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An Evaluation of Chaos Modulation In Wireless Acoustic Sensor Networks

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An Evaluation of Chaos Modulation
In Wireless Acoustic Sensor Networks

by

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A THESIS
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Abstract

Wireless sensor networks are deployed in different regions of interest, and used in many applications such as surveillance and telemedicine. Advancements in wireless communication technology and miniaturization of electronic devices have led to sensors nodes which can be deployed in different terrains such as underwater with acoustic sensing functionality. However, non-ideal channel conditions in such terrains can affect the sensor network performance.

In this thesis, the chaos modulation schemes are shown to perform better than conventional Direct Sequence Spread Spectrum in propagation delay channels because they employ non-coherent demodulators. Furthermore, since propagation delay is rampant in the underwater environment, an integrated simulation framework is used to evaluate the network level performance with choice of modulation scheme in the underwater environment. Ergodic Chaos Parameter Modulation scheme performs best and thus proposed for use in underwater acoustic localization using wireless acoustic sensor networks.
Acknowledgements

I would like to thank my supervisor Dr. Henry Leung for working with me to define the research project and overseeing its progressive elaboration through the different phases which were needed to make the research acceptable.

I appreciate everyone who has contributed in one way or another to this work, especially those who consciously or inadvertently coached me through different parts of the learning curve. Such people, whom I refer to as coaches, include: Ben, Achintha, Chatura, Uros, Ricardo, Jaya, Xiaobim and Emeka (Emy).

I also deeply appreciate my mother, Mofoluwake Oluwameto Ayotunde Oluge for her unflinching support in prayers and consistent words of encouragement; never failing to believe that I would succeed in this endeavour.

Through it all my siblings were always checking in with me. Seun and Lekan Ajala, Femi, Tori and Subomi Ayotunde Oluge, thank you so much.

My heartthrob Ayooluwatomi Akinbule, thank you so much for patiently standing by me.

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It has been a pleasure working and learning from you all.
Dedication

To all who never give up, always looking forward to the triumph of hope beyond the scope of human limitation.

Hope does not disappoint.
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<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
</tr>
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<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>CPM</td>
<td>Chaotic Parameter Modulation</td>
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<tr>
<td>CSK</td>
<td>Chaos Shift Keying</td>
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<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
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<tr>
<td>DCSK</td>
<td>Differential Chaos Shift Keying</td>
</tr>
<tr>
<td>DSCDMA</td>
<td>Direct Sequence Code Division Multiple Access</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
</tr>
<tr>
<td>ECPM</td>
<td>Ergodic Chaotic Parameter Modulation</td>
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<tr>
<td>EMA</td>
<td>External Model Access</td>
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<tr>
<td>FHSS</td>
<td>Frequency-Hopping Spread Spectrum</td>
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<tr>
<td>FM</td>
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</tr>
<tr>
<td>FSK</td>
<td>Frequency Shift Keying.</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
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<tr>
<td>IETF</td>
<td>Internet Engineering Task Force</td>
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<tr>
<td>IntServ</td>
<td>Integrated Services</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
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<tr>
<td>MAC</td>
<td>Medium Access Control</td>
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<td>MATLAB</td>
<td>MATrix LABoratory</td>
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<td>x</td>
<td>x</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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</tr>
<tr>
<td>OPNET</td>
<td>Optimized Network Engineering Tool</td>
</tr>
<tr>
<td>PN</td>
<td>Pseudo Noise</td>
</tr>
<tr>
<td>PSK</td>
<td>phase shift keying</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of service</td>
</tr>
<tr>
<td>RFC</td>
<td>Request for Comments</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TMM</td>
<td>Terrain Modelling Module</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
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<tr>
<td>UWASN</td>
<td>Underwater Wireless Acoustic Sensor Network</td>
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<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<td>WASN</td>
<td>Wireless Acoustic Sensor Network</td>
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<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
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Chapter One: Introduction

1.1 Background
A sensor network is a number of connected sensor nodes, usually deployed inside a phenomenon of interest, or very close to it. A phenomenon refers to something known by sense perception. Sensor networks may consist of many different types of sensors such as seismic, low sampling rate magnetic, thermal, visual, infrared, acoustic and radar; which are able to monitor a wide variety of ambient conditions [2]. The sensed environment and sensor network application play a crucial role in determining the type of sensor that will be used. The focus in this study is the application of chaos modulation schemes to wireless acoustic sensors networks (WASNs) in propagation delay prone environments such as found underwater [9]. This is useful for the maritime industry which plays a crucial role in the economy and ecosystem.

1.2 Literature Review
Wireless acoustic sensor networks are useful in a variety of applications such as localization, tracking and home applications such as baby alarm systems. In these applications, the networks are required to locate acoustic sources using acoustic sensor arrays and this has been used in many environmental and security applications [55]. Acoustic waves are particularly endeared to underwater water wireless communication due to the relatively low absorption in underwater environments. The multipath, pathloss and noise impacts of the underwater terrain on acoustic waves are discussed in [20] with comparison to electromagnetic and optical waves. They propose engineering counter measures in the form of physical layer techniques such as Direct Sequence Spread Spectrum and multicarrier modulation such as orthogonal frequency division multiplexing (OFDM) to mitigate the effect of channel non-idealities such as multipath.
Acoustic signals were also presented to offer medium antenna complexity, lowest data rate and longest transmission range. However, the effect of propagation delay, especially arising from this long transmission range, on the choice of modulation is not treated.

An evaluation of the network performance with regards to choice of medium access control mechanisms (MAC) and different topologies is discussed in [6]. Chen and Varshney [5], as well as Yigitel et al [51] also give some depth of insight into the state of the art in Quality of Service (QoS) support for wireless sensor networks (WSNs). These works and other surveys [2,5, 9, 52] inadvertently share a common theme on the flexibility of design and implementation of wireless sensor networks. While this has expanded the application to many different fields, it has also produced divergent views, resulting in lack of standardization and diverse application-specific requirements. As pointed out in [38], this has deprived wireless sensor networks from having a single de-facto standard MAC protocol.

While, these methods have achieved remarkable levels of efficiency, when the packets gain access to the medium, non-idealities of the channel take their toll on the transmitted packets and medium access control mechanisms can no longer guarantee the condition of the packets when they arrive at the sink; irrespective of the QoS measures implemented. The aforementioned references do not take cognizance of the existence of these non-idealities in the results presented thus making such results rather optimistic. According to [34], incorporating non-ideal conditions such as multipath fading and pathloss into the simulation exerts a non-negligible impact on the performance of wireless local area networks. Since the wireless acoustic signal used in WASNs is also subject to same intrinsic channel effects, this sets the stage for a similar investigation into the impact on WASN performance.
The starting point for such investigation begins with a realization that the transmission of information over a channel is accomplished by mapping the digital information to a sequence of symbols which vary some properties of an electromagnetic wave called the carrier. This process is called modulation, and is responsible for transmission of the message signal through the communication channel with the best possible quality [33]. Hence the choice of a modulation scheme that is robust to channel impairments is always an interesting concern for communication systems, and more so when the channel is a wireless medium. The study in [34] focused on conventional narrowband modulation schemes; namely differential phase shift keying (DPSK) and quadrature amplitude modulation (QAM) and the results show that these schemes cannot be relied on to mitigate network performance degradation in the presence of non-ideal channel conditions. However, it is well established in literature [32, 33] that converting the narrowband signal to a wideband signals before transmission reduces the effect of channel non-idealities such as multipath.

The conventional technique for narrowband to wideband signal conversion is the use of pseudo-noise (PN) sequences and is further discussed in chapter two. Worthy of note however, is that most existing research works [10, 14,18,19,21, 54] acknowledge that conventional broadband modulation schemes, otherwise known as spread spectrum techniques offer excellent performance in mitigating the effect of non-ideal channel conditions, and particularly excel in significantly reducing the effect of multipath.

In [15], Kennedy et al. suggest the application of an alternative spread spectrum technique to WLANs. This alternative approach is derived from the emerging field of chaos communication where the information to be transmitted is mapped to chaotic signals (instead of PN sequences) which are reputed to be inherently wideband and also robust to multipath [1,28,48].
It was established, through noise performance comparison (AWGN), that the performance of chaos modulation schemes is worse than those of the conventional broadband schemes with their performance limits stemming from their chaotic properties [18,25]. Citing the existence of other non-ideal application scenarios such as industrial application, where the channel impairments go beyond the ideal scope of AWGN, Kennedy et al. propose the application of a chaos modulation scheme to WLANs. They support the proposal by highlighting several advantages offered by chaos modulation schemes such as demodulation without carrier synchronization as well as simple circuitry. These were also mentioned to be downsides for conventional spread spectrum techniques. This forms a good platform for the novel work done by Leung et.al in [22] and the comparison in [55]. These works, however, focus on the physical layer and network performance comparisons are not included in the results.
1.3 Research Contribution

This thesis contributes the performance evaluation of chaos modulation schemes when applied to a wireless acoustic sensor network. The network is operating in the presence of non-ideal propagation delay channel condition; which is characteristic of the underwater terrain. Network level results are presented using the metrics of throughput and end-end delay.

The application of chaos schemes is based on the reputation of their inherent wideband characteristics which makes them candidates for spread spectrum communication. The selected underwater operating environment can be taken as a possible extreme of the non-ideal scenarios where the WASN will have to operate. Hence, the results are more representative of the WASN network performance in this environment because the simulation incorporates terrain effects in the operating environment.

In such situations, chaos schemes such as ECPM that use non-coherent demodulators offer a better network performance and I have shown this network performance improvement and hence propose ECPM as an alternative to conventional schemes in propagation delay terrains.
1.4 Research Scope and Methodology

The field of wireless sensor networks is a really broad area which has been deeply researched. Our focus however is on wireless acoustic sensor networks, and a network performance comparison when chaos modulation schemes are employed in the physical layer of these networks using the OPNET simulation platform.

Chapter 2 will focus on an overview of different mechanisms in the physical layer and a study of the physical layer architecture of the OPNET simulator.

Chapter 3 will address the integration of chaos modulation schemes into the physical layer of the OPNET simulator and compare the link level performance in the presence of propagation delay.

An application scenario is presented in chapter 4 when the integrated modulation schemes are applied to an underwater acoustic sensor network and qualitative deductions are made. The results in OPNET are used to study the network level performance.

Simulations are mainly done in OPNET, while we resort to MATLAB for implementation of the chaos communication schemes. This is because the innate characteristics of wireless signals such as multipath propagation are more difficult to model in packet-oriented simulation tools like OPNET. As reported in [34], this is because such tools use packets as the basic processing unit, compared to the signal-based simulation tools such as MATLAB where an entire communication tool box has been developed for flexible modelling of different communication channels.
Figure 1.1 Comprehensive simulation framework for network performance evaluation

The comprehensive simulation framework above gives the end-to-end view of how realistic results are generated in this thesis for the purpose of comparison. The packets generated at the application layer serve as input to the MAC layer. The flow control functionality of the transport layer is maintained by the OPNET simulation kernel and the networks are single-hop star topology networks which do not require the routing functionality of the network layer. At the physical layer, the applicable parameters are dependent on the operating environment under consideration. To account for the non-idealities and environmental encumbrances of the underwater terrain, the physical layer of the OPNET simulator is modified. This yields a realistic underwater propagation model. The modulation curves are plotted through the external model access functionality from the results of MATLAB simulations.
2.1 Modulation: An Overview

Transmitting information over a wireless channel requires certain modifications to the sensed information to make the transmission feasible. One of such is Modulation.

From a bandpass perspective, modulation is the process of varying one or more properties of a high frequency, periodic waveform (called the carrier signal), with a modulating signal which typically contains information to be transmitted. The three key parameters of a periodic waveform are its phase, amplitude, and its frequency. Any of these properties can be modified in accordance with a low frequency (base band) signal to obtain the modulated signal (passband).

In analog modulation, typically, a high-frequency sinusoid waveform is used as carrier signal to transform a baseband message signal into a passband signal so that a small sized antenna can be used for propagation. In digital modulation, which can be considered as digital-to-analog conversion, the carrier is modulated by a discrete signal.

The most fundamental digital modulation techniques are based on keying techniques below:

- PSK (phase-shift keying): a finite number of phases are used.
- FSK (frequency-shift keying): a finite number of frequencies are used.
- ASK (amplitude-shift keying): a finite number of amplitudes are used.
- QAM (quadrature amplitude modulation): a finite number of at least two phases and at least two amplitudes are used.
2.2 Spread-Spectrum Communication: An Overview

In dense deployments of wireless systems, as is the case in sensor network, many nodes must be provided with simultaneous access to the same or neighboring frequency bands. Irrespective of the modulation scheme selected, the effect of such simultaneous transmissions results in interference. The optimum strategy in this situation, where every node appears as (potential) interference to every other node, is for each communicator's signal to look like white noise which is as wideband as possible [46]. This can be done in two ways [14]:

- By spreading each symbol using a pseudorandom sequence to increase the bandwidth of the transmitted signal.
- By representing each symbol to be transmitted by a piece of ‘noise-like’ waveform.

The conventional approach to this is the first method in which a pseudorandom sequence is used to “spread” the signal to be transmitted, such that it occupies a much wider bandwidth before the actual modulation using a conventional modulation scheme based on phase shift keying (PSK) or frequency shift keying (FSK). It was first developed to provide a secure means of communication for military use under adverse conditions [21].

The alternative approach to generating “noise-like” transmission is to represent the transmitted symbols not as weighted sums of periodic basis functions, but as inherently non-periodic chaotic basis functions [14].

Next we describe both approaches to spread spectrum communication, noting that our focus in this work is to make comparisons among the different alternative methods which use chaotic signals as carriers; with attention on wireless acoustic sensor network scenario.
2.2.1 Conventional Spread Spectrum Communication

Conventional spread-spectrum techniques have evolved around two main schemes:

- Direct sequence (DS) and
- Frequency-hopping (FH)

In conventional direct sequence-spread spectrum (DSSS) systems, the binary data sequence is ‘spread’ in the frequency domain by multiplying it with a digital pulse train (binary chips) which is running at a much higher rate. This is usually a Pseudo Noise (PN) sequence and is called the spreading sequence. These pseudorandom codes are used to spread each data bit with a large number of chips thus achieving a larger bandwidth. Examples of typical spreading sequences are m-sequences and Gold sequences. The rate of the binary data sequence to be transmitted is called Bit Rate, while the rate of the spreading sequence is called the chip Rate. The ratio of the chip and bit rates is ideally equal to the ratio of the signal bandwidths after and before spreading and is called the spreading factor of the system [26].

In frequency-hopping spread spectrum, the wide bandwidth does not result from spreading the data as in the DSSS technique. Instead, in FHSS the carrier frequency “hops” among a set of synthesized frequencies, according to a pre-determined hopping sequence. The combination of those frequencies generates a wide bandwidth.

The limitations of conventional spread-spectrum systems include the need to achieve and maintain carrier and symbol synchronization as well as the finite number of available spreading sequences; the latter is due to periodic nature of the spreading sequences while the former is due to the dispersing techniques used at the receiver [10, 14].
For practical systems (such as WASNs), holistic synchronization is a really steep requirement to attain due to different propagation times for different users [10].

Furthermore, the periodicity of PN sequences, which arises from the finite length of the shift registers used to generate them, can compromise the overall security of the spread spectrum system. If \( m \) is the number of shift registers, the PN sequence will be repeated after a period \( L \) defined by: \( L = 2^m - 1 \).

Thankfully, there is an alternative approach to spread-spectrum communication using chaotic signals, [14] which retains the advantages of the conventional approach and overcomes some of the limitations especially that of synchronization [21] and the finite number of available spreading sequences.

![Figure 2.1. Spread spectrum using PN sequences (DSSS) and Frequency hopping](image)
2.2.2 Conventional Spread Spectrum to Chaos Based Digital Communication Systems

Chaotic signals belong to a class of signals produced by nonlinear dynamical systems [14], which offer a number of attractive features for spread spectrum communication. This is because they are inherently random-like, aperiodic, wideband, and difficult to predict without prior knowledge of the initial conditions of the system. Much research efforts have been devoted to the application of chaotic signals in spread spectrum communication (SS) systems. Figure 2.3b is a block diagram of a chaotic SS digital communication scheme. Compared to figure 2.3a (placed here for ease of comparison), clearly, the basic difference in principle is the application of chaotic modulation (spreading) and chaotic demodulation (despreading) techniques. These approaches exploit different characteristics of a chaotic system to achieve spread spectrum communication.

Figure 2.3a Conventional Spread Spectrum System

Figure 2.3b General structure of chaotic Spread Spectrum System
As the chaotic sequences are generated by simply altering the initial conditions of the chaotic system, there is no need for an extra PN generator block. Hence, the system is simplified while retaining the randomness and wideband nature required for spread-spectrum communication.

Chaotic digital modulation is concerned with mapping symbols to chaotic waveforms which are described mathematically using state equations.

For a discrete time chaotic system the state equation can be expressed as [25]:

\[ x(t) = f(x(t-1), \theta), \tag{2.1} \]

Where \( x(t-1) = [x(t-1), x(t-2), \ldots, x(t-d)]^T \) is the d-dimensional state vector at time (t-1), \( f \) is the chaotic function used for mapping, and \( \theta \) is the bifurcating parameter lying in the chaotic regime \([\theta_{min}, \theta_{max}]\).

From equation (2.1), there are three variables: the chaotic state \( x(t) \), the nonlinear map \( f \); and the bifurcating parameter \( \theta \). Based on this, current chaos based spread spectrum schemes can be categorized according to these three variables [25].

However, irrespective of category, all chaotic systems are characterized by a unique property called “sensitive dependence on initial conditions” meaning that a small perturbation to the initial conditions causes a large change in the state of the system. This property implies that chaotic signals are easy to generate in theoretically infinite quantities by simply varying the initial conditions [14, 21]. This can be leveraged to provide a low-cost solution to overcome the problem of the finite number of available spreading sequences in conventional spread-spectrum system generation.
These advantages, most of which build upon research that followed the work of Pecora and Carroll [30] on synchronization in chaotic systems, have led to an evolving paradigm shift over the past decade, from evading chaotic behavior, to controlling and exploiting it. For example, the adoption of chaos-based spreading sequences is key to the performance improvement of Direct Sequence Code Division Multiple Access (DSCDMA) as proposed in [36]. In addition, the theoretically infinite, aperiodic sequences produced also means that the communication will be a lot more secure than that offered through the use of conventional communication schemes.

2.3 The Optimized Network Engineering Tool (OPNET) Simulation Platform

OPNET is a discrete event simulator, where simulation is executed as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system [31]. This choice is mainly because it has a robust hierarchical node model in which different process models can be developed for different layers of the network protocol stack. Furthermore, graphical user interface aids visualization for rapid model construction, data collection and other simulation tasks. This is coupled with availability of free licensing through the OPNET University program.

Wireless functionality is included in OPNET's Modeler Wireless Suite which allows the simulation of radio communication. Generally, in Opnet, the models are classified as distributed systems composed of multiple subsystems that interact with each other. In the wireless module documentation, this architecture is referred to as the transceiver pipeline because it provides a model for the flow of data from a transmitter to one or more receivers.

In this work, more realistic simulation results of a wireless acoustic sensor network are achieved by creating a simulation environment that incorporates the channel non-idealities.
To do this, the transceiver pipeline is modified and comparison is made between delay and throughput results in ideal (AWGN) and Rayleigh fading channels. The modulation curves specific to each scenario is developed using the OPNET external model access functionality.

The Radio transceiver Pipeline consists of fourteen stages and has a similar structure for each supported link type. The Simulation Kernel relies on this 14-stage computational pipeline to evaluate the characteristics of radio communication when transmissions occur. Most of these stages can be executed on a per-receiver basis whenever a transmission occurs and the simulation Kernel manages packet transfer by implementing a series of computations, each of which models particular aspects of link behavior. The sequence of the computations and their interface are standardized for each type of link.

Hence, a link’s underlying implementation can generally be thought of as a sequentially executed set of pipeline stages. The pipeline stage sequence of a link is executed once for each packet transmission that is submitted at the source of the link. In other words, when a packet is sent to a transmitter, the Simulation Kernel proceeds to call appropriate pipeline stages to process the packet. Because radio links provide a broadcast medium, each transmission can potentially affect multiple receivers throughout the network model.

In addition, for a given transmission, the radio link to each receiver can exhibit different behavior and timing. As a result, a separate pipeline must be executed for each eligible receiver. Certain pipeline stages are executed when the packet is transmitted and others are executed later due to the delay associated with the traversal of the link and transmission of the packet.

Stages 0-5 of the transceiver pipeline are included within the transmitter node and the stages 6-13 are included within the receiver node.
Table 1, shown below is a mapping of each pipeline stage to the corresponding wireless channel characteristic it evaluates.

Table 1 Transceiver Pipeline Stages and their function [derived from [59]]

<table>
<thead>
<tr>
<th>Pipeline stage</th>
<th>Name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 0</td>
<td>Receiver Group</td>
<td>Create an initial group of possible candidates capable of receiving transmissions from that object.</td>
</tr>
<tr>
<td>Stage 1</td>
<td>Transmission Delay</td>
<td>This result is the simulation time difference between the beginning of transmission of the first bit and the end of transmission of the last bit of the packet.</td>
</tr>
<tr>
<td>Stage 2</td>
<td>Closure</td>
<td>The purpose of this stage is to determine the ability of the transmission to reach the receiver channel. If it exists, there is closure between transmitter and receiver.</td>
</tr>
<tr>
<td>Stage 3</td>
<td>Channel Match</td>
<td>The purpose of this stage is to classify the transmission with respect to the receiver channel. The packet is categorized as “Valid”, “Noise” or Ignored</td>
</tr>
<tr>
<td>Stage 4</td>
<td>Transmitter Antenna Gain</td>
<td>The purpose of the transmitter antenna gain stage is to determine the gain provided by the transmitter’s associated antenna</td>
</tr>
<tr>
<td>Stage 5</td>
<td>Propagation Delay</td>
<td>The purpose of this stage is to calculate the amount of time required for the packet’s signal to travel from the radio transmitter to the radio receiver. This depends on the distance from the source to destination.</td>
</tr>
<tr>
<td>Stage 6</td>
<td>Receiver Antenna Gain</td>
<td>It is executed separately for each eligible destination channel, and its invocation takes place at the time that the leading edge of the packet arrives at the receiver location (i.e., after the propagation delay has elapsed).</td>
</tr>
<tr>
<td>Stage 7</td>
<td>Receiver Power</td>
<td>The purpose of this stage is to compute the received power of the arriving packet’s signal. In general, the calculation of received power is based on factors such as the power of the transmitter, the distance separating the transmitter and the receiver, the transmission frequency, and transmitter and receiver antenna gains.</td>
</tr>
<tr>
<td>Stage 8</td>
<td>Interference Noise</td>
<td>The purpose of this stage is to account for the interactions between transmissions that arrive concurrently at the same receiver channel.</td>
</tr>
<tr>
<td>Stage 9</td>
<td>Background Noise</td>
<td>The purpose of this stage is to represent the effect of all noise sources except for other concurrently arriving transmissions (these are accounted for by the interference noise stage).</td>
</tr>
<tr>
<td>Stage 10</td>
<td>Signal-to-Noise Ratio</td>
<td>The purpose of SNR stage is to compute the current average power SNR result for the arriving packet. This calculation is usually based on values obtained during earlier stages, including received power, background noise, and interference noise.</td>
</tr>
<tr>
<td>Stage 11</td>
<td>Bit Error Rate</td>
<td>The purpose of the BER stage is to derive the probability of bit errors during the past interval of constant SNR.</td>
</tr>
<tr>
<td>Stage 12</td>
<td>Error Allocation</td>
<td>The purpose of the error allocation stage is to estimate the number of bit errors in a packet segment where the bit error probability has been calculated and is constant.</td>
</tr>
<tr>
<td>Stage 13</td>
<td>Error Correction</td>
<td>The purpose of this stage is to determine whether or not the arriving packet can be accepted and forwarded via the channel’s corresponding output stream to one of the receiver’s neighboring modules in the destination node.</td>
</tr>
</tbody>
</table>
2.4 Catalogue of Modulation Types in OPNET and Physical Layer Modifications

Opnet uses a modulation table as a mapping between signal-to-noise ratio (E_b/N_0) values measured on a radio communications link, and the expected value of the bit error rate (BER) that would result. Modulation types can be assigned to radio transmitter and radio receiver modules. Hence, depending on the modulation selected, this attribute specifies the name of a modulation table used to look up the bit error rate as a function of the signal-to-noise ratio. The default modulation schemes in OPNET are listed in the table below:

Table 2 Default modulation Schemes in OPNET [60]

<table>
<thead>
<tr>
<th>Modulation type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>bpsk</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>bpsk_phc</td>
<td>Binary Phase Shift Keying, Phase Coherent</td>
</tr>
<tr>
<td>cck_11</td>
<td>Complementary Code Keying, 64-Levels</td>
</tr>
<tr>
<td>dpsk</td>
<td>Differential Phase Shift Keying</td>
</tr>
<tr>
<td>fsk2</td>
<td>Dual Frequency Shift Keying</td>
</tr>
<tr>
<td>gmsk</td>
<td>Gaussian Minimum Shift Keying</td>
</tr>
<tr>
<td>msk</td>
<td>Minimum Shift Keying</td>
</tr>
<tr>
<td>qam16</td>
<td>16-ary Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>qam64</td>
<td>64-ary Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>qpsk</td>
<td>Coherent Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>qpsk_phc</td>
<td>Coherent Quadrature Phase Shift Keying</td>
</tr>
</tbody>
</table>

The list above does not include chaos modulation schemes. Hence the OPNET physical layer modification done in this study includes expanding the options to accommodate chaos modulation.
There is always at least one invocation of stages 10 through 12 to evaluate performance over the full duration of a valid packet. However, an additional invocation will occur for each of these stages (9–12) whenever a new packet arrives, to compute new signal conditions [41] and the transmission data attributes will be updated.

The SNR is computed according to the formula:

\[
10.0 \times \log_{10} \left( \frac{\text{rcvd\_power}}{\text{accum\_noise} + \text{bkg\_noise}} \right);
\]

Where: rcvd\_power = Received power of arriving packet
accu\_noise = packet's accumulated noise levels calculated by the interference and background noise stages
bkg\_noise = Background noise

The SNR is converted from log scale and expressed as \( \frac{E_b}{N_0} \), where \( E_b \) is the received energy per bit (in Joules) and \( N_0 \) is the noise power spectral density (in watts/hertz).

Typical background noise sources include thermal noise, noise from sensor electronics, and otherwise unmodeled radio transmissions (such as commercial radio, amateur radio, or television, depending on frequency).

It is calculated according to the formula

\[
\text{bkg\_noise} = (\text{rx\_temp} + \text{bkg\_temp}) \times \text{rx\_bw} \times \text{BOLTZMANN};
\]

Where: \( \text{rx\_temp}, \text{rx\_bw} \) = receiver temperature and band width.
\( \text{bkg\_temp} \) = effective background temperature; BOLTZMANN = Boltzmann’s constant

From equation (2.2), we see that a major determining factor for the SNR is the received signal power. It is important to examine the influence of channel conditions on this parameter. When a
wireless signal propagates through space, it loses power. The amount of the power lost is referred to as path loss and it describes the loss in power as the radio signal propagates in space. This is caused by dissipation of the power radiated by the transmitter as well as by effects of the propagation channel. The expression for pathloss is given by [34]:

\[ P_r = P_t K_a \left[ \frac{d_0}{d} \right]^\ell \]  

(2.4)

Where, \( P_r \) is the received power and \( P_t \) is the transmit power. \( K_a \) is a constant that depends on the antenna characteristics and the average channel attenuation. \( d_0 \) is a reference distance for the antenna far field. \( d \) is the T-R distance. \( \ell \) is the path loss exponent that depends on the propagation environment.

Table 3 shows the pathloss exponent for different environments based on an experiment by Seidel and Rappaport [33].

The equivalent expression as found in pipeline stage 7 in OPNET [59] is given by

\[ P_r = \frac{\lambda^2}{16 \pi^2 d^2} \cdot \frac{P_t (f_{\text{max}} - f_{\text{min}})}{B} \cdot G_{tx} \cdot G_{rx} \]  

(2.5)

Referring to the derivation in [34], (2.5) is modified by setting \( K_a = \frac{\lambda^2}{16 \pi^2 d_0^2} \).

Substituting in (3.15). We arrive at:

\[ P_r = \frac{\lambda^2}{16 \pi^2 d^2} \cdot \frac{P_t (f_{\text{max}} - f_{\text{min}})}{B} \cdot G_{tx} \cdot G_{rx} \quad \gamma \geq 2 \]  

(2.6)

Where \( B \) is the bandwidth; \( f_{\text{max}} \) and \( f_{\text{min}} \) are the maximum and minimum frequency of the radio signal respectively. \( G_{tx} \) and \( G_{rx} \) are the antenna gains of the transmitter and receiver.
Comparing equation (2.6) with the equivalent expression in OPNET (2.5), equation (2.6) is more inclusive than the default OPNET implementation such that simulation can adapt to different environments.

This is done by changing the value of the path loss exponent using different values taken from table 3.

The received power stage of the transceiver pipeline in Opnet is modified to allow for this variable pathloss exponent in simulation so as to obtain more realistic simulation results. This is applicable to the case where sensor nodes are deployed in different environments with variable signal attenuation and variable distances from the sensor network coordinator. This is usually the case in sensor network deployments where data collected from different environments need to be compared (table 3). Figure 3.7 shows the setting in the node model while figure 3.8 is the sensor network which is coordinated by a sensor network coordinator

Table 3: Path Loss Exponents for Different Terrestrial Environments [33]

<table>
<thead>
<tr>
<th>Environment</th>
<th>Path Loss Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area</td>
<td>2.7 to 3.5</td>
</tr>
<tr>
<td>Shadowed urban area</td>
<td>3 to 5</td>
</tr>
<tr>
<td>In-building line of sight</td>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>Obstructed in building</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Obstructed in factory</td>
<td>2 to 3</td>
</tr>
</tbody>
</table>
Chapter Three: **Chaos Modulation and Integration in OPNET**

### 3.1 General Communication scheme

The generic block diagram for simulation of the chaos communication schemes discussed is shown in Figure 3.1 [55]. In this work, the binary information signal to be transmitted is first spread or mapped to a broadband noise-like chaotic signal. The broadband signal is then up-converted up to the radio frequency (RF) by some RF modulation for transmission over the channel. At the receiver, the demodulator must decide which bit was transmitted in the distorted received signal. When wrong decisions are made, bit errors occur.

Therefore, quality of the digital communications system is characterized by the bit error rate (BER) which quantifies the average number of bit errors for specified channel conditions. For modelling, MATLAB [57], has a comprehensive communications systems tool box with both AWGN and Rayleigh fading propagation channels. Hence, the performance of each chaotic spread spectrum communication system can be compared based on their performance in different channels. This is done for the different schemes discussed below and comparative evaluation is done by comparing the bit error rate (BER), at the same SNR values. For digital communication schemes, the characteristic BER curve is plotted as a function of the ratio of signal energy per bit \( E_b \) to channel noise power spectral density \( (E_b/N_o) \). The SNR at the demodulator input is related to the \( E_b/N_o \) by the equation below [25, 15]:

\[
\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}} = \frac{E_b}{N_o} \frac{1}{BT} 
\]  

(3.1)
Where B is the channel bandwidth and T is the bit duration of the binary data. However, depending on the chaos modulation scheme being considered, the only changes will be in the modulation and demodulation blocks. The advantage is that comparison is being made on the same simulation platform. Furthermore, in all cases, the tent map will be used as chaos generator for spreading the input data. For sequences generated by this map, the auto-correlation is a delta-function. The tent map has been widely studied \[55, 22, 23\] for use in digital chaotic communication and can be written as:

\[ x(t) = \theta - 1 - \theta \cdot |x(t - 1)| \tag{3.2} \]

Where \( x(t) \in [-1,1] \) and \( \theta \in [1,2] \) is called the bifurcation parameter or simply chaotic parameter for which the sequence is, non-periodic and non-converging. Figure 3.2 shows the mapping (3.2a) and the autocorrelation (3.2b) of the tent map.

![Block diagram for the simulation model used for comparison](image)

Figure 3.1 Block diagram for the simulation model used for comparison [55].
Figure 3.2a: The Tent map

Figure 3.2b: The autocorrelation of the generated chaotic signal using the Tent map.
3.2 Simulation of Chaotic Modulation Schemes

Simulation of the modulation schemes is done with the objective of showing a comparison between the performance in AWGN and propagation delay channel using the BER in these channels. Three modulation schemes are considered in this work selected for comparison based on the adopted categorization in [25] and for comparison with conventional DSSS. The schemes are:

1. Differential Chaos Shift Keying (DCSK): This represents modulation schemes using the chaotic state $x(t)$ and is also a good industry baseline. It means that the chaotic signal generated from a chaos system directly serves as the carrier.

2. Ergodic Chaotic Parameter Modulation (ECPM): This represents chaos modulation schemes in which the digital information is modulated by merging it into the chaotic bifurcating parameter $\theta$. By controlling $\theta$ in an appropriate chaotic regime, the information signal will be carried by the chaotic signal for spread spectrum transmission. Demodulation at the receiver is then a parameter estimation process, and this scheme is called chaotic parameter modulation (CPM) [25]. This scheme is also selected to show its application scenario as work continued from [25].

In all cases, the simulations are performed in MATLAB and the results are integrated into the OPNET pipeline stage 11 using the external model access interface in OPNET.
3.2.1 Differential Chaos Shift Keying (DCSK)

In this scheme, each binary digit is mapped to two chaotic sample functions; hence each of the transmitted bits consists of two parts one serves as reference (reference chip), while the other represents the data to be transmitted (information bearing chip).

![Reference Chip and Information bearing chip](image)

Figure 3.3: The reference and information bearing chips in a DCSK scheme.

Let the reference chaotic signal used as reference be \( x(t) \) and the bit duration be \( T \). When the data bit, \( d(n) \), to be transmitted is a “0”, the reference signal \( x(t) \) generated from the chaotic system is transmitted within the first half of the bit duration \( [0, \frac{T}{2}] \). To represent this digital information (that is “0”), \( x(t) \) is again transmitted in the second half of the bit duration \( [\frac{T}{2}, T] \). When the data to be transmitted is a “1”, \( x(t) \) is transmitted within the first half of the bit duration, but in the second half of the bit duration its additive inverse (negative waveform) is transmitted.

\[
X'(t) = \begin{cases} 
  x(t), & 0 \leq t < \frac{T}{2} \\
  x\left(t - \frac{T}{2}\right), & \frac{T}{2} \leq t < T \\
  -x\left(t - \frac{T}{2}\right), & \frac{T}{2} \leq t < T \\
\end{cases}
\]

\( d(n) = 0 \)

\( d(n) = 1 \)

At the receiver, the signal is delayed by half a bit period and correlated with the undelayed signal to get the output data.
stream. That is, the received signal within the first half bit period, \([0, \frac{T}{2}]\), is multiplied with that received in the period \([\frac{T}{2}, T]\).

A positive value for the correlation between the signals within the first half bit duration and the second half bit duration indicates that a “0” is received. On the other hand, a negative correlation value means the reception of the data "1". The decision is made by a comparator, which has a constant, zero threshold level, as shown below

\[
\hat{d}(n) = \begin{cases} 
0 & m(n) \geq 0 \\
1 & m(n) < 0 
\end{cases}
\]

Where \(m(n)\) is the sampled output of the correlator.

The performance of Differential Chaos Shift Keying (DCSK) in additive white Gaussian noise (AWGN) channels has been studied in [13, 45]. For such channels, the closed form analytical expression for the noise performance which was experimentally verified [13] is stated below:

\[
BER = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{E_b}{4N_0}} \left(1 + \frac{M N_0}{2E_b}\right)^{-1} \right) \quad (3.3)
\]

Where, \(E_b = \text{energy per bit}\), \(N_0\) is the channel noise power spectral density and \(M\) is the length of the chaotic spreading sequence.

The BER curve for DCSK in AWGN is shown in figure 3.4 and 3.5.
Figure 3.4: Performance of DCSK in AWGN

The curve in figure 3.4 is used to produce the OPNET modulation curve which is shown in figure 3.5.
3.2.2 Ergodic Chaotic Parameter Modulation (ECPM)

In this scheme, the digital information, (say $S_t$), is modulated by merging it into the chaotic bifurcating parameter $\theta$. Recall the discrete time chaotic system state equation:

$$x(t) = f(X(t - 1), \theta),$$  \hspace{1cm} (3.4)\]

Where $f$ is the chaotic map, and $\theta$ is the bifurcating parameter. For digital communication, the message signal $S_t$ takes on only two values, that is, 0 or 1. Therefore, in the modulation process, only two parameter values are needed to represent the message signal. That is,

$$\theta = \begin{cases} 
\theta_0 & \text{if } s_t = 0 \\
\theta_1 & \text{if } s_t = 1 
\end{cases} \hspace{1cm} (3.5)$$

After giving an initial value, the output signal of this chaotic modulation system, $X'(t)$, is still chaotic and has the desired wideband characteristic needed for spread spectrum. This can be represented as:

$$X'(t) = \begin{cases} 
x(t) = f[x(t - 1), \theta_0] & \text{if } s_t = 0 \\
x(t) = f[x(t - 1), \theta_1] & \text{if } s_t = 1 
\end{cases} \hspace{1cm} (3.6)$$

The goal of the demodulation process is to determine which bifurcating parameter $\theta_i$ is used and therefore the binary data transmitted in chaotic signal $X'(t)$. This is done using the mean-value estimation method [22, 23, 41, 55] to determine whether the parameter used to generate the received signal is $\theta_0$ or $\theta_1$. Since $\theta_i$ can only take on two values for binary digital communications, the mean-value estimation process is further simplified to a binary decision process.
The criterion for using this method is for the chaotic map to have a monotonic mean-value function which guarantees the existence of the inverse of the mean value function. This has been shown to be true for the tent map [22,25 and 55] in the range $\theta \in [1.1, 1.6]$.

The mean value estimation algorithm is summarized in three points as follows [25]:

1. Compute an estimate of the mean value of the received signal $y_t$ using the ensemble average, that is

$$\hat{M}(\theta_0) = \frac{\sum_{i=1}^{N} y_t^{+}}{N} = \frac{1}{N} \sum_{t=1}^{N} y_t$$  \hspace{1cm} (3.7)

   Where $M(\theta)$ is called the mean-value function of the chaotic map, and $\theta_0$ is the bifurcating parameter to be estimated.

2. To avoid deriving the inverse mean-value function, $M^{-1}$, a numerical technique is used to locate the minimum of $D(\theta) = | \hat{M}(\theta) - \hat{M}(\theta_0) |$ where $D(\theta)$ is a unimodal function with a unique global minimum at the selected $\theta_0$ and $\hat{M}(\theta)$ is a numerical approximation of $M(\theta)$, the mean value of the chaotic map.

3. This numerical approximation for $M(\theta)$ is computed using the ensemble average

$$\hat{M}(\theta) = \frac{1}{N} \sum_{t=1}^{N} x_{\theta_i}(t) \text{ and } \{ x_{\theta_i}(t) \mid t = 1,2,3, \ldots \} \text{ is the data sequence generated by the}$$

   dynamical system given in (4.5), with $\theta = \theta_i$.

The BER curves for ECPM are shown below followed by the modulation curves used in OPNET.
Figure 3.6: Performance of ECPM in AWGN

Figure 3.7: Opnet modulation curve for ECPM in AWGN
3.3 Performance Comparison of Chaotic Schemes with Direct Sequence Spread Spectrum

Direct Sequence Spread Spectrum (DSSS) was described earlier in section 2.2.1. It is selected for comparison with the chaos modulation schemes in this work because of its wide spread application, especially in the equally widely deployed Zigbee sensor network which uses the IEEE 802.15.4 standard. Furthermore, the academic license used in this study covers the Zigbee module in OPNET. This provides a useful means to also present network level results in comparison with chaos communication schemes.

3.3.1 Direct Sequence Spread Spectrum in Zigbee/802.15.4

IEEE 802.15.4 standard defines the physical and MAC layers specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). Zigbee builds upon the IEEE 802.15.4 standard and defines the network layer specifications and provides a framework for application programming in the application layer.

Figure 3.8: A mapping of Zigbee/802.15.4 to Network layers [58]
When operating in the 2450 MHz band, a 32 PN sequence, 16-ary quasi-orthogonal spreading mechanism is used in the 802.15.4 physical layer. During each data symbol period, four information bits are used to select 1 of 16 nearly (or quasi) orthogonal pseudo-random noise (PN) sequences to be transmitted. Spreading the information signal is accomplished by the multiplication of the information signal with the PN sequence.

The receiver’s objective is to recover the spread information in the received signal into its original form. Despreading is accomplished by cross-correlating the arriving signal with locally generated PN codes within the receiver.

The signal waveforms for the simulation are shown in the figures below:

![Figure 3.9: Spreading the data and modulating the carrier](image)

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3.3.2 Noise Performance Comparison

For the sake of logical deductive argument, it is important to show the AWGN performance comparison between chaotic schemes and DSSS. The curves in figure 3.11 corroborate with results presented in [1, 15]. The reason behind the poorer performance of chaotic modulation schemes when compared with the classical schemes is mainly due to the non-periodic nature of chaotic signals [14]. For conventional modulation schemes, the basis functions are periodic and the bit duration $T_b$, is an integer multiple of the period of the basis functions. In chaotic modulation schemes, the basis functions are not fixed waveforms but aperiodic chaotic signals.
Hence, the cross correlation and autocorrelation of basis functions recovered from the received signal and evaluated for the bit duration become random numbers which vary about a mean value. Known as the estimation problem, this results in a non-zero variance of the estimated transmitted signal, and as a rule of thumb, the smaller the variance, the lower the bit error rate (BER) [18]. Hence ECPM performs better than DCSK as seen in the difference in variance and area of overlap in the histograms of two received digital symbols. A smaller overlapping area indicates fewer errors [25].

Figure 3.11: Comparison of chaotic schemes to DSSS in AWGN
For DCSK, performance improvement has been reported to be achieved by increasing the bit duration, hence, the estimation time [55] or preferably by keeping the transmitted energy per bit constant using a pre-FM stage [18]. This improved version using the latter method, has been reported to be very robust to multipath [25, 15], and therefore replaces DCSK in the next section.
3.3.3 Performance Comparison in Propagation Delay Channels

As seen in the preceding section, conventional broad band schemes perform better than the chaos modulation schemes. This was narrowed down to the nature of the chaotic signal which leads to the estimation problem. However, there are certain situations where the conventional schemes cannot be employed; such as environments with large propagation delay where the characteristics of the transmission medium affect the speed at which the carrier propagates through the medium and possible fluctuating delays in signal reception. The coherent demodulator, employed in the conventional schemes such as DSSS, is sensitive to delays in signal reception [25]. Such delays can further degrade the network performance because they lead to inaccuracies in timing settings between the transmitter and receiver which results in the loss of transmitter-receiver synchronization and possible network outage.

Coherent demodulators are those which require a local reference carrier whose phase is an exact replica of, or a close approximation to that of the incoming carrier. In chaotic modulation schemes such as EPCM, there is no need for such a local reference carrier. Hence, it is expected that the impact on their performance due to the propagation delays arising from the transmission medium is not as pronounced.

The channel model used, which is shown in figure 4.16 [25] corrupts the transmitted signal by some additive Gaussian noise \( n(t) \) and produces a propagation delay \( \tau_p \).

\[
\tau(t) = s(t - \tau_p) + n(t) \tag{3.7}
\]

Using lowpass equivalent notation, the RF frequency is considered to have been removed completely. Incorporating the propagation delay \( \tau_p \), the received signal can be expressed by ,

37
\[ r(t) = \text{Re}\{[x'(t - \tau_p) e^{j\theta} + z(t)] e^{j2\pi f_c t}\} \] (3.8)

\[ = s(t, \tau_p, 0) + n(t) \]

Where \( \theta = e^{2\pi f_c t} \) is the carrier phase distortion, \( z(t) \) denotes the baseband equivalent channel noise and \( s(t - \tau_p) \) has been replaced by \( \text{Re}\{x'(t - \tau_p) e^{j2\pi f_c t}\} \).

In the above model, the propagation delay \( \tau_p \) is generated using a Gaussian random process with zero mean and maximum delay of \( \frac{T_b}{2} \) relative to each bit duration \( T_b \).

\[
P_f(\tau_p) = \frac{1}{\sqrt{\pi T_b}} \exp\left[\frac{-\tau_p^2}{T_b}\right] \quad (3.9)
\]

\( \frac{T_b}{2} \) is chosen as the upper bound because this represents the duration for differential correlation in FM-DSCK. Hence a delay of such magnitude will have considerable impact on a digital, correlator-based communication system. Absolute values are taken to cater for negative values of delay that are generated.
The demodulator output of DSSS is based on coherent correlation between the received signal and the reference signal. That is:

\[ m = \int_{0}^{\tau_b} x'(t - \tau_p)x(t)dt \]  \hspace{1cm} (4.27)

The higher the delay \( \tau_p \) between these two signals the smaller the correlation between the reference and received signal so that the output \( m \) is almost identical to zero in some cases. In such cases, the receiver fails in the attempt to recover the transmitted data symbol leading to service outages. This explains the poor performance of DSSS in this case.
In the case of FM-DCSK, since the correlation is between the received signal and a delayed version of itself, that is:

\[ m = \int_{\frac{T_b}{2}}^{\frac{T_b+\tau_p}{2}} x'(t - \tau_p) x'(t - \frac{T_b}{2} - \tau_p) \, dt \quad (4.28) \]

\[ = \int_{\frac{T_b+\tau_p}{2}}^{\frac{T_b+\tau_p}{2}} x'(t) x'(t - \frac{T_b}{2}) \, dt \]

The effect of the propagation delay \( \tau_p \) is a shift in the correlation window within which the demodulator can still operate and recover the transmitted signal although with some loss in quality. A reduction in the propagation delay range will further improve the performance of FM-DCSK [25].

ECPM does not employ the use of a correlator for demodulation. Hence, the effect of the propagation delay is simply a shift in the sample time from \( nT_b \) to \( nT_b + \tau_p \).

This can be seen in the demodulator output of ECPM system given as:

\[ m = \int_{0}^{T_b} x'(t - \tau_p) \, dt = \int_{\tau_p}^{\frac{T_b+\tau_p}{2}} x'(t) \, dt \quad (4.29) \]

This shift in time does not really cause much error to the demodulators, and their performances therefore remain almost unchanged even under large propagation delay imposed by the operating environmental conditions.
This makes a case for the use of chaos in underwater wireless acoustic sensor networks where such delays can be experienced as discussed in the next chapter.

From the well-established claims above, for which further discussions can be found in the referred texts, the author acknowledges that although classical broadband schemes such as DSSS performs better than chaos modulation schemes in AWGN due to the robustness of the signal recovery process using coherent demodulation techniques; these techniques make the performance of broadband schemes highly sensitive to delays. Hence, this presents a use case for chaos modulation schemes since they employ non-coherent demodulation techniques.

By including terrain parameters in the simulation, it is interesting to study the performance of chaos modulation schemes and how they change in response to environmental encumbrances and terrain effects. The next chapter therefore focusses on terrains where the possible strengths of chaos modulation schemes can be engaged. Referring to [15], in these scenarios, while the noise performance is important, other properties of the modulation scheme, such as robustness to channel non-idealities and simple implementation also assume a significant level of consideration.
Chapter Four: Application of Chaos Modulation to Wireless Acoustic Sensor Networks

4.1 Introduction

The last chapter revealed a use case for chaos modulation schemes in propagation delay channels. Such a channel can be found in underwater terrains where acoustic signals are used for relaying sensed data. Hence, a performance comparison of chaos modulation schemes is presented from a wireless acoustic sensor network stand point by incorporating the link-level simulation results from MATLAB into a network level simulator – OPNET.

The approach to this comparative evaluation is unique in that it incorporates the channel non-idealities in the operating environment such as well as local topography and terrain effects. This makes it more realistic than existing simulations such as presented in [12] where these non-idealities are not considered thus making the results rather optimistic. To characterize the network performance observed from using different chaos schemes, the BER as a function of $E_b/N_0$ curves (generated with OPNET EMA) are used in the simulation.

The different properties of chaotic systems mentioned earlier (2.2.2), have been applied to implement different chaos based communication schemes [12, 18] and their performances evaluated [17, 19, 25]. However to the best of the author’s knowledge, this is the first work to integrate the results of such comparison into a packet based simulator, consider performance in underwater scenarios while showing the impact on network level performance.

The results from this approach are useful in making decisions related to network design because they are based on parameters in the local environment, thus enhancing the level of preparedness for deployment and protecting network elements from communication outages due to unforeseen
features of the local topography. To achieve this, the Terrain Modelling Module (TMM) in OPNET is employed for which a brief overview is given in the next section.

4.2 Terrain Modelling in OPNET

The terrain modelling module in OPNET facilitates the inclusion of terrain data sourced from terrain data files, along with environmental factors, in the pathloss calculations for a transmission path. This will be added to the closure stage of the Radio Transceiver Pipeline (stage 2). Thus, when terrain modeling is being used, the terrain along the transmission path contributes to the determination of whether the transmitter and receiver can “see” each other [64]. In addition, the path loss calculated here is saved and used in the receiver power stage of the pipeline (stage 7).

The architecture of a TMM model and its inputs are shown in Figure 4.1 [64].

Figure 4.1. Terrain Modelling in OPNET

The terrain parameters in this work are obtained from free sources such as the United States Geological Survey (USGS) online data base [66] and other references from existing research work. The network in each scenario is assumed to have a star topology with a sensor network coordinator serving as access point or hub. Terrain parameters describe the environmental conditions along the signal path as it propagates through the medium from transmitter to receiver.
4.3 Underwater Terrain

Water bodies such as oceans and seas play a critical role in our everyday life because they constitute a natural habitat to a major source of food and play a major role in regulating the balance of our ecosystem. According to the National Oceanic and Atmospheric Administration, the Ocean covers seventy one percent of the Earth's surface and contains 97 percent of the planet's water, yet more than 95 percent of the underwater world remains unexplored. The ocean and lakes play an integral role in many of the Earth's systems including climate and weather and is key to transportation as well as recreation [60]. Hence, under water sensor networks can help ocean and lake-dependent industries such as shipping by providing them with information needed to make decisions.
From a research perspective, long-term, consistent exploration using sensor networks can improve our understanding of the ocean’s role in many of Earth’s systems. Since the underwater terrain inherently comes with propagation delay and chaos modulation schemes excel in such conditions as seen in the last chapter. This makes the application of chaos modulation schemes to underwater wireless acoustic sensor networks an interesting area to study.

![Seaweb network in the Eastern Gulf of Mexico on February 2003](image)

**Figure 4.3** Seaweb network in the Eastern Gulf of Mexico on February 2003 [7,35]

As shown in figure 4.3, basic underwater acoustic (UWA) networks comprise of various instruments such as autonomous underwater vehicles (AUV’s) and sensors (UWASNs) that communicate with each other using acoustic signals. The network is then connected to a surface station which can be further connected to a backbone, such as the Internet, through an RF link [7,40].

The focus here, however, is on the part of the network that is underwater (UWASN) in which the sensor network nodes are stationary, the channel is assumed to be slowly varying and stays constant during a packet interval [41].
For such networks, the major challenges facing communication in the underwater environment are [9]:

- Low propagation speed which contributes to large propagation delay for acoustic communication.
- The underwater channel is severely impaired, especially due to multipath and fading problem.
- High bit error and temporary losses of connectivity (shadow zone) will be experienced.
- Limited battery power that usually cannot be recharged.
- Underwater sensors are prone to failures because of fouling and corrosion.
- The available bandwidth is limited and depends on the transmission distance.

The first three challenges are interrelated and will directly influence the performance of the modulation scheme. In particular, the propagation delay will lead to inaccuracies in timing settings between the transmitter and receiver which results in the loss of transmitter-receiver synchronization. Since the propagation delay cannot be precisely pre-determined, this will affect the performance of coherent correlator-based demodulators which require a local reference carrier whose phase is an exact replica of, or a close approximation to that of the incoming carrier. It is therefore important to study the impact of such an environment on the network performance of sensor networks which use chaos modulation schemes in comparison with those that use the classical schemes.
4.3.1 Signal Transmission in Underwater Terrain

There are three methods of signal transmission in underwater communication. These are acoustic communication (sound), radio wave communication (Electromagnetic) and optical communication (light).

Optical communications has the advantage of high data rates that could exceed 1 Gigabits per second [8]. However, when used in underwater environment, the light is rapidly absorbed and the communication affected by its scattering. Consequently, transmission of the optical signal requires high precision in pointing the narrow laser beams [44].

Electromagnetic waves strongly attenuate especially in salt water and propagate over long distances through conductive seawater only at low frequencies which require large antenna and high transmitter power [33, 9]. Hence, Radio wave and optical methods are not suitable in deep underwater environment.

Acoustic communication has been widely used as a sensing mechanism in underwater networks leading to the term underwater Acoustic Networks (UWA).

Referring to [9], although radio wave communication has faster propagation speed compared to the acoustic communication, acoustic communication is widely chosen in deep underwater environment due to the low attenuation of sound in water. Although propagation delay is a strong concern, such non-ideality is the right fit for this study and justifies the choice of the underwater terrain as it enables performance comparison of chaos modulation schemes with conventional DSSS in a wireless acoustic sensor network.

Table 4 [9], shows the different characteristic of the acoustic, radio waves and optical propagation in seawater.
Table 4 Comparison of the acoustic, radio wave and optical communication in seawater [9]

<table>
<thead>
<tr>
<th></th>
<th>Acoustic</th>
<th>Radio</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of propagation</td>
<td>1500 m/s</td>
<td>3x10^8 m/s</td>
<td>3x10^8 m/s</td>
</tr>
<tr>
<td>Power Loss</td>
<td>&gt;0.1 dB/m/Hz</td>
<td>~28 dB/Km/100 MHz</td>
<td>Turbidity</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>~ KHz</td>
<td>~ MHz</td>
<td>~ 10 – 150 MHz</td>
</tr>
<tr>
<td>Antenna Size</td>
<td>~ 0.1m</td>
<td>~0.5m</td>
<td>~0.1m</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>~KHz</td>
<td>~MHz</td>
<td>~10^{14} - 10^{15}Hz</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>~ 50m – 5Km</td>
<td>~1m – 100m</td>
<td>1m – 100m</td>
</tr>
</tbody>
</table>

4.3.2 Underwater Acoustic Channel Modelling

The underwater acoustic channel is modeled by making modifications to the radio transceiver pipeline stages in OPNET modeler. This helps to account for different environmental factors that exist underwater.

a. Propagation Delay

The speed of sound in seawater depends on the water properties such as temperature $T_u$, salinity $S$ (or conductivity $G$) and pressure $P$ (or depth). It increases with an increase in any of these three parameters. Several equations have been proposed for the speed of sound $c$, as given in [9]. However, most agree that the speed of acoustic signals is approximately 1500 m/s, which is much less than the speed of radio waves by five orders of magnitude [60]. Thus, packets experience large propagation delays. The general relation is as given in equation 5.3 [56]:

$$v = f(T, P, G(S))$$

(4.1)

$$v = 1402.394 + T(K_4 + S(K_2 + K_3S P)) + K_4P^2 + T((K_5 + K_8 S) + K_7T) + K_6S$$

$$+ P(K_9 + P(K_{10} + P(K_{11}T + K_{12}S)))$$

48
Where $K_1 \sim K_{12}$ are constants [56], the sound speed is 1505.100285 m/s.

The standard propagation delay routine of Opnet (pipeline stage 5) is modified by replacing the speed of light, $c$, with this value. Although the speed of sound changes with depth and transmission range, typically, in many applications and models, the sound speed is only associated with water depth $z$.

Sound speed profiles for ocean (deep water) have been plotted in [56], while the typical shallow water sound speed profile is often described as isotropic speed or linear equation with a small negative gradient. Propagation delay can be calculated as shown in equation 4.2.

$$t = \frac{D}{v} \quad (4.2)$$

Where $t$ is the propagation delay (in seconds), $D$ is the distance between the sensor and the sensor network coordinator (meters) and $c$ is the speed of sound (m/s).

b. Noise

Noise in an acoustic channel consists of ambient noise and site-specific noise [56]. The ambient noise comes from sources such as turbulence, breaking waves, rain, and distant shipping. Site specific noise often contains significant non-Gaussian components and only exists in certain places such as ice-cracking in polar region, snapping shrimp in warm waters [56]. They are mostly noticeable pulses that distort signals in a short term and are not considered for the general case in this study. Thermal noise becomes dominant for frequencies beyond 100 KHz [56].
Below this frequency, surface motion, caused by wind-driven waves, is the major factor contributing to the noise in the frequency region 100Hz – 100 kHz.

The background noise pipeline (stage 9) is modified taking the noise of turbulence, ship and wind and thermal noise into consideration. The ambient noise from all these sources is given by the equations below [9, 56].

\[
\begin{align*}
10\log N_t(f) &= 17 - 30\log f \\
10\log N_s(f) &= 40 + 20(s - 0.5) + 26\log f - 60\log(f + 0.03) \\
10\log N_w(f) &= 50 + 7.5w^2 + 20\log f + 40\log(f + 0.4) \\
10\log N_{th}(f) &= -15 + 20\log f
\end{align*}
\]  

As can be seen above, the noise is modelled as the result of a variety of causes that include wind (wind speed, w), and shipping (indicative of the amount of naval traffic near the network area, 0 ≤ S ≤1 where 0 corresponds to no shipping and 1 to a very busy shipping route). According to [64], system design can be carried out by taking the values of s = 0.5, w = 0 as parameter values and these have been adopted in this work.

The total noise is given as [9, 56]

\[
N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)
\]  

(4.4)
c. Transmission loss

The transmission loss in the underwater terrains can be modelled by the sum of spreading loss and attenuation loss. The total transmission loss (TL) in dB is a function of internode distance \(d\) and operating frequency \(f\) which is given by the Urick’s path loss formula [9, 47]:

\[
TL (d, f) = \ell \cdot \log(d) + g(f) \cdot d + A
\]  

(4.5)

The first term is the spread loss, where \(\ell\) is the pathloss exponent [9]; and its value determines whether the spread loss for sound wave propagation is spherical or cylindrical.

Usually, \(1 \leq \ell \leq 2\), [56]; but according to references cited in [9], path loss exponent for underwater communication can use 1.5 corresponding to practical spreading.

The second term is the attenuation loss which includes losses due to the absorption, leakage out of ducts, scattering and diffraction. Absorption describes those effects in the ocean for which a portion of the sound intensity is lost through convection of heat. \(g(f)\) is the absorption coefficient, which accounts for the loss due to the absorption of sound energy. This is given by Thorp’s formula [9,41]:

\[
g(f) = \left(\frac{0.11f^2}{1 + f^2}\right) + \left(\frac{44f^2}{4100 + f^2}\right) + 2.75 \times 10^{-4}f^2 + 0.003
\]  

(4.6)

The last term in equation 4.6 is the transmission anomaly and accounts for the degradation of the acoustic intensity caused by multiple path propagation, refraction,
diffraction, and scattering of sound. The value is usually between 5 and 10 dB [3]. The acoustic intensity is given by [3,47],

\[ I_t = \frac{P_t}{2\pi \lambda m H} \]  \hfill (4.7)

To account for these losses, the power model is implemented by modifying the received power pipeline stage seven to include the transmission loss in underwater channels according to the expressions above. This is then stored in a transmission data attribute and used to compute the SNR (OPNET stage 10) and the E_b/N_0.

Referring to [47], the expression for the SNR at the sensor network coordinator is:

\[ SNR = SL_t - TL - N(f) \]  \hfill (4.8)

Where, \( SL_t \), is the signal level at the transmitter, and is determined by the acoustic intensity through the relation [47]

\[ SL_t = 10 \log \left( \frac{I_t}{0.67 \times 10^{-18}} \right) \]  \hfill (4.9)
4.4 Underwater Wireless Acoustic Sensor Network Simulation Set up

Upon sensing the channel idle, the sensor node will transmit:

\[ L = R \sigma \text{ Bits per time slot period} \quad (4.10) \]

Where \( \sigma \), is the slot duration in seconds per timeslot and \( R \) is the data rate for the transmission, given by

\[ R = \frac{K}{T} \text{ bits per second (bps)} \quad (4.11) \]

\( K \) (number of bits per symbol) is dependent on the choice of modulation; and determines the number of bits that will be mapped by the modulator unto the carrier and transmitted over the channel every \( T \) seconds.

\[ T \text{ is called the symbol interval } = \frac{K}{R} = KT_b = T_b \log_2 M \quad (4.12) \]

Where \( T_b = \frac{1}{R} \), is called the bit interval.

The symbol rate, \( R/K \), is the rate at which changes occur in the varying parameter (such as amplitude) of the carrier, to reflect the transmission of new information. \( M \) is the number of alternative symbols from which a symbol, \( k \) bits long, will be selected.

The network traffic is generated according to formula \([42]\),

\[ \text{Traffic generated } = N \lambda_i L \quad (4.13) \]

Where, \( N = \text{Number of nodes} \); \( \lambda_i = \text{mean arrival rate per node } i \); \( L \) is the packet length.

From \((4.10)\), substituting for \( L \) in \((4.13)\) gives

\[ \text{Traffic generated } = N \lambda_i R \sigma \quad (4.14) \]
Since $R$ is directly related to $M$ through $K$; Equation (4.14) shows how the mean arrival rate, $\lambda$, as well as the physical layer parameter $R$, both influence the network level performance.

### 4.5 Simulation results

#### 4.5.1 Analytical Relationship between BER and Throughput

As discussed in section 2.3, the Simulation Kernel relies on a 14-stage computational pipeline to evaluate the characteristics of radio communication when transmissions occur. The received SNR is calculated according to equation (4.8) and mapped to a BER value by the simulation kernel.

$L = $ packet length in bits

$BER = $ probability, $p$ that a bit is received in error

$P_s = $ probability that a packet is received successfully = Throughput

$P_{err} = $ probability that a packet is received in error

The following assumptions are made in this analysis:

A1. Bit errors in the packet are independent

A2. A packet is received in error if at least 2.5\% of the bits in the packet are received in error

Based on the assumptions above,

$$P_{err} = \sum_{i=\frac{L}{40} + 1}^{L} \binom{L}{i} p^i (1-p)^{L-i} \quad (4.17)$$
Where, \( \binom{L}{i} = \frac{L!}{i!(L-i)!} \)

By the total probability theorem:

\[ P_{s} + P_{serr} = 1 \]

Hence,

\[ P_{s} = 1 - P_{serr} \]

Therefore,

\[ P_{s} = 1 - \sum_{i=\frac{L}{2}+1}^{L} \binom{L}{i} p^{i} (1-p)^{L-i} \quad (4.18) \]

From the above since, \( P_{s} = f(BER, L) \), equation 4.18 gives the analytical relationship between BER and throughput.

The analytical curves are plotted in figure 4.6 and compared with simulation results in Figures 4.7 (with analytical curves for each modulation scheme shown in dotted lines). Each acoustic packet is set to 20 bytes long and data rate is 100 bps.

The differences seen in the analytical and simulated curves are attributed to the independent bit error assignment in assumption A1. The pipeline stage documentation does not disclose how the OPNET simulation kernel assigns the bit errors in the arriving packets.
Figure 4.6: Analytical BER-Throughput relationship
The nodes are assumed to be stationary, from the sensor network coordinator and arranged in a star topology. The start time of packet transmission for the data packet is determined during the simulation by the simulation kernel and the propagation delay at that sensor distance is calculated from equation 4.2. This is the time delay experienced by the packet due to propagation through the medium; and it adds on to the overall delay experienced by the packet between the time it was created and the time it is received by the sensor network coordinator.

With this set up, the network scenario is applied for localization in the underwater terrain. The Min-Max algorithm [37, 39] is implemented in the sensor network coordinator to determine the location of the slowly drifting object (implemented with default trajectory in OPNET).

For simplicity, the Min-Max algorithm is used since by default, OPNET already provides the option to include coordinates of the nodes in the packets during the closure stage of the transceiver pipeline where the ability of the transmission to reach the receiver is determined. Hence, the distance, D, between the roaming node and the anchor node is calculated and stored in the packet, as the first step in the localization process. These distances are sent to the sensor network coordinator as input into the Min-Max localization algorithm. The end-to-end delay will affect the delivery of the packets and hence the localization time.

The basic idea of the Min-Max algorithm is to form a bounding box for each anchor using its position and distance estimate, after which the intersection of these boxes is then computed. The position of the roaming node is set to the center of the intersection box. This is illustrated in Figure 4.4 and the node model for the sensor nodes is shown in Figure 4.5.
As shown, the bounding box of an anchor node, say X1 is created by adding and subtracting the estimated D1 from the anchor position (X1, Y1).

\[
[X1 - D1, Y1 - D1] \times [X1 + D1, Y1 + D1]
\]

(4.15)

The intersection of the bounding boxes is computed by taking the maximum of all coordinate minimums and the minimum of all maximums [39]:

\[
\left[\max(Xi - Di), \max(Yi - Di)\right] \times \left[\min(Xi + Di), \min(Yi + Di)\right]
\]

(4.16)

The sensor network coordinator needs packets from three different nodes to perform localization. Since each packet experiences different end-end delay, the localization time differs for each instance. The throughput and localization time are the metrics used in evaluating the network performance for each modulation scheme. The results for these metrics are plotted in figure 4.10, while the comparative throughput is shown in figure 4.11.

The differences in performance with choice of modulation scheme are as a result of the different BER values applied to the received packets during the simulation. This is because the received SNR and hence the BER for that transmission is delay dependent. Thus, when the propagation delay is high, BER is high and this will affect the Localization performance because the packet can be rejected if at least 20% are in error. Even at low SNRs, ECPM is still able deliver packets below this error threshold.
Figure 4.8: Opnet Node model for Underwater Acoustic Sensor Network

Figure 4.9: Illustration of the Min-Max Algorithm
With increase in generated traffic, packet collision and hence packet retransmissions increase, leading to further delays in the receipt of the required number of packets needed for localization. As shown in figure 4.8, the increase in packet delivery time is highest in DSSS due to the higher BER values for the packets received. ECPM performs better than DSSS because it is insensitive to such delays and so yields a much lower average localization time. This also shows in the higher throughput levels of the network (Figure 4.9), thus presenting ECPM as the modulation scheme of choice. Hence, it is proposed that ECPM be used for Wireless underwater acoustic sensor networks because of its ability to give higher throughput with lower values of SNR. Non-coherent detection of the transmitted signal also serves ECPM well in propagation delay-prone terrains such as exists for underwater wireless acoustic sensor networks.
Figure 4.6: Average localization time with choice of modulation scheme.

Figure 4.7: Throughput in UWASN with choice of modulations scheme.
Chapter Five: **Medium Access Control in Wireless Acoustic Sensor Networks**

The last two chapters progressively showed that chaos modulation schemes are more effective in propagation delay terrains than conventional, coherent demodulator-based, spread spectrum schemes such as DSSS. From a network perspective however, it is important to combine such effectiveness in the physical layer with efficient upper layer schemes. Such efficiency can be entrenched in the medium access control (MAC) layer.

**5.1 Medium Access Control in Wireless Sensor Networks**

The MAC layer is responsible for managing access to the transmission medium by arbitrating among competing services and/or sensor nodes.

Most of the existing MAC protocols for wireless sensor networks can be divided into two categories:

(i) Time division multiple access (TDMA)-based or contention-free and

(ii) Carrier sense multiple access (CSMA) based with (possible) collision avoidance (CA) or contention-based

TDMA-based protocols have the advantage of collision-free medium access. However, they suffer heavily from problems like clock synchronization, and scalability due to fixed time-slot assignments. Furthermore, due to the routine-nature of operation, contention-free approaches are less likely to respond well in case of random and bursty traffic conditions; which might cause intolerable performances. In comparison, CSMA–CA protocols potentially have lower delay and better throughput potential at low traffic loads [38]. They scale easily and so are more suitable for wireless sensor networks, with no need for information relating to topology.
In addition, CSMA methods generally offer lower delay and better throughput at low traffic loads [38]; which is the generic case in wireless sensor networks.

Realistic sensor networks deployment include sensor which offer multiple services. The MAC layer is responsible to ensure that services of higher interest are given higher priority in terms of access to the transmission medium. One method of achieving this is by implementing quality of service mechanisms in the MAC layer.

5.2 Perspectives to Quality of Service (QoS) Support

Different technical communities may perceive and interpret QoS in different ways. In the internetworking community for instance, QoS is accepted as a measure of the service quality that the network offers to the applications/users. Hence, RFC 2386 by the IETF [10] characterizes QoS as a set of service requirements to be met when transporting a packet stream from the source to its destination. In this scenario, QoS refers to an assurance by the Internet to provide a set of measurable service attributes to the end-to-end users/applications in terms of delay, available bandwidth, and packet loss. From the perspective of an application, however, QoS generally refers to the quality as perceived by the application. These views are only concerned with the services that the networks provide and do not bother about management of network resources to provide the QoS support. The major concern for these networks is higher priority for bandwidth hungry applications.

It is unlikely that there will be a “one-size-fits-all” QoS support solution for each application. With this in mind, we focus our attention on QoS requirements imposed by different levels of interest, hence different levels of priority for each service offered by the network, especially from the perspective of provisioning at the medium access control layer.
It is assumed that the application of interest here is the acoustic data being delivered by the acoustic sensors on the sensor nodes. Thus we separate QoS requirements having other perspectives from this perspective. Hence for our purpose, we adopt the QoS perspective put forward by the ITU recommendation E.800 (09/08) which defines QoS as: “Totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service”. This addresses the control mechanisms behind the resource reservation rather than the provided service quality itself. In practice, it is achieved by assigning different priorities to various users, applications, data flows, frames or packets based on their requirements, by controlling the resource sharing.

5.3 Quality of Service Provisioning Techniques

In order to facilitate multiple applications over wireless sensor networks, it is important to provision the network for QoS. There are two main types of QoS provisioning techniques defined in wired and wireless networks. These are:

1. **Hard QoS**: Used for applications with strict bounds on QoS guarantees.

2. **Soft QoS**: Used for applications with statistical QoS guarantees.

The survey in [5] provides an extensive coverage of QoS mechanisms at the MAC layer for wireless sensor networks. Table 5 condenses these into a concise form for our purpose.
Table 5 MAC layer QoS Mechanisms

<table>
<thead>
<tr>
<th>QoS Mechanism</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptation and learning</td>
<td>Adapting operation parameters of the sensor nodes to the current network conditions learnt by observations such as traffic pattern, network topology, collision probability or channel condition.</td>
</tr>
<tr>
<td>Error control</td>
<td>Reduce energy consumption while providing reliable and fast delivery of the sensory data.</td>
</tr>
<tr>
<td>Data suppression and aggregation</td>
<td>Minimize radio communication by reducing the traffic load of the network, hence provides energy saving.</td>
</tr>
<tr>
<td>Power control</td>
<td>Adjust the transmission power of the sensor nodes according to the minimum power required for successful transmission.</td>
</tr>
<tr>
<td>Clustering</td>
<td>Grouping neighboring sets of sensor nodes to facilitate data aggregation. Hence can be used to provide QoS support in terms of energy consumption and reliability.</td>
</tr>
<tr>
<td>Service differentiation</td>
<td>Differentiates and prioritizes the traffic carried on the network based on one or more criteria and forms several traffic classes.</td>
</tr>
</tbody>
</table>

Service differentiation is the widely adopted QoS implementation scheme to provide QoS guarantees [51]. There are two types; namely integrated services (IntServ) or Differentiated services (DiffServ).

Figure 5.1: IntServ and DiffServ models [5]

The objective of both differentiation models is to prioritize flows or packets, map their priorities into service qualities and provide required service quality by sharing limited resources among them.
The DiffServe model has a major drawback in its costly memory requirements however it is easy to implement as it assigns a degree of importance to every packet, and this is visible to every entity in the network. This makes it adoptable to WSNs compared to IntServ which follows the hard QoS approach that is difficult to achieve due to time varying channel characteristics of the wireless medium. Hence the DiffServe model will be adopted in this study.

Service differentiation is in two phases:

- Priority assignment: Assigning priority levels to the packets based on type of service
- Traffic differentiation: Which is resource sharing according to the priority assigned to the carried data i.e. differentiation between priority levels

Priority assignment can be static, dynamic or a hybrid of both. Table 6 summarizes the different categories of priority assignments with the decision parameters used in each category, while the main techniques used at the MAC layer to provide traffic differentiation is shown in table 7.

Among the numerous WSN MAC protocols, some have been proposed which offer service differentiation. Table 8 gives a summary of these QoS protocols.

Table 6 Priority assignment and decision parameters in each category

<table>
<thead>
<tr>
<th>Static priority assignment</th>
<th>Dynamic priority assignment</th>
<th>Hybrid priority assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic class</td>
<td>Remaining hop count</td>
<td>Priority of the packets is determined in a hybrid manner by considering both static and dynamic decision criteria.</td>
</tr>
<tr>
<td>Source type</td>
<td>Traversed hop count</td>
<td></td>
</tr>
<tr>
<td>Data delivery model</td>
<td>Packet deadline</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Remaining energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Traffic load</td>
<td></td>
</tr>
</tbody>
</table>
Table 7: Some techniques for traffic differentiation at the MAC layer

<table>
<thead>
<tr>
<th>Differentiation Method</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Changing Contention Window (CW) size</td>
<td>The Contention CW determines the sensor node which will be served next. Hence, the desired service quality can be provided to specific traffic classes by favoring the sensor nodes which have data belonging to that particular traffic class.</td>
</tr>
<tr>
<td>Changing inter-frame space (IFS) duration</td>
<td>IFS is defined as the amount of time that sensor nodes stay quiet just before the contention or backoff period. Employing different IFS values for sensor nodes having different kinds of traffic classes provides service differentiation among them and gives precedence to the ones using shorter IFS</td>
</tr>
<tr>
<td>Changing backoff exponent</td>
<td>The backoff mechanism is used to alleviate the congestion and reduce the probability of collision by increasing the contention duration. Hence, using different backoff exponents for different traffic classes can also be considered as a technique for service differentiation.</td>
</tr>
<tr>
<td>Transmission slot scheduling</td>
<td>Reserving consecutive slots for a video sensor node which transmits delay sensitive real-time video frames can increase the service quality considerably.</td>
</tr>
</tbody>
</table>
Table 8 summary of QoS protocols

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSIFT based on SIFT protocol</td>
<td>Carrier Sense Multiple Access (CSMA)-based MAC protocol and provides traffic differentiation by varying the inter frame space (IFS) and contention window (CW) size for each traffic class.</td>
</tr>
<tr>
<td>MAC by Saxena et al.</td>
<td>Uses a CSMA/CA approach and assumes three types of traffic carried in the network: streaming video, non-real-time and best effort. Updates the CW size and duty cycle adaptively, based on network statistics like transmission failures and traffic type.</td>
</tr>
<tr>
<td>Reinforcement learning (RL) based MAC protocol</td>
<td>It adaptively changes the duty cycle of the sensor nodes based on not only local observations but also by the observations of neighbor nodes.</td>
</tr>
<tr>
<td>Q-MAC</td>
<td>Utilizes intra-node scheduling to select the next serviced packet from five different priority queues and inter-node scheduling to coordinate the medium access among multiple neighboring nodes.</td>
</tr>
<tr>
<td>IEEE 802.15.3/802.15.4 and extensions</td>
<td>Two mechanisms are used to realize service differentiation: variable contention window size and variable backoff exponent.</td>
</tr>
</tbody>
</table>

Of these protocols, the contention window adjustment approach in [38, 52] are the most recent comparison [8] to the best of the authors knowledge. Hence, this approach is applied in this work for service differentiation, while modifying the CSMA/CA algorithm in [61]. The network is assumed to offer three services, prioritized from a user perspective, as high, medium and low.
5.4 Simulation of the MAC layer

QoS is implemented in the process model of OPNET’s CSMA-based MAC layer to facilitate the operation of service differentiation in the sensor network with reference to the approach in [38, 52]. The service offered by the acoustic sensors is classified high priority. The key to traffic prioritization in the CSMA-based MAC layer is to allocate different MAC layer parameters to different traffic classes, thus achieving differentiated QoS support or service differentiation in the network.

There are many existing works which use this approach and a summary of the mechanisms currently used was provided in Table 4. Of these, the most recent with claims of superior performance is that proposed in [52]. Common to them is the contention window adjustment mechanism and assignment of different contention window MAC layer parameters to differentiate between traffic flows.

The traffic class of a packet is determined by the type of service embedded in the packet and this type of service parameter determines the queue to which the packet is assigned by the packet classifier. The contention window adjustment is done dynamically by monitoring the behavior of the network with a period P and collecting two related metrics about the current state of the network which are the total number of transmission attempts $T_a$ and number of collisions $T_c$. The probability of collision $P_c = \frac{T_c}{T_a}$, is then computed for that observation time frame if the number of transmission attempts exceeds a certain threshold $T_{TH}$. This is then used as input to the contention window adaptation algorithm described in the flowchart of figure 3.1.
\( \alpha \) is the adaptation coefficient for that traffic class and can be used to scale up (\( \alpha_{up} \)) or scale down (\( \alpha_{down} \)) the contention window size based on the traffic class. The sensor network will have three types of traffic: High priority (HP), Medium priority (MP) and Low priority (LP) which will be respectively tagged as type 1, 2, 3 so they can be prioritized upon arrival from the application layer as shown in Figure 5.2 [52]

\[
\text{Initialization:}
\quad \text{Set } CW_{\text{cur}} = (CW_{\text{min}} + CW_{\text{max}})/2
\]

Check network traffic statistics every \( P \) seconds

\[
T_a < T_{TH}
\]

\[
P_c = \frac{T_{co}}{T_a}
\]

\[
P_e(t) \leq P_e(t-1)
\]

\[
\Delta CW = \alpha_d(CW_{\text{min}} - CW_{\text{cur}})
\]

\[
\Delta CW = \alpha_{up}(CW_{\text{max}} - CW_{\text{cur}})
\]

\[
CW = CW_{\text{cur}} + \Delta CW
\]

Figure 5.2: Flow chart for QoS-Aware MAC [52]
Figure 5.3: Packet Classification

Packets are selected for medium access through CSMA on a priority basis, using the calculated contention window value assigned by the QoS algorithm for the packets in each class.

Medium access control employs slotted CSMA/CA similar to [61] with changes only to the contention window which is taken from the QoS algorithm. When a packet's arrival occurs during a slot, the node senses the channel but only transmits at the beginning of the next slot. The values for minimum CW sizes of high, medium and low priority traffic are selected as 2, 4, 6; and the maximum CW sizes are 8, 14, 16 respectively following the pattern in [62] where the sizes are set as multiples of 2. The adaptation coefficients are simply the reciprocal of the difference (CWmin/max - CWcur) multiplied by 1, 2, 3 for high, medium and low priority traffic respectively; so that the coefficients are integers. The process model for the operation is shown in Figure 5.4. Within the INIT state, variables are initialized and the parameters for each traffic class are computed. Once these values have been computed, the process model transitions into
the wait state. A node which has a packet to transmit first senses the channel for the beacon packet which is sent by the sensor network coordinator to synchronize the nodes and update the network on the start of the next data frame and packet structure [61].

With this information the node locates the next backoff period boundary and the CSMA/CA algorithm starts using the contention window obtained from the QoS algorithm. Transmitter synchronization here is limited to transmitting only at the beginning of the slot while receiver synchronization is achieved through the simulation kernel. This is because the OPNET simulation kernel delivers the complete packet to the receiver via a stream interrupt, hence receiver synchronization is assumed to be achieved [42]. The acoustic packets are considered high priority and the sensors are also assumed to provide temperature and sensor depth as underwater environment metrics with medium and low priority respectively. However, in the simulation, all packets are 20 bytes long and packet inter-arrival times are exponentially distributed which is a setting in the OPNET modeler.

Figure 5.4 OPNET Process Model
5.5 Packet Format

The Packet format comprises of three main fields:

1. **The header**: This comprises the frame synchronization byte, the frame type, node addressing information (source and destination) and type of service in the payload field.

2. **The payload**: This contains the data from the sensor nodes. The frame is shown in figure 5.5. Since this structure has been adopted for all traffic types, the length of the payload is specified in the function block of the process model for each type of service so as to differentiate the observed performance based on the parameter setting, especially contention window size, allocated to each traffic class.

3. **Footer**: Used by the simulation kernel for synchronization.

Figure 5.5 is the general packet structure for traffic in the sensor network and the sensor network coordinator serves as destination for all data traffic.

<table>
<thead>
<tr>
<th>Sections</th>
<th>HEADER</th>
<th>PAYLOAD</th>
<th>FOOTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>Frame Sync</td>
<td>Frame Type</td>
<td>NID (Source)</td>
</tr>
</tbody>
</table>

Figure 5.5 The structure of the MAC data packet

The payload is 14 bytes long and each field under the header and footer are 1 byte each.

The volume of traffic generated is varied by interarrival time of packets in the sensor nodes.

Figures 5.6 and 5.7 show the throughput and delay results obtained for AWGN when the application modules for all traffic sources are set to enabled.

It can be seen that the different traffic profiles have different throughput and delay. This is due to service differentiation using the contention window assignments for medium access control.
Figure 5.6: Throughput profile with QoS-CSMA in MAC layer

Figure 5.7: End to End delay profile with QoS-CSMA in MAC layer
As shown in figures 5.6 and 5.7, with the QoS mechanism in place lower delay and higher throughput can be attained for acoustic packets when the packets generated by the acoustic sound sources are assigned highest priority in the network. In comparison with other MAC schemes, the QoS MAC attains throughput levels comparable to TDMA and outperforms traditional CSMA/CA as used in Zigbee model (in-built in OPNET) as well as SMAC which use static medium access schemes. Although TDMA performs better, it is not easy to change the slot assignment within a traditional TDMA environment, because all nodes must agree on the slot assignments. Hence, the preference of a CSMA based MAC protocol. Furthermore, in accordance with common networking lore, CSMA methods have a lower delay and promising throughput potential at lower traffic loads, which generally happens to be the case in wireless sensor networks.

For the underwater environment, ECPM performs best among the modulation schemes. Figure 5.9 shows the throughput comparison with choice of MAC layer-modulation scheme combination. It is seen that QoS-CSMA with ECPM offers comparable performance with TDMA.
Figure 5.8: Comparative successful packet delivery rate with conventional MAC protocols

Figure 5.8: Comparative throughput with MAC-Modulation Scheme combinations
Chapter Six: Conclusion

This study considered the performance evaluation of chaos modulation schemes in wireless acoustic sensor networks. The results show that the chaos schemes perform better than DSSS in propagation delay because of the non-coherent detection scheme employed in their demodulator. The underwater environment, which is reputed for propagation delay is used as a deployment scenario. The simulations included different terrain parameters acting together as obtains in realistic underwater wireless acoustic sensor network deployments. This is considered as a unique approach to present a logical and deductive argument in presenting the network performance to make a case for the use of chaos modulation schemes in propagation delay terrains. Furthermore, since sensors can have multiple functionalities besides acoustic sensors medium access control layer with service differentiation is proposed for such networks with high priority on the acoustic packets for higher throughput.

The rationale for the study was born out of the realization that the effect which limits the performance of wireless sensor networks in most operating environments is not only the additive thermal noise, but also non-ideal conditions such as propagation delay. In these terrains, the parameters of distinction between different communications systems include robustness to the non-ideal conditions of the operating environment.

Moreover, wireless sensors are often deployed in areas which are un-approachable to humans and away from any sustained power supply. Such environments readily exist in non-terrestrial scenarios such as underwater acoustic sensor networks. Under these conditions, dramatic changes in the terrain of deployment can quickly render the sensor network dysfunctional, resulting in service outages. This is because the sensor nodes cannot communicate the sensed information due to the effect of environmental encumbrances on the communication system.
As a result of the critical role it plays in the communication system, one way by which this can happen is the lack of robustness of the modulation scheme to channel non-idealities. Hence, it was important to incorporate terrain parameters into the network performance comparison.

Although drawing largely from existing research, the approach differentiates this study different from existing works such as [25,12], which do not include the terrain effects of the environment. Most of these works acknowledge that the application of chaos to communications has been found to offer many advantages over the conventional spread spectrum systems including security, simple hardware implementation, and potential for performance enhancement [16].

In this work, a terrain based comparison was done. The results show that in operating environments where the medium introduces propagation delay, ECPM has the best performance under such conditions. This is because it does not make use of coherent demodulation but simply estimates the chaotic parameter whenever the signal arrives. It is this insensitivity to delay that is responsible for the better performance of ECPM over DSSS and FM-DCSK under the influence of propagation delays.

The merit of ECPM is very evident; especially in such applications such as localization. The loss of transmitter-receiver synchronization, as a result of propagation delay, causes the BER performance of DSSS to fall below that ECPM. FM-DCSK also outperforms DSSS because it uses self-correlating demodulator and does not need a reference carrier to estimate the phase of the incoming packet. From the results, it can be deduced that chaos-based are more robust to propagation delay. Hence, the results show the advantage of the chaos modulation schemes, especially ECPM.
References


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