic communications bring many challenges to deal with. Major challenges of underwater acoustic communication can be listed as [2]:

- High and variable propagation delay
- Limited bandwidth
- High bit error rate
- Half-duplex communication
- High energy consumption
- High cost
- Narrow frequency band

- Difficulty of rechargeability due to lack of sun power
- Corrosion

3. SYSTEM MODEL

Radio propagation is impaired by absorption over the sea surface due to humidity [18]. The higher the frequency, the more the signal strength decreases. Therefore, a radio unit with 433 MHz frequency for communication with 250 m range is chosen, using an antenna of 20 cm height [19].

The sensing units of the nodes are placed underwater. 200 m of sensing range is chosen as of a typical underwater magnetic sensor [20], which can be used in intrusion detection.

3.1 Bottom-anchored Node Architecture

The sensing units can be placed just below the surface, at the bottom or at any depth underwater using the bottom anchor link. Since the target sea depth is not more than 10 meters at most, size of this dimension is negligible, compared to the sensing range. A buoy is used to hold the antenna over the sea surface. Sensing units are connected to the buoy by the wired link. Figure 3.1 illustrates a sample node anchored to the bottom.

The target network architecture is bottom anchored floating buoy nodes as illustrated in Figure 3.1.

3.2 Floating Node Architecture

The model can also be applied to floating sensors, when all floating sensors are assumed to be in the same movement pattern within the shallow water area. In this architecture, sensor unit is placed just under the buoy. Floating sensor node architecture is shown in Figure 3.2.

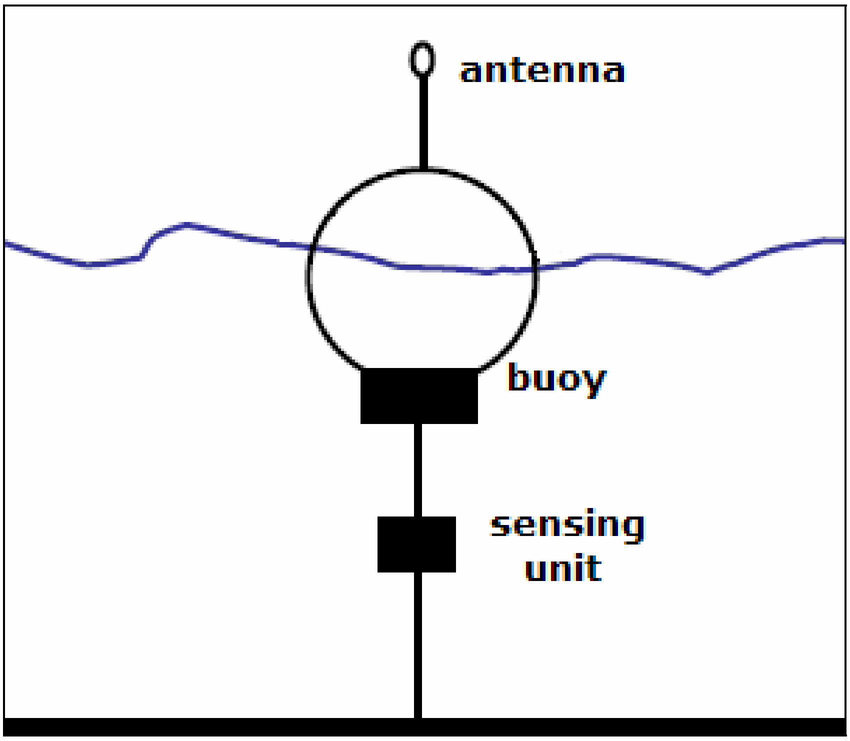

Figure 3.1 : Bottom-anchored node architecture

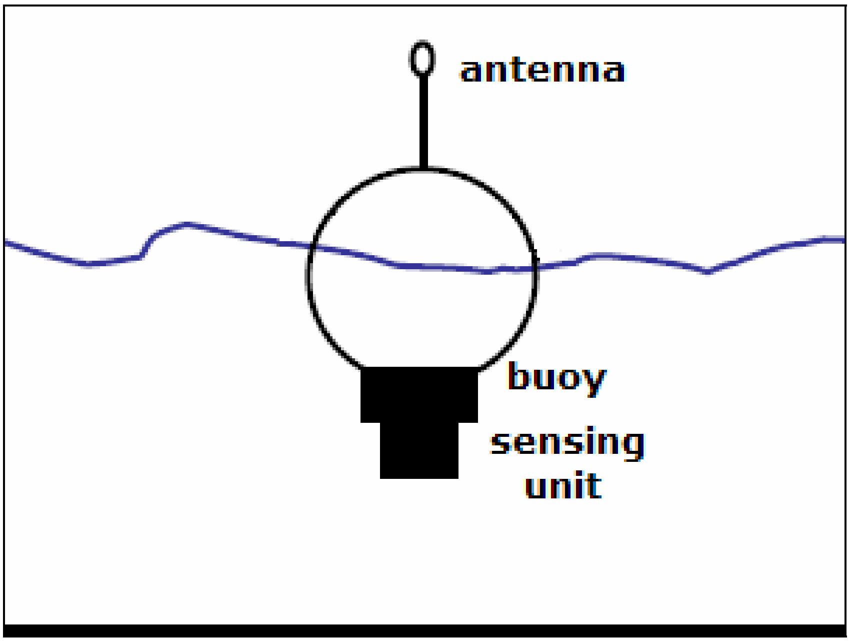

Figure 3.2 : Floating node architecture

3.3 Communication Model

Unit Disk Graph (UDG) model is used for communication [21], i.e. if the target node or point to communicate is within the predefined communication range, then it is connected. If it is out of the range, it is not connected. This is a simple model, which allows obtaining the effect of wave heights only through the simulations. Figure 3.3 graphs communication probability versus range. Figure 3.4 illustrates two nodes communicating [22].

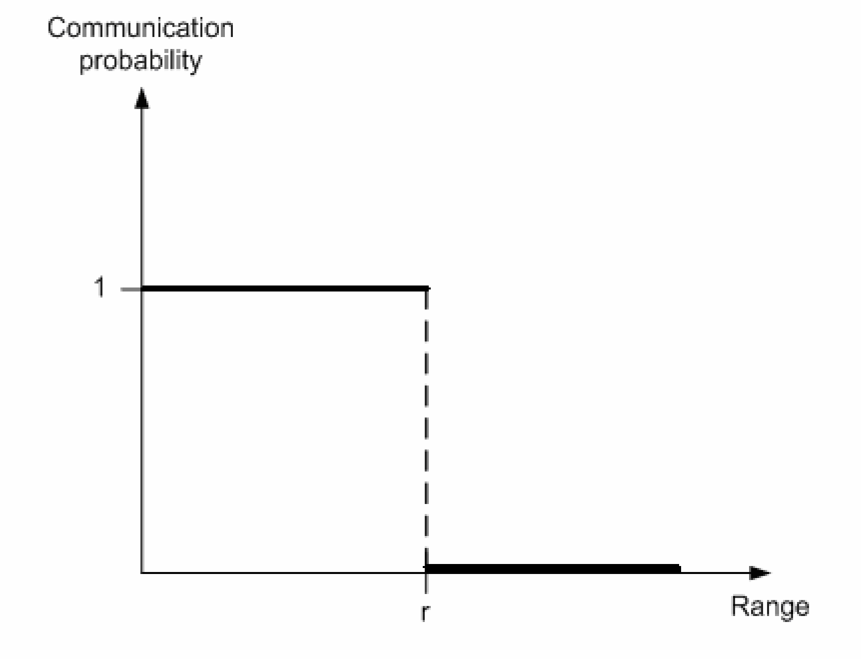

Figure 3.3 : Communication probability vs. range

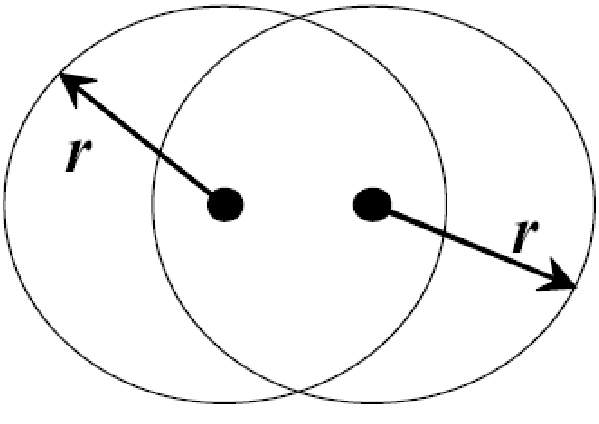

Figure 3.4 : Unit Disk Graph communication model

3.4 Sensing Model

Binary sensing model [23] is used, similar to the communication model. If the event to be sensed is within the sensing range, then it is sensed; otherwise it cannot be sensed. Figure 3.5 shows sensing probability versus range.

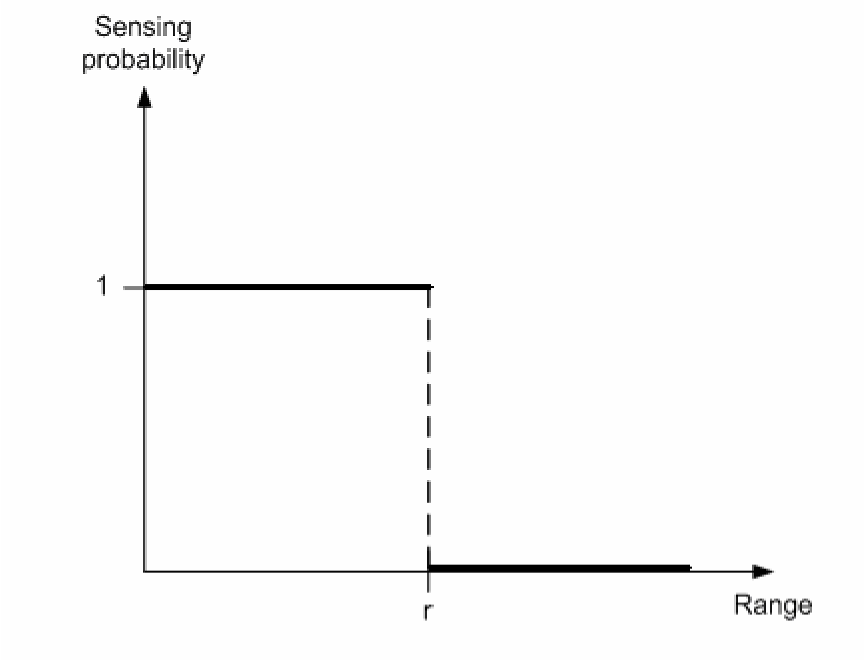

Figure 3.5 : Sensing probability vs. range

4. WAVE MODEL

Water waves are mostly created by wind. As the wind blows, tiny ripples appear over the sea surface, which allows wind to affect the surface more, resulting in a cumulatively increasing energy and wave size. The highest point of the wave over the sea surface is called crest, while the lowest point under the surface is called trough. The vertical distance from the crest to the trough gives the wave height. The horizontal distance between two crests or two troughs is called the wave length and the time required for two crests or two troughs passing through a spatial point is called the period [24]. Figure 4.1 illustrates a water wave and its characteristics.

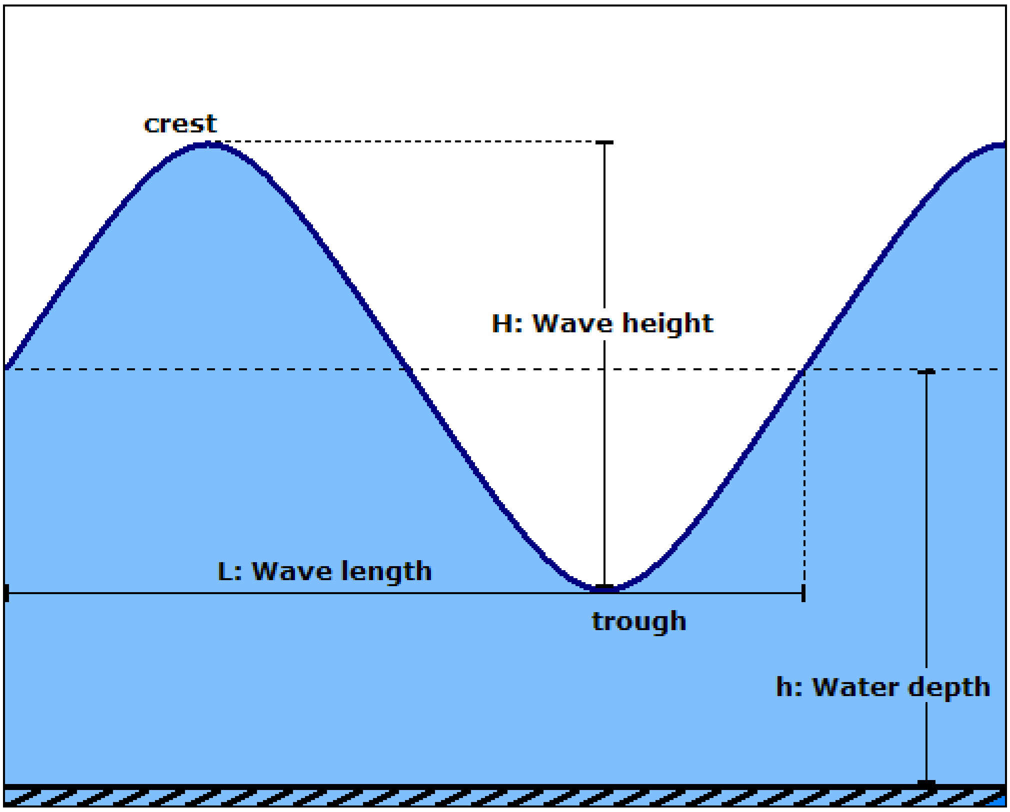

Figure 4.1 : A water wave and its characteristics

4.1 Shallow Water Wave Height Model

As a wave moves into a shallow water area, the ratio of water depth to wave length gets very small and the wave becomes a shallow water wave [25]. In this case, the speed of the wave is controlled only by the water depth. The wave speed (C) can be obtained by:

$$C = \sqrt{gh}\,, \qquad \textbf{(4.1)}$$

where g is the gravitational acceleration and h is the water depth. The wave length (L) is the product of wave speed (C) and the wave period (T):

$$L = CT\,. \qquad \textbf{(4.2)}$$

The circular frequency (ω) of the wave and the circular wave number (k), i.e. the number of times the wave has the same phase per unit of space, can be calculated by:

$$\omega = \frac{2\Pi}{T}\,, \qquad \textbf{(4.3)}$$

$$k = \frac{2\Pi}{L}\,. \qquad \textbf{(4.4)}$$

If the angle between the sea shore and the wave is θ, then horizontal (k_x) and vertical (k_y) components of circular wave number are given by:

$$k_x = k\cos(\theta)\,, \qquad \textbf{(4.5)}$$

$$k_y = k\sin(\theta)\,. \qquad \textbf{(4.6)}$$

Using the values obtained from (4.3), (4.5), and (4.6), height of a point (z) over a moving sinusoidal wave can be computed depending on the maximum wave height (H), time (t) and point coordinates (x, y) by:

$$z = \frac{H}{2}\sin(\omega t - k_x x - k_y y)\,. \qquad \textbf{(4.7)}$$

A sample wave with 2 meters of height at time 0 is given in Figure 4.2. Water depth is 6 meters, resulting in a wave speed of 7.67 meters per second. Wave length is 61 meters, angle between wave direction and shore is 75°.

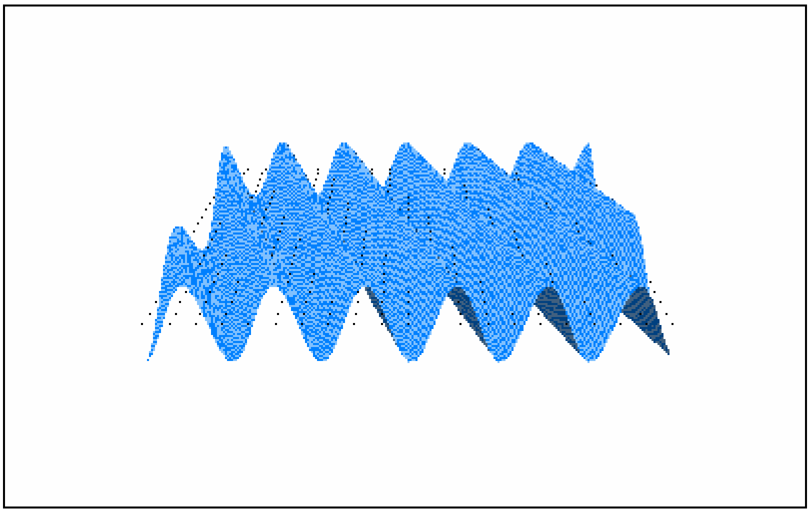

Figure 4.2 : A sinusoidal shallow water wave with 2 m height

This model is used to develop a simulation environment for various wave heights.

4.2 Sea States

The relationship between wind speed and wave heights have led to the introduction of Universal Sea State Code's used all over the world [25]. These states characterize wave states with corresponding wave heights. Table 4.1 gives the average wave heights for sea states 0 to 9.

Table 4.1: Sea States vs. Average Wave Heights

Sea state code	Average wave heights (m)
0	0
1	0 – 0.3
2	0.3 - 0.6
3	0.6 - 1.2
4	1.2 - 2.4
5	2.4 - 4.0
6	4.0 - 6.1
7	6.1 - 9.1
8	9.1 - 13.7
9	above 13.7

Wave models, for the sea states simulated, are sketched in Appendix A.1.

5. SIMULATIONS AND RESULTS

5.1 Simulation Environment

The simulation program is developed with C++ to analyze the effect of wave heights obtained from the sinusoidal shallow water wave model. All simulations are performed in a 1000x1000 m^2 area. There are two sink nodes on the shore, providing the communication with the simulation area.

Only line-of-sight (LOS) communication is assumed possible. Nodes have different heights according to their coordinates and wave model including the antenna height. Higher antenna heights provide higher connectivity. A line is generated between the antennas of the originating node and the target node. If any point over the line is left below the wave, the node pair is disconnected at that moment. Figure 5.1 shows communication obstructed by wave. Since the wave and node heights are dependant on time, heights are calculated for three successive snapshots over the time. Each snapshot corresponds to a transmission attempt. If two nodes are not connected in any of these snapshots, the node pair is considered to be disconnected. Increasing the number of snapshots increases the connectivity with the cost of higher delay. Node connectivity between each pair is calculated in the beginning of the simulation. Then, neighbors of each node are determined in order the form the graph connected to the sink nodes. Finally, area sensing coverage and node sensing coverage are calculated using the connected node data.

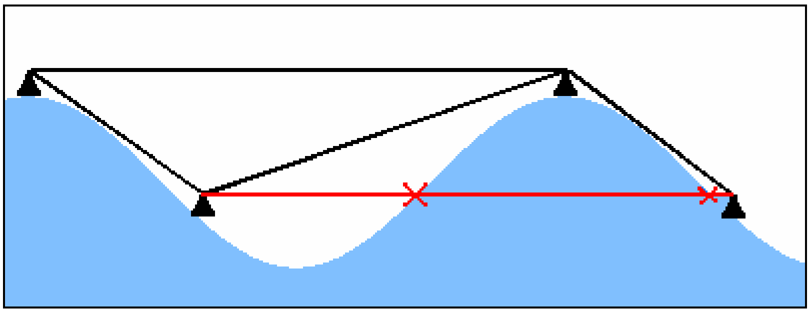

Figure 5.1 : Communication obstructed by wave

5.2 Performance Metrics

Performance metrics are connectivity, area coverage, and node coverage. Connectivity gives the percentage of nodes connected to the sink nodes. Area coverage is the percentage of area that can be sensed at least one node. Node coverage is the percentage of nodes whose whole sensing area can be sensed by at least one other node, i.e. 2-node coverage.

In addition, k-node coverage is used as a performance metric to determine the node coverage degree. If the point, which can be sensed by the minimum number of sensors, is covered by k number of sensors, the system is called k-covered. This is used to provide sensing redundancy information about the network.

5.3 Results

Performance of the network is evaluated under various sea states. Sea states 0, 3, 4, 5, and 6 are chosen for evaluation. Sea state 0 with maximum wave height of 0.02 meters is evaluated as the base state. Maximum wave heights of 1, 2, 3.5, and 5 meters, corresponding to the sea states 3, 4, 5, and 6 respectively, are used in the simulations.

There are two types of node deployment strategy used in the simulations: Grid deployment and random deployment. Simulations begin with 36 nodes, which is the minimum number needed to sense the whole simulation area and the node number increases up to 144 nodes in the simulations.

First set of simulations were performed with grid deployment. Figure 5.2 illustrates a sample grid deployed network with 49 nodes on sea state 5. Two sink nodes on the shore are represented by black boxes, while the other nodes in the connectivity graph are represented by square borders. All other nodes are colored so that each color represents a separate connected graph. Sensing coverage area is colored by green. Appendix A.2 contains network graphs for some of the network graphs simulated.

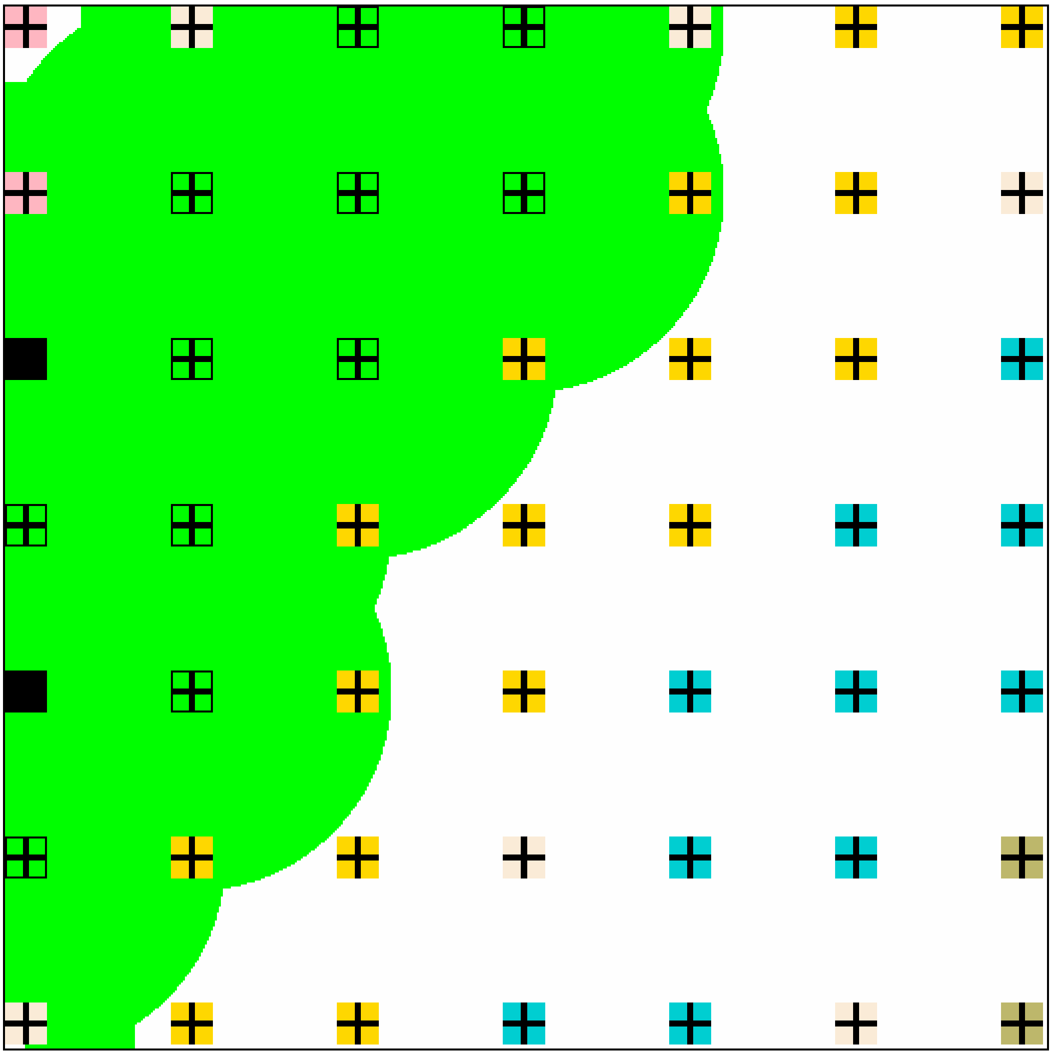

Figure 5.2 : Grid deployed network with 49 nodes on sea state 5

Number of nodes is increased gradually to enhance the network connectivity and coverage. Figure 5.3 shows connectivity for five sea states with increasing number of nodes. Initially, with 36 nodes, the network is fully connected only in sea state 0; while in the other sea states, connectivity has severely been affected by the wave heights. Increasing the node numbers from 36 to 100, the network converges to full connectivity in all sea states.

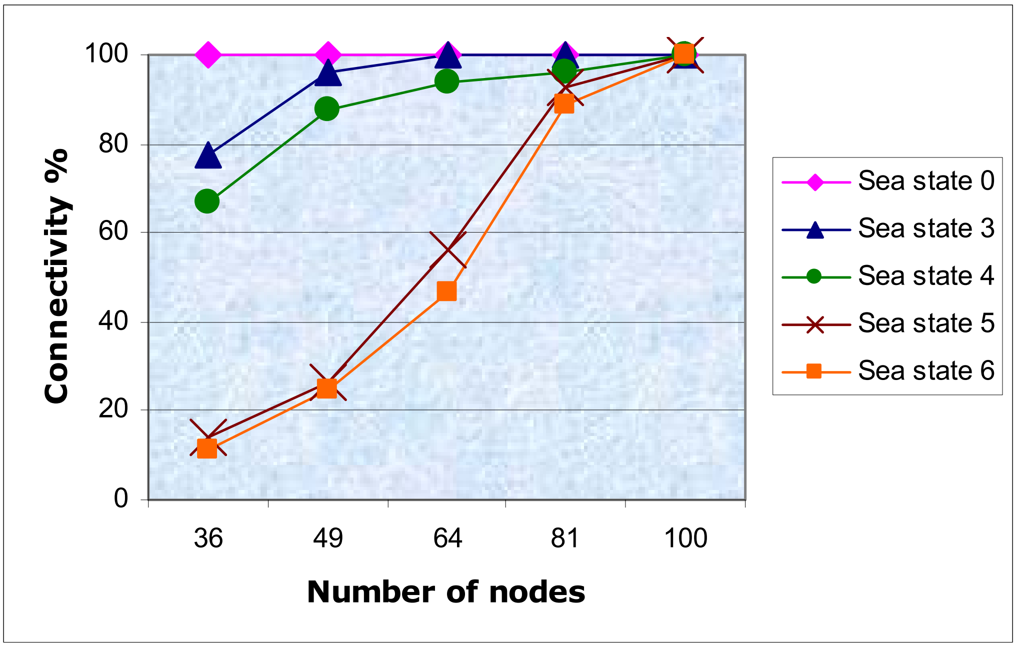

Figure 5.3 : Connectivity vs. node number (grid deployment)

Area coverage under the five sea states versus number of nodes is given in Figure 5.4. Area coverage reaches to 100 percent as the number of nodes is increased from 36 to 81. Although full connectivity is not reached in all sea states, area is fully covered with 81 nodes. However, number of nodes should be increased further to 100 for 100 percent 2-node coverage (Figure 5.5), to provide minimum sensing redundancy for the network.

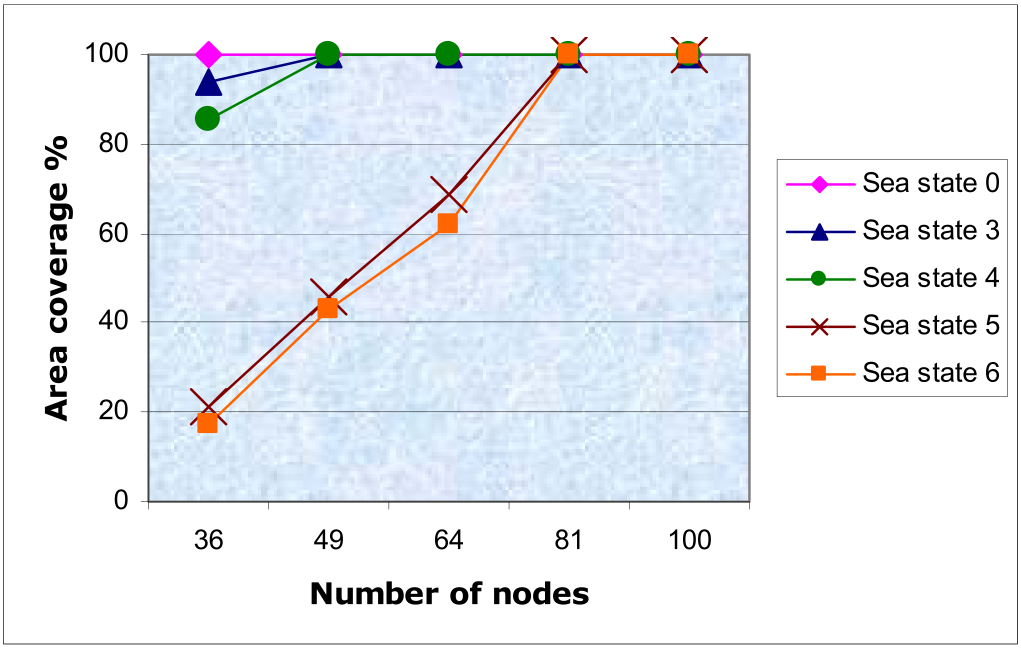

Figure 5.4 : Area coverage vs. node number (grid deployment)

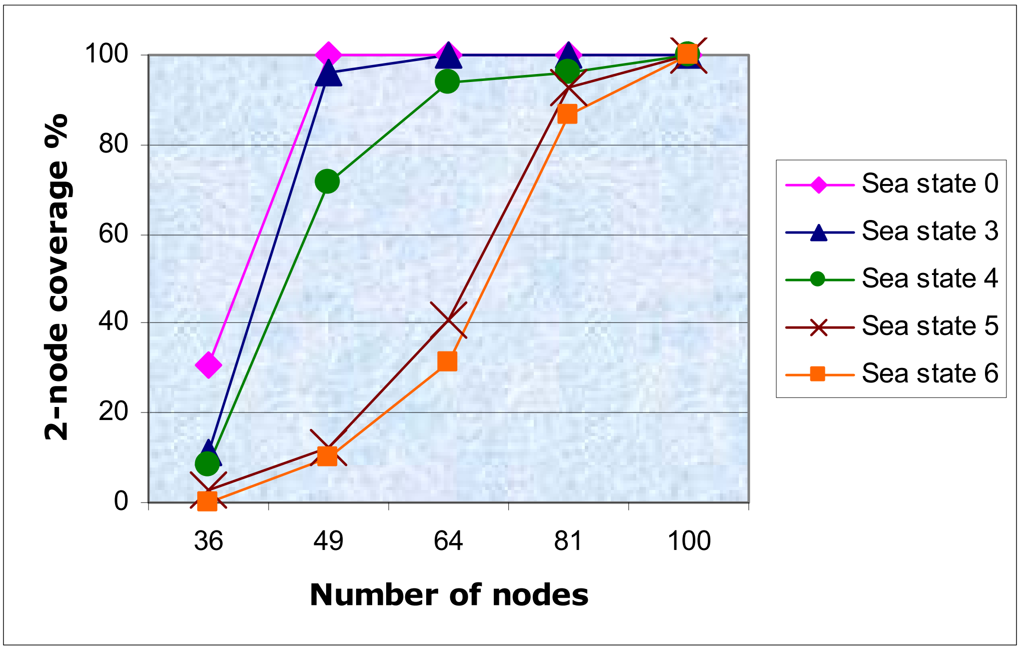

Figure 5.5 : 2-node coverage vs. node number (grid deployment)

As the minimum sensing redundancy is provided by increasing node density, further degrees of redundancy are analyzed by finding the k-coverage, where any point over the target space can be covered by at least k sensors. Figure 5.6 illustrates the k-coverage for all sea states. Deploying 100 nodes results in 4-coverage for all states. As the number of nodes decreases, k-coverage begins to drop for higher sea states.

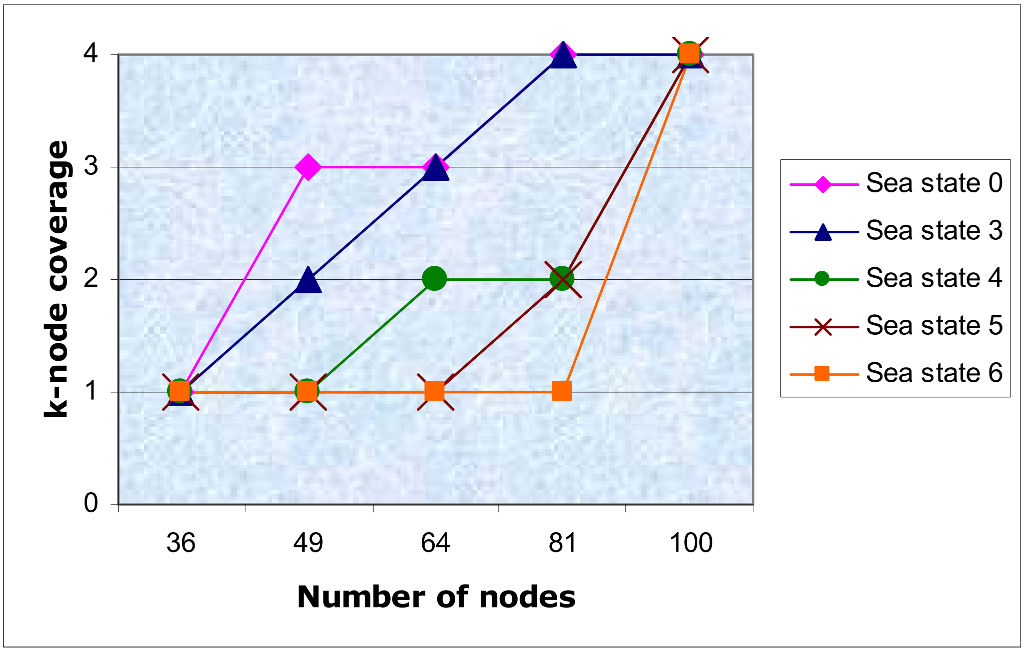

Figure 5.6 : k-node coverage vs. node number (grid deployment)

Evaluating all performance metrics together, network properties under sea states 5 and 6 are very similar, requiring more node density in order to achieve full performance, while performance under sea states 3 and 4 are more similar to base state, sea state 0. It can be concluded that when maximum wave height exceeds 3 meters, the results obtained for the target simulation area are affected severely.

Next set of the simulations were performed for random node deployment within the same area. Figure 5.7 shows a sample randomly deployed network with 36 nodes on sea state 4. 10 samples of random deployment are used in the simulations.

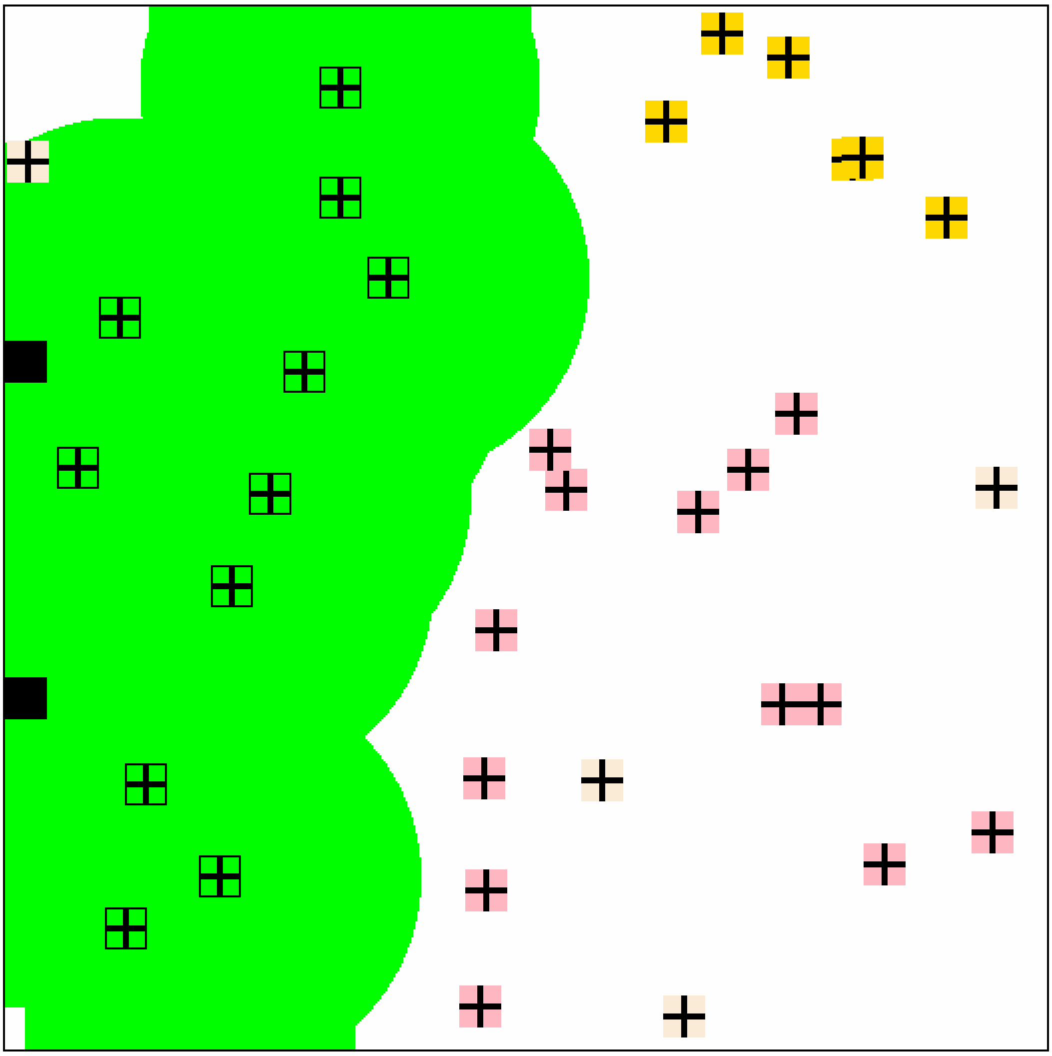

Figure 5.7 : Randomly deployed network with 36 nodes on sea state 4

Figure 5.8 shows connectivity versus number of nodes for the randomly deployed network. Increasing node number from 36 to 64, full connectivity is achieved. Although less number of nodes is sufficient for full connectivity, compared to grid deployment, network behavior under same sea states are similar; full connectivity for sea states 5 and 6 are provided with more nodes than the other sea states.

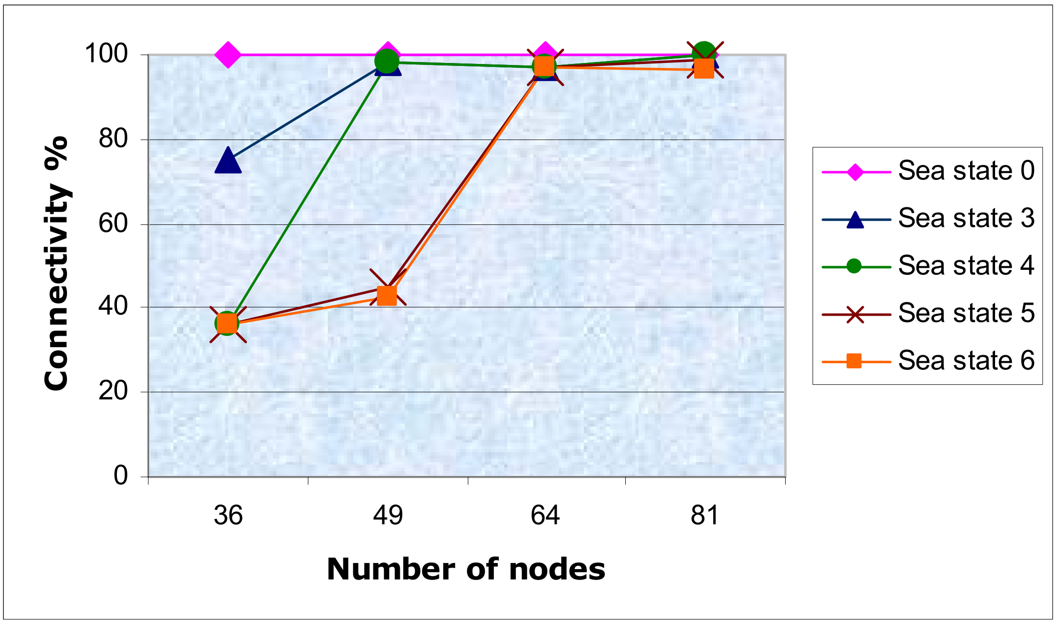

Figure 5.8 : Connectivity vs. node number (random deployment)

Area coverage percentage for random deployed network is sketched in Figure 5.9. Achieving the full connectivity, results in full area coverage for all states. Therefore, connectivity and area coverage versus number of nodes are parallel to each other.

Figure 5.10 gives the 2-node coverage percent for randomly deployed network. As in the grid network, although full connectivity and area coverage is achieved, number of nodes should be increased further, to provide a more redundant system.

For the random deployment model, sea states 5 and 6, i.e. shallow water areas where the maximum wave height is 3 meters or higher, sensors need to be deployed dense than the other sea states need. This is consistent with the results obtained through grid deployment model for the target simulation area.

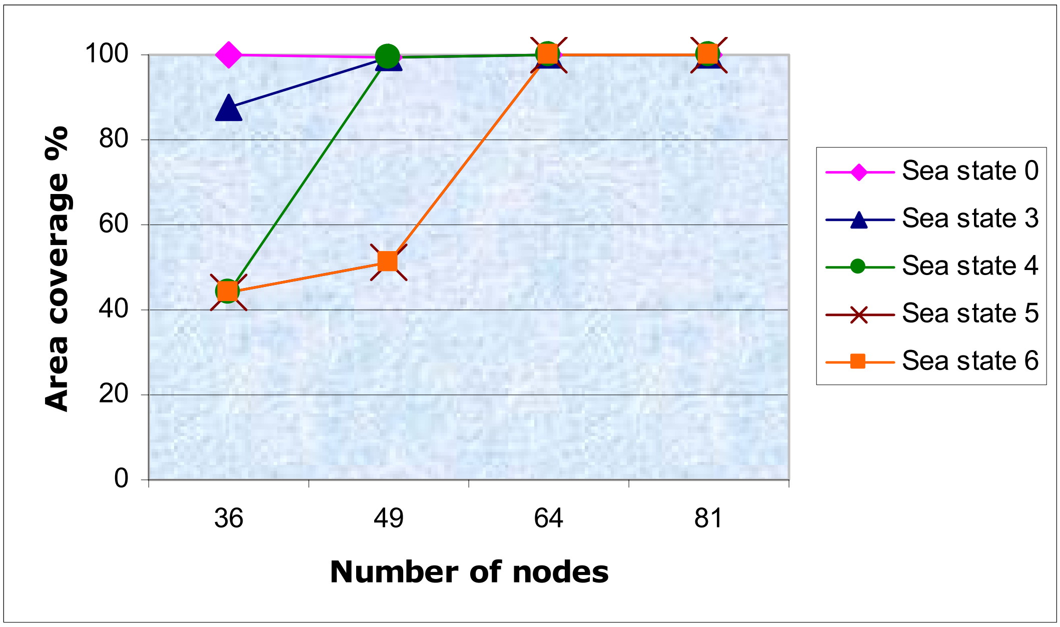

Figure 5.9 : Area coverage vs. node number (random deployment)

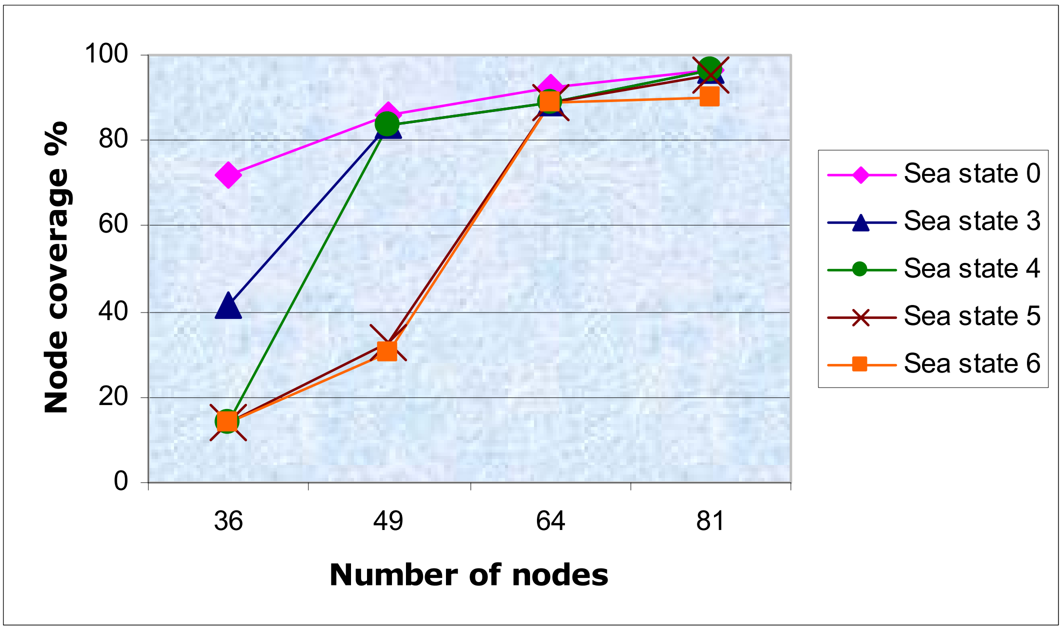

Figure 5.10 : 2-node coverage vs. node number (random deployment)

Finally, connectivity of the randomly deployed network is investigated for lower transmission ranges. Figure 5.11 shows connectivity percent for 150 meters of transmission range, while Figure 5.12 sketches the results obtained for 200 meters of transmission range.

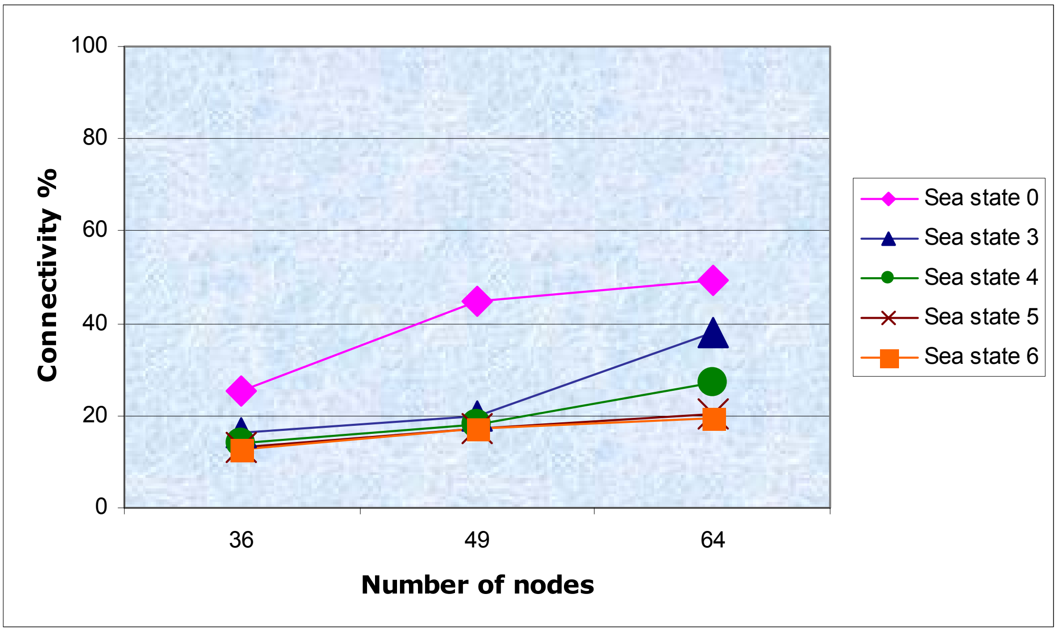

Figure 5.11 : Connectivity vs. node number (random deployment – 150 m range)

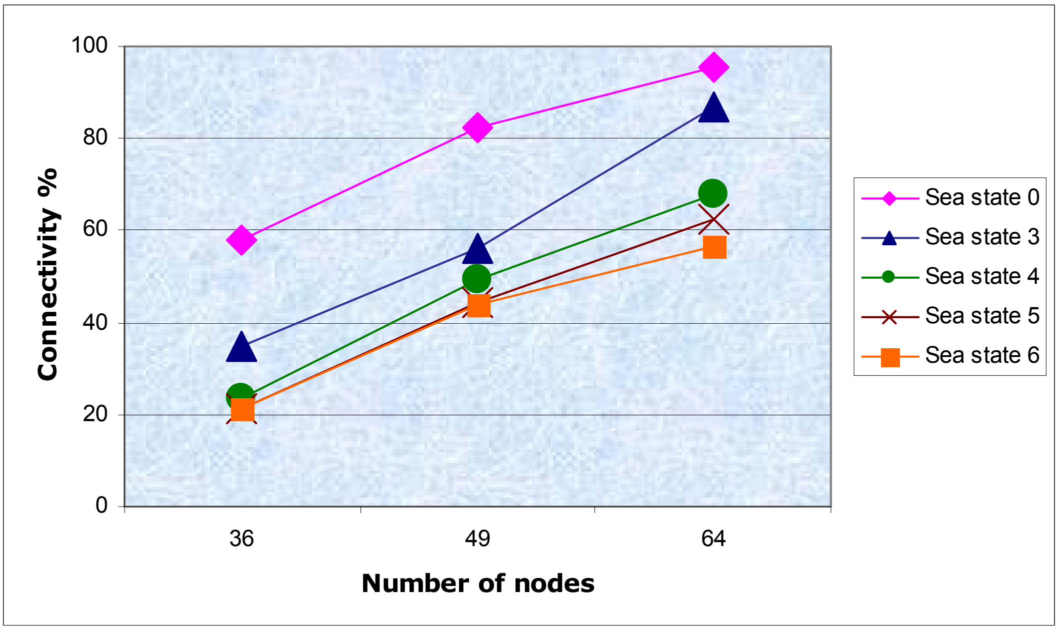

Figure 5.12 : Connectivity vs. node number (random deployment – 200 m range)

Lower transmission ranges decrease the total energy consumption of the network with the cost of lower connectivity percent. Decreasing the transmission range from 250 meters to 150 meters connectivity is affected severely. With 64 nodes, the connectivity is between one-two fifth of the connectivity obtained by using 250 meters of transmission range. 150 meters of transmission range is insufficient for the simulated network. If the transmission range is chosen as 200 meters, the connectivity is roughly 60% of the connectivity obtained by 250 meters of transmission range for sea state 4 and higher.

6. CONCLUSION

In this thesis, the effect of wave height to network connectivity and sensing coverage for sea surface floating sensor networks is analyzed, using the shallow water wave models developed. The wave model utilizes the fact that the wave speed is controlled by only water depth in shallow water.

Simulation results showed that wave heights have severe effects on network performance. If the sea state or the maximum wave height is given for the target area, the number of nodes required for the application can be calculated using the shallow water wave model developed. The extra number of nodes needed to overcome the impairing effect of the waves can be deployed as communication gateways only, excluding or deactivating the sensing module. In this manner, total cost and energy consumption of the network can be decreased resulting in a longer network lifetime.

For future work, the shallow water wave models can be implemented by using a test bed consisting of a water tank and a wave generator. Moreover, the performance of the network can be analyzed in an area of irregular or mixed waves, considering that statistical and measured wave models are present for that area. Deployment strategy can be another area to be studied, in order to obtain the most suitable deployment strategy to such as deploying higher number of nodes near shore to increase network lifetime in order to maximize connectivity and coverage for the given area, node number, and the wave model.

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APPENDICES

APPENDIX A.1 : Wave Model Graphs
APPENDIX A.2 : Network Graphs

APPENDIX A.1 Wave Model Graphs

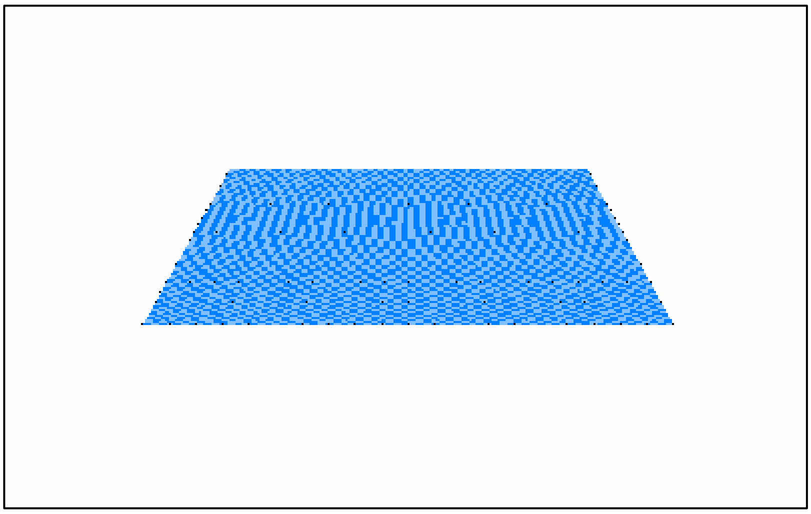

Figure A.1 : Sea state 0 with 0.02 meters of maximum wave height

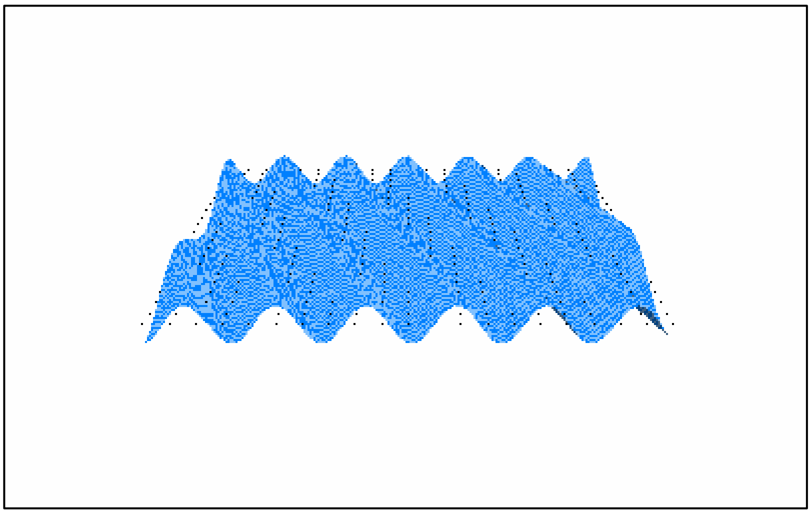

Figure A.2 : Sea state 3 with 1 meter of maximum wave height

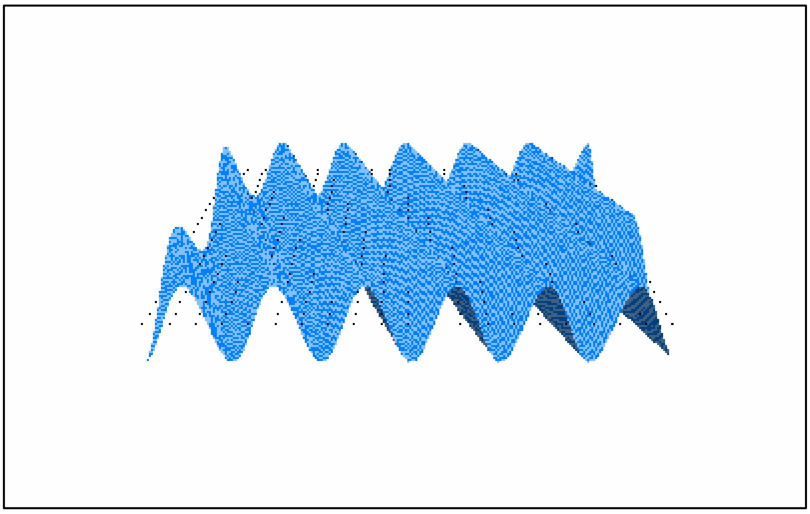

Figure A.3 : Sea state 4 with 2 meters of maximum wave height

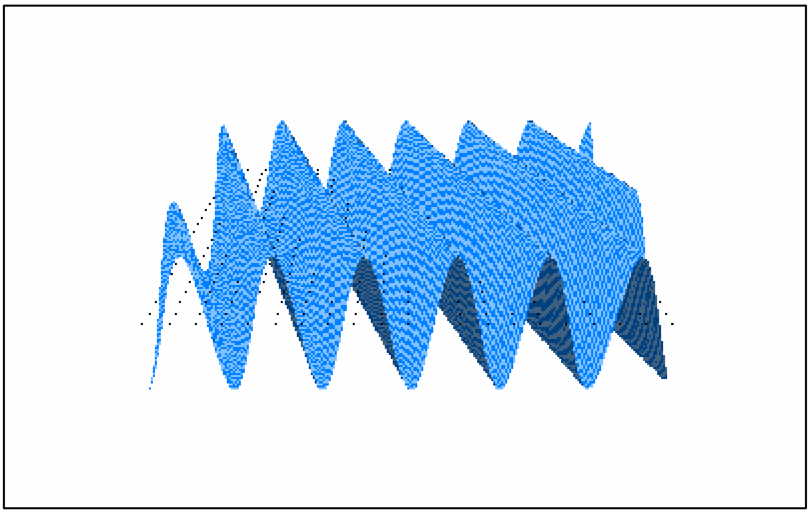

Figure A.4 : Sea state 5 with 3.5 meters of maximum wave height

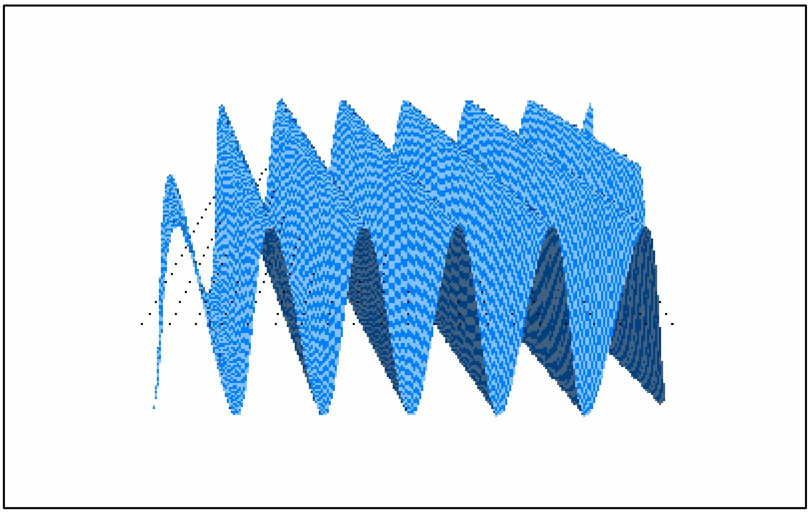

Figure A.5 : Sea state 6 with 5 meters of maximum wave height

APPENDIX A.2 Network Graphs

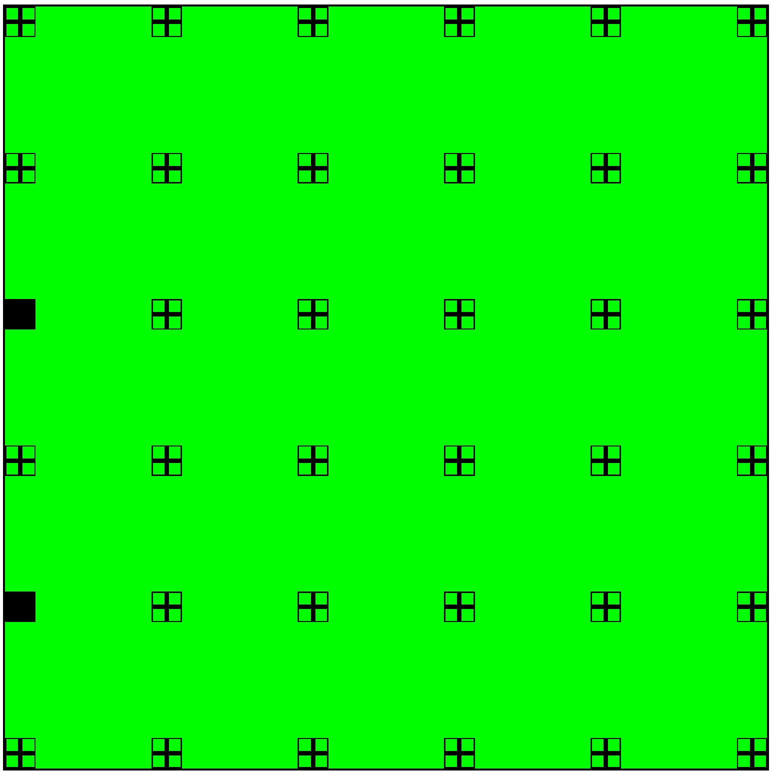

Figure A.6 : Grid deployed network with 36 nodes on sea state 0

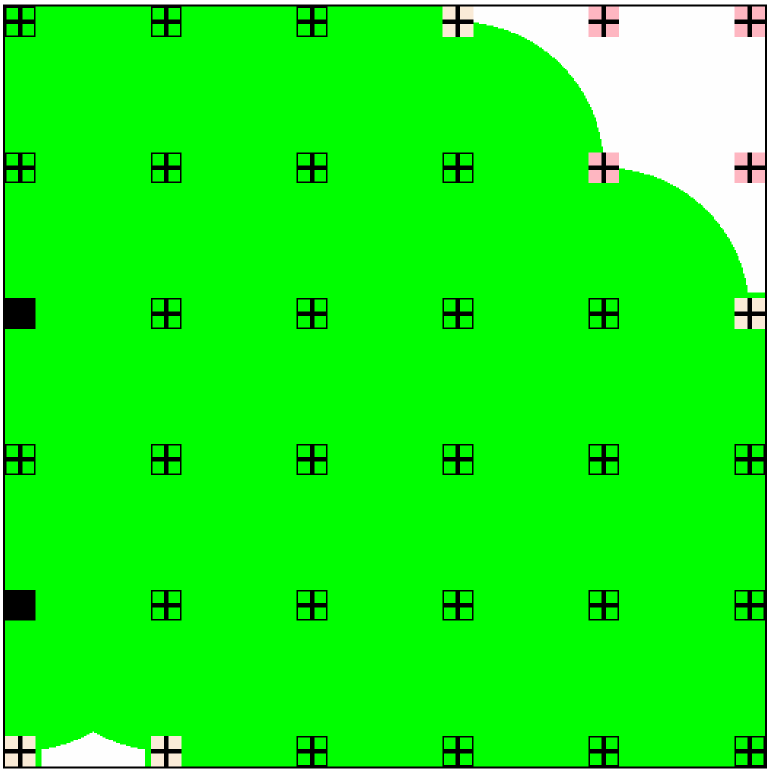

Figure A.7 : Grid deployed network with 36 nodes on sea state 3

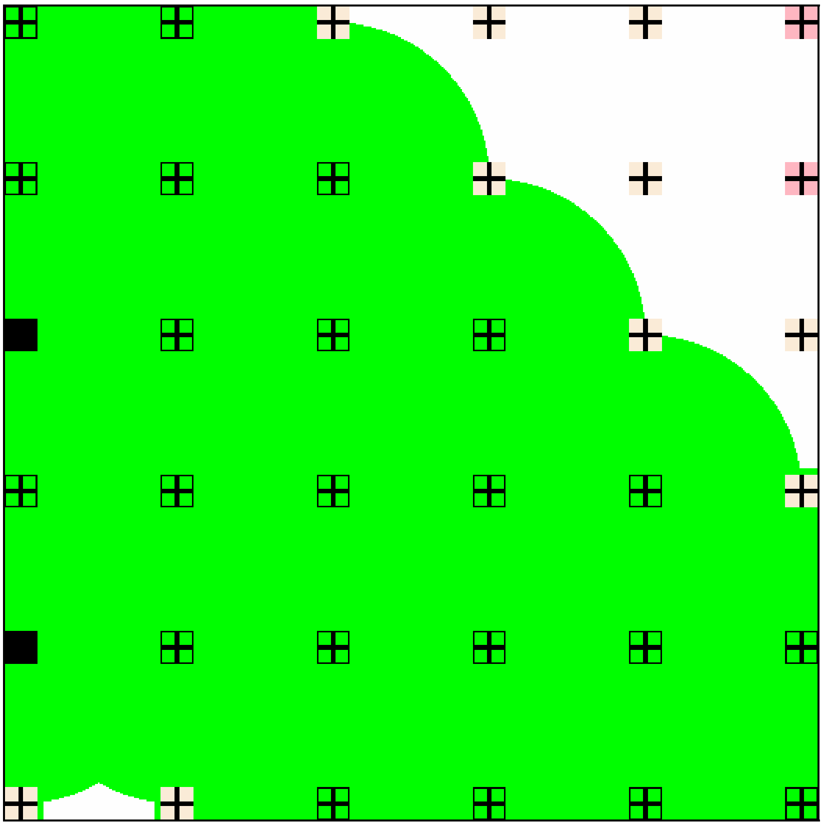

Figure A.8 : Grid deployed network with 36 nodes on sea state 4

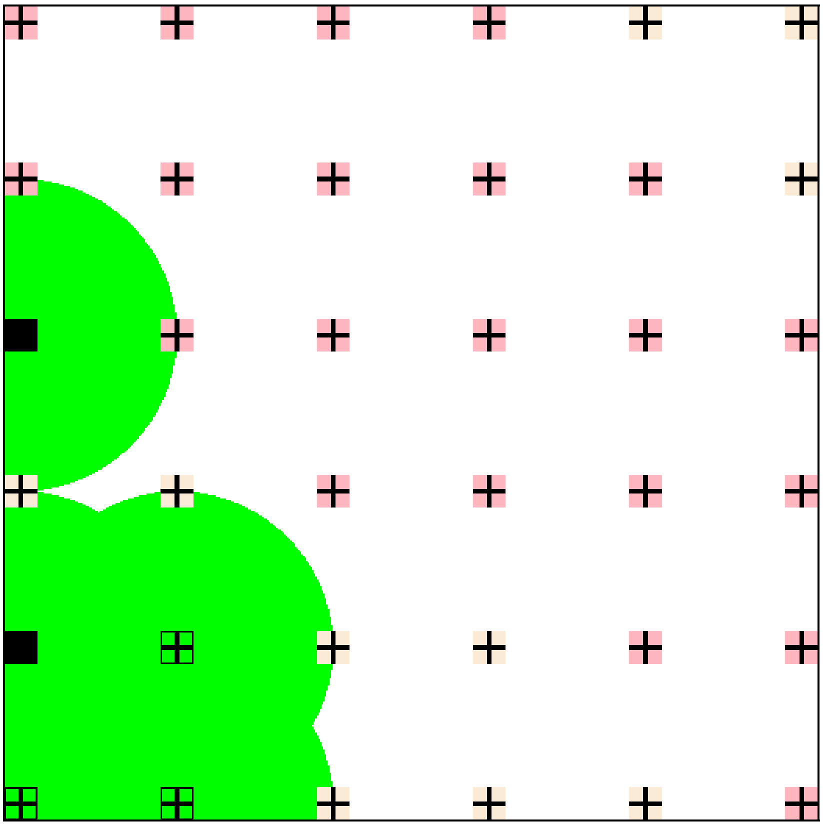

Figure A.9 : Grid deployed network with 36 nodes on sea state 5

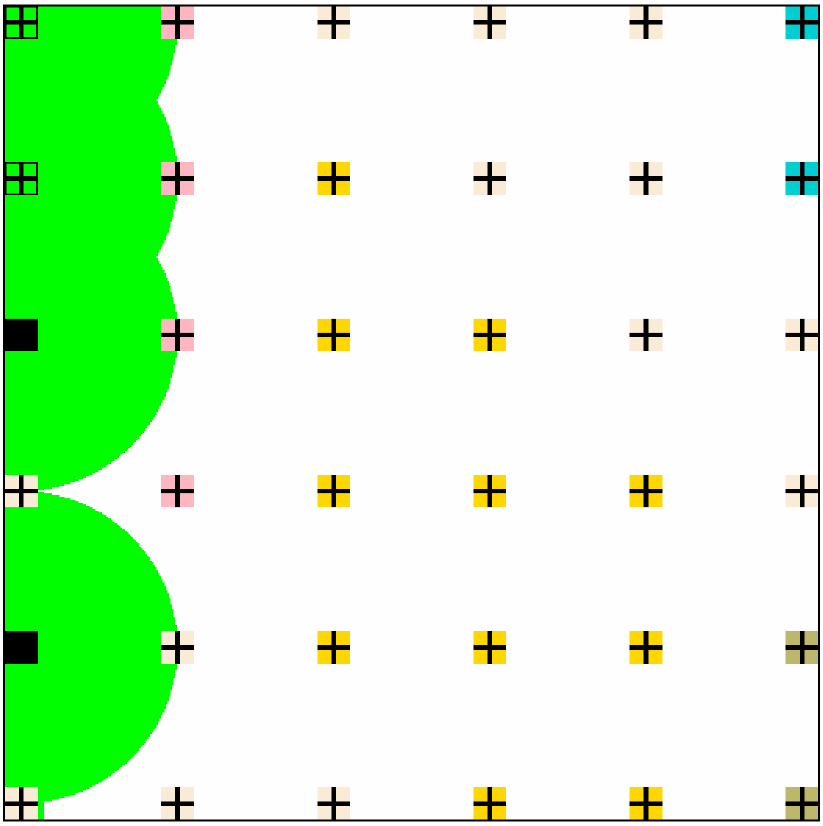

Figure A.10 : Grid deployed network with 36 nodes on sea state 6

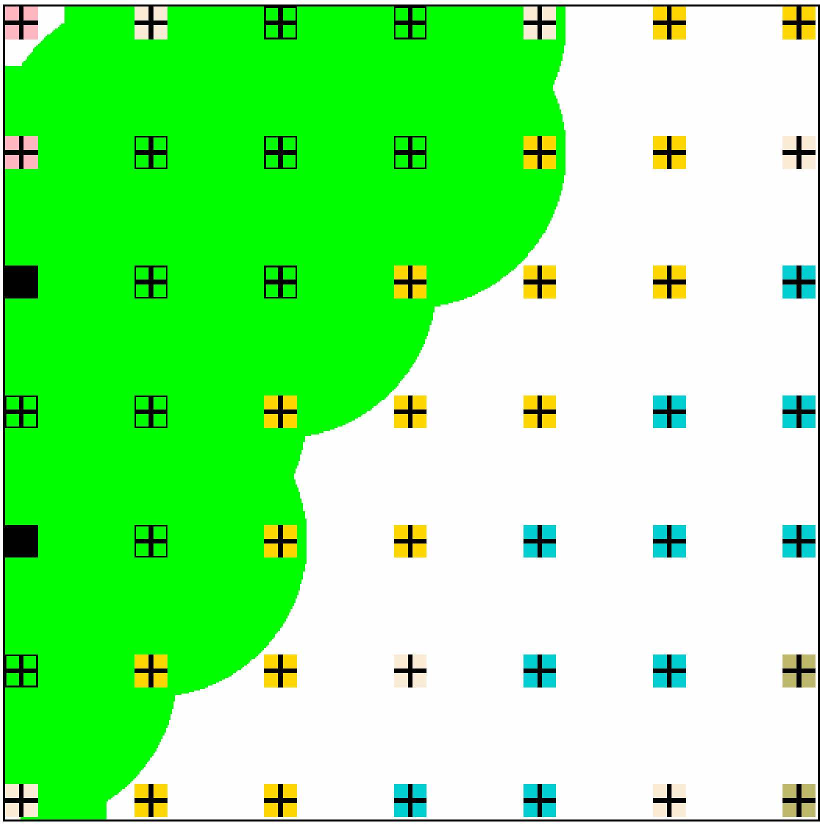

Figure A.11 : Grid deployed network with 49 nodes on sea state 5

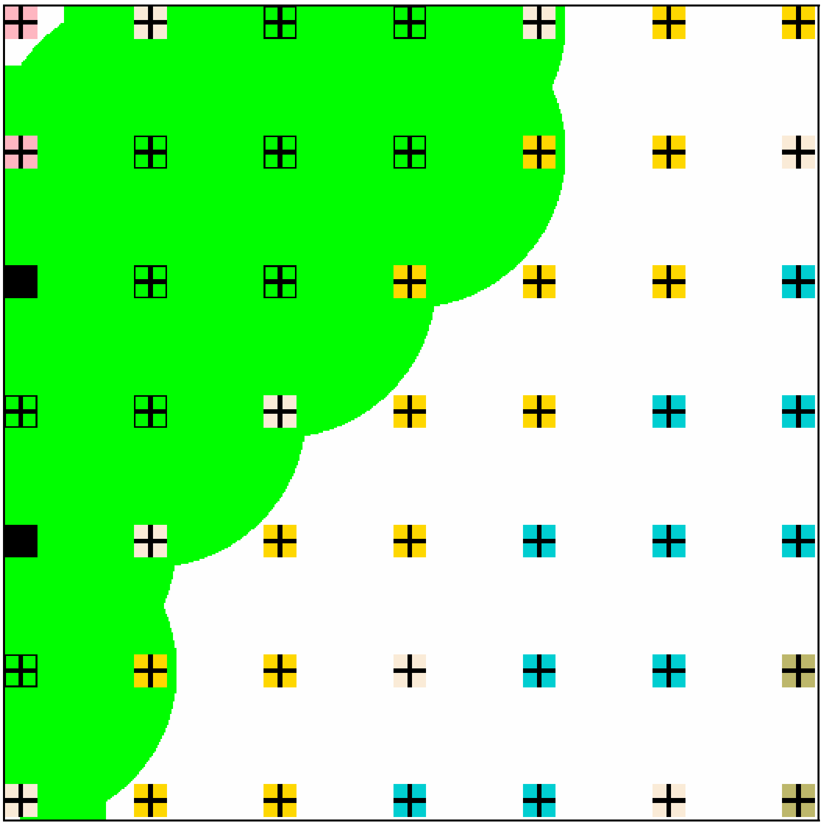

Figure A.12 : Grid deployed network with 49 nodes on sea state 6

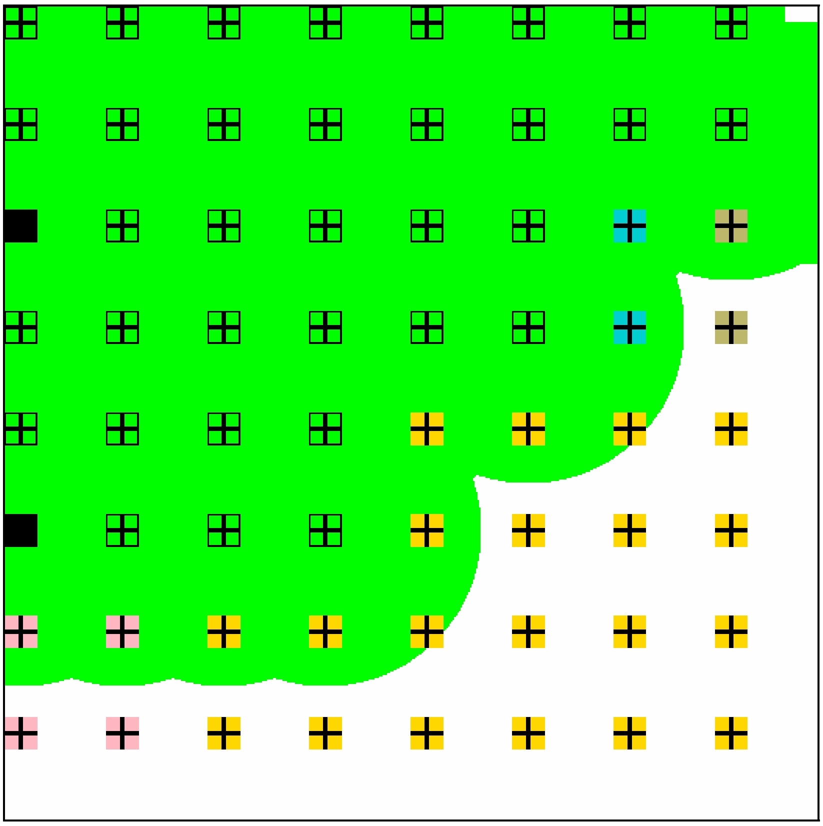

Figure A.13 : Grid deployed network with 64 nodes on sea state 5

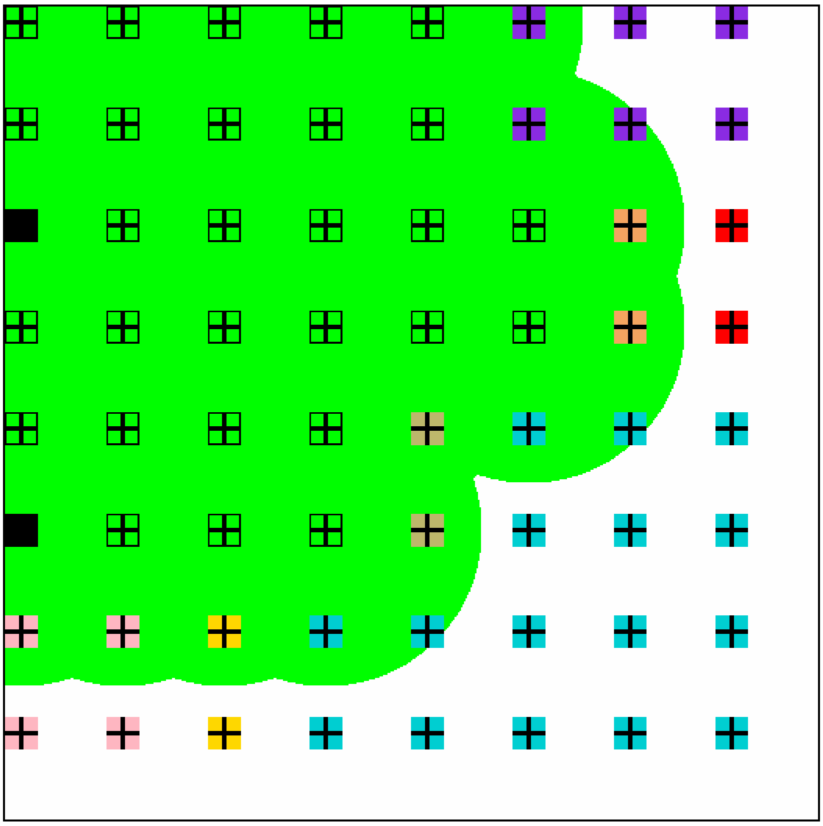

Figure A.14 : Grid deployed network with 64 nodes on sea state 6

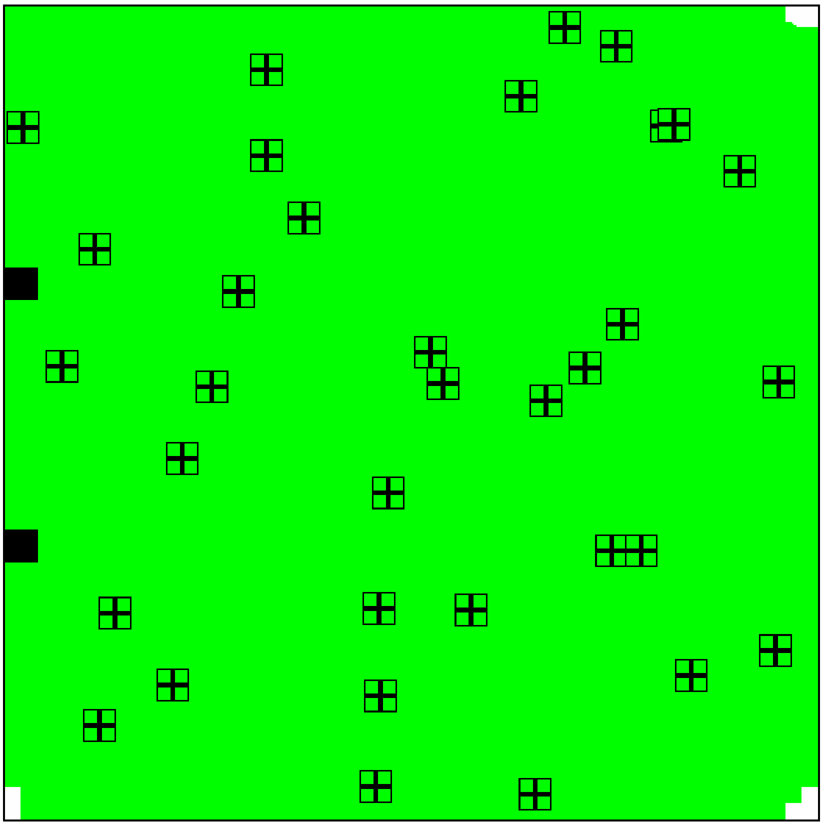

Figure A.15 : Randomly deployed network with 36 nodes on sea state 0

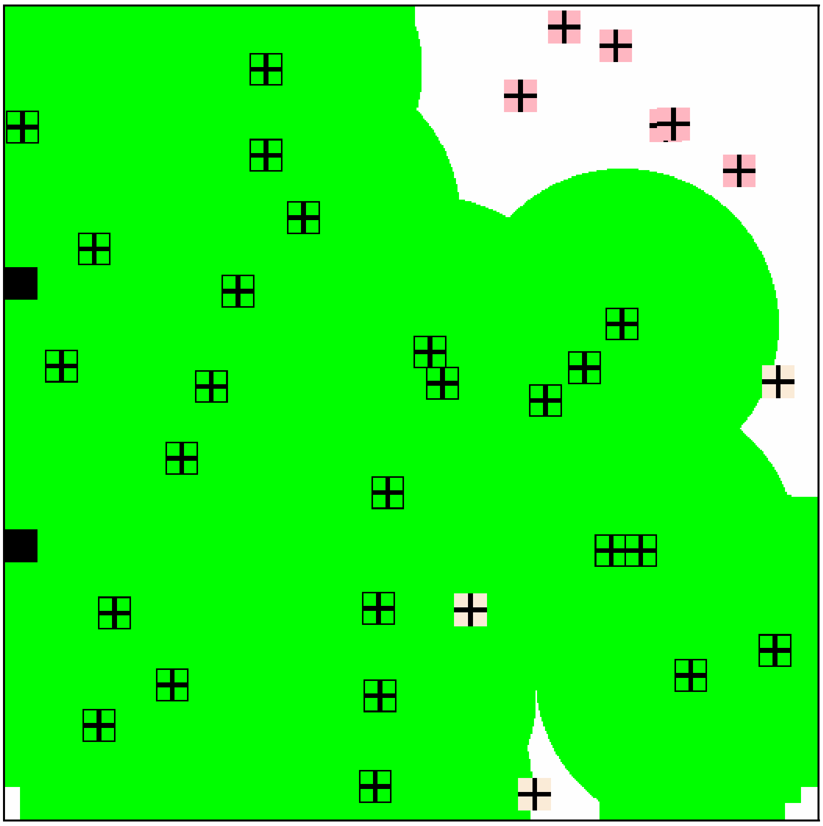

Figure A.16 : Randomly deployed network with 36 nodes on sea state 3

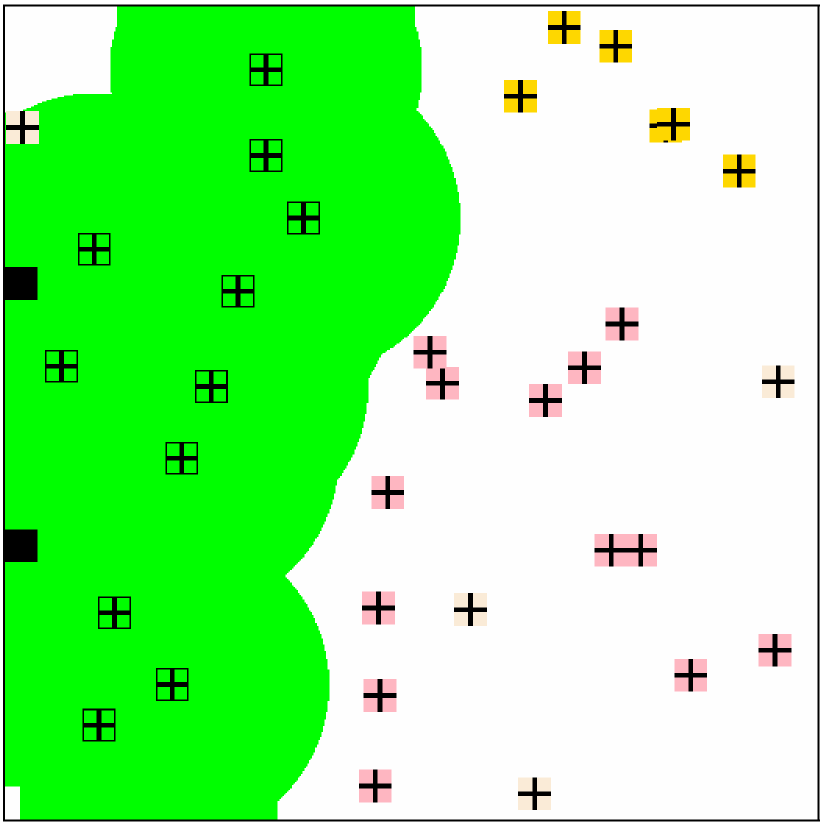

Figure A.17 : Randomly deployed network with 36 nodes on sea state 4

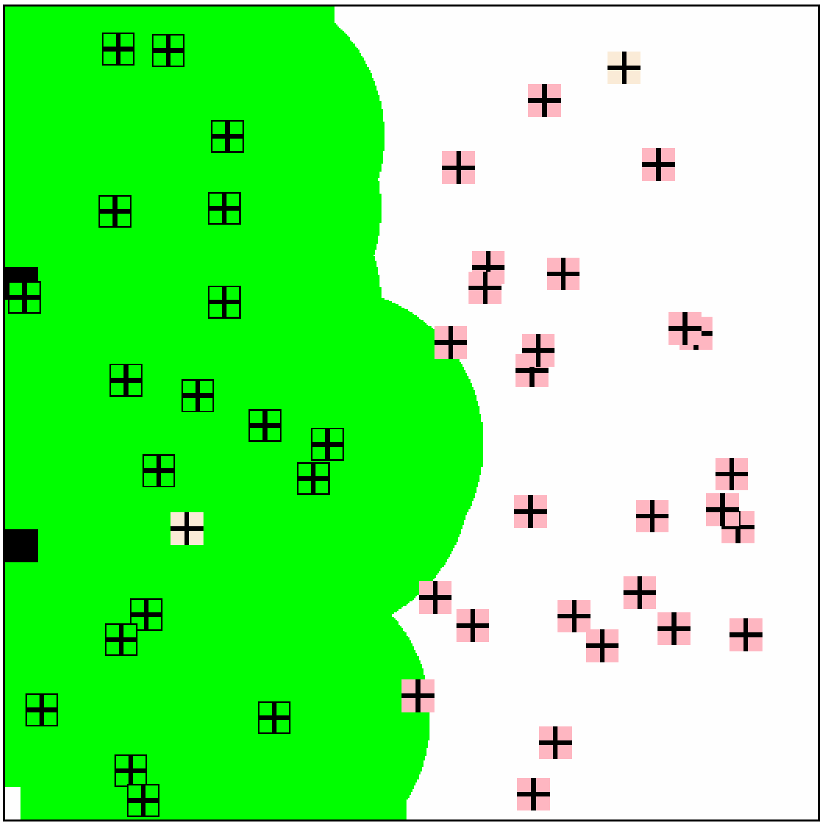

Figure A.18 : Randomly deployed network with 49 nodes on sea state 6

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