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SAKARYA UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

THE COMPARISON OF ENERGY CONSUMPTIONS FOR OOK AND BPSK MODULATIONS IN WIRELESS SENSOR NETWORKS

MSc THESIS

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Electrical and Electronic Engineering Department

JUNE 2023

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Thesis Advisor: Assist. Prof. Dr. Nükhet SAZAK

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The following jury accepted the thesis work titled "THE **COMPARISON OF ENERGY CONSUMPTIONS FOR OOK AND BPSK MODULATIONS IN WIRELESS SENSOR NETWORKS**" prepared by OMRAN TABAJOU on **01/06 /2023** by unanimously of votes as a MSc THESIS in Sakarya University Graduate School of Natural and Applied Sciences, **Electrical and Electronic Engineering** Department.

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I declare that the thesis work titled "THE COMPARISON OF ENERGY CONSUMPTIONS FOR OOK AND BPSK MODULATIONS IN WIRELESS SENSOR NETWORKS", which I have prepared in accordance with Sakarya University Graduate School of Natural and Applied Sciences regulations and Higher Education Institutions Scientific Research and Publication Ethics Directive, belongs to me, is an original work, I have acted in accordance with the regulations and directives mentioned above at all stages of my study, I did not get the innovations and results contained in the thesis from anywhere else, I duly cited the references for the works I used in my thesis, I did not submit this thesis to another scientific committee for academic purposes and to obtain a title, in accordance with the articles 9/2 and 22/2 of the Sakarya University Graduate Education and Training Regulation published in the Official Gazette dated 20.04.2016, a report was received in accordance with the criteria determined by the graduate school using the plagiarism software program to which Sakarya University is a subscriber, I have received an ethics committee approval document.

(01/06/2023)

OMRAN TABAJOU

To the God, to those who I have always sought their satisfaction, rather than other people, I dedicate this research, to you: my mother and my late father, the dearest to my heart, may Allah bless his soul, To my virtuous teacher, Dr. Nükhet Sazak, who believed in me, supported me, helped me, and had all the credit for achieving the success I am celebrating today, To you, my family, my brothers, Dr. Adnan, Eng. Musa'ab, the beautiful and brilliant Daleen, the smart teacher, Rawa, Arc. Israa, and the tender hearted, Maysa, to my companion, and friend of all days, with their ups and downs, my sweetie wife, Eng. Reem, I dedicate this paper to you as a gesture of gratitude to your continuous support, To the childhood that filled my world and cheered my senses, to the most beautiful eyes of my children, To loyal close friends, my dear brother-in-law, Mr. Bassam, the lawyer Adnan and the engineer Anas, who have never ceased to provide help, assistance and support to me in the toughest circumstances, To those who feel happy to our success and saddened by our failure, I dedicate this thesis: to the relatives in heart, blood and loyalty.

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Omran Tabajou

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ABBREVIATIONS

WSN	: Wireless Sensor Network
OOK	: On-Off Keying
BPSK	: Binary Phase Shift Keying
IoT	: Internet of Things
RF	: Radio Frequency
SNR	: Signal-to-Noise Ratio
BER	: Bit Error Rate
UWB	: Ultra-Wideband
QAM	: Quadrature Amplitude Modulation
QPSK	: Quadrature Phase Shift Keying
PSK	: Phase Shift Keying
DBPSK	: Differential Binary Phase Shift Keying
LAN	: Local Area Network
RFID	: Radio Frequency Identification
DPSK	: Differential Phase Shift Keying
PRK	: Phase Reversal Keying
AWGN	: Additive White Gaussian Noise
ME	: Minimum Energy
BW	: Bandwidth
MSK	: Minimum Shift Keying
CPSK	: Continuous Phase Frequency Shift Keying
PA	: Power Amplifier
BS	: Base Station
QoS	: Quality of Service
PSD	: Power Spectral Density

SYMBOLS

S(t)	: Time-Domain Signal
t	: Time
A	: Amplitude
$\mathbf{f_c}$	: Carrier Frequency of the Signal
T	: Duration
a(t)	: Time-Domain Signal
$\mathbf{p(t-kT)}$	: Shifted Version of a p(t) by an Amount of kT Units in Time Domain
$\mathbf{a_k}$	: Constant Value
$\mathbf{P_b}$	: Bit Error Probability
Q	: Q-Function
$\mathbf{E_b}$	: Energy per Bit
$\mathbf{N_0}$	: Power Spectral Density of the Additive White Gaussian Noise
$\mathbf{P_{avg}}$	: Average Power
$\mathbf{R_b}$	: Bit Rate
$\mathbf{P_c}$	: Carrier Power
$\mathbf{E_{bit_{OOK}}}$	: Energy per Bit for an On-Off Keying (OOK) Modulation
$\boldsymbol{\alpha}$	: Modulation Index
$\mathbf{E_{bit_{BPSK}}}$	: Energy per Bit for Binary Phase Shift Keying (BPSK) Modulation
$\mathbf{P_{E_{OOK}}}$	: Average Power Consumption of the OOK Signal
BW	: Bandwidth of the Communication System
d	: Distance Between the Transmitter and the Receiver
$\mathbf{G_t}$	: Transmitter Gain
$\mathbf{G_r}$	: Receiver Gain
$\boldsymbol{\lambda}$	: Wavelength of the Carrier Signal
K	: Boltzmann's Constant
PAR	: Peak-to-Average Ratio
$\mathbf{P_{E_{BPSK}}}$	: Average Power Consumtion of the BPSK Signal

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THE COMPARISON OF ENERGY CONSUMPTIONS FOR OOK AND BPSK MODULATIONS IN WIRELESS SENSOR NETWORKS

SUMMARY

Given that the majority of sensor nodes in wireless sensor networks (WSNs) are battery-powered and have limited energy resources, energy efficiency is a crucial consideration. By putting appropriate strategies into practice, the energy efficiency of WSNs might be significantly increased and thus provided a longer network lifespan, lower maintenance costs, and better performance.

The energy efficiency of wireless sensor networks is significantly impacted by modulation. To achieve the optimal balance between energy economy and performance, the modulation method for a given WSN application relies on variables including energy consumption, transmission distance, interference, noise and bandwidth efficiency. BPSK (Binary Phase Shift Keying) and OOK (On-Off Keying) are two digital modulation methods used in WSNs.

For low-power wireless communication systems like WSNs, OOK modulation is a straightforward and effective modulation technique. It is a desirable alternative for WSNs thanks to its interoperability, affordability, and simplicity. OOK is a digital modulation method that sends binary data by switching the carrier signal on and off. Either the entire strength (ON) of the carrier signal is carried, or it is not transmitted at all (OFF). A binary 0 in OOK modulation is represented by the carrier signal being off, whereas a binary 1 is represented by the carrier signal being on. OOK is easy to use and effective in utilizing bandwidth, although it is sensitive to noise and interference and has a short range of transmission.

BPSK is another digital modulation method that transmits binary data using phase shift keying. A single bit is used in BPSK, a kind of Phase Shift Keying (PSK) modulation, to indicate two distinct carrier signal phases. A binary 0 in BPSK is represented by no phase shift, whereas a binary 1 is represented by a 180-degree phase shift of the carrier signal. Thanks to its simplicity and low energy consumption, it is preferred to be used in WSNs. In comparison to OOK, BPSK has a larger transmission range and is less vulnerable to noise and interference. It does, however, use more bandwidth than OOK.

In WSNs, OOK and BPSK are both often used depending on the application and particular requirements. OOK, for instance, may be employed in situations where energy efficiency is important, such in low-power gadgets with short battery lives. The usage of BPSK, on the other hand, may be appropriate in situations when a greater transmission distance is required, such as in extensive industrial monitoring systems.

In this thesis, the energy model of WSNs for BPSK and OOK modulation was reviewed, underlining how crucial they are for lowering power usage. The energy consumptions per bit (E_{bit}) of OOK and BPSK modulations were investigated for narrow bandwidth (< 50 kHz) and low data rate (< 50 kbps) WSNs with the propagation distance (d) no more than 150 meters in this study. For this purpose, the mathematical formulas and parameters which were previously published in the

literature were utilized. The energy consumption per bit (E_{bit}) versus propagation distance (d) graphs were obtained for three distinct bandwidth (BW) values (10 kHz, 25 kHz and 50 kHz) in the OOK and BPSK modulation schemes. From the comparisons of results, it was observed that BPSK became more energy efficient than OOK with the increase of the propagation distance. Then the critical propagation distance ($d_{critical}$) at which BPSK started to become superior to OOK in terms of energy consumption per bit was defined and derived mathematically. The contribution of this thesis is to propose a new concept defined as the the critical propagation distance ($d_{critical}$) at which BPSK starts to become more energy efficient than OOK and present a mathematical expression to determine $d_{critical}$ for any given bandwidth without any simulation requirement.

KABLOSUZ ALGILAYICI AĞLARDA OOK VE BPSK MODÜLASYONLARI İÇİN ENERJİ TÜKETİMLERİNİN KARŞILAŞTIRILMASI

ÖZET

Kablosuz algılayıcı ağlar (KAA'lar) düşük güçlü ve küçük boyutlu çok sayıda algılayıcı düğümden meydana gelmektedir. Kendi kendine organize olabilme, bakım gereksinimlerinin az olması, algılayıcı düğümlerin rasgele yerleştirilebilmesi özellikleri sayesinde KAA'lar; askeri uygulamalardan tarıma, sağlık uygulamalarından endüstriyel uygulamalara kadar bir çok farklı alanda uygulama potansiyeline sahiptirler. Geleneksel ağların kurulmasının zor olduğu yerlerde kullanılabilmesini sağlayan ve onları üstün kılan özellikleri, sınırlı enerji kapasitelerinin etkin kullanımı gerekliliğini de beraberinde getirmektedir. Algılayıcı düğümler genellikle enerji kaynağı olarak pil kullanmaktadırlar ve uzak veya erişimin zor olduğu yerlerdeki uygulamalarda pilleri şarj etme ya da değiştirme olanağı yoktur. Pili biten düğüm ölü varsayıldığından ve ağın ömrü düğümlerin ömrüne bağlı olduğundan kısıtlı enerji kapasitesinin etkin kullanımı en önemli tasarım ölçütlerinden biri olmasına yol açmaktadır.Bu yüzden enerji verimliliği, KAA sistem tasarımının önde gelen ölçütlerinden biridir.

Literatürde sınırlı enerji kaynağını etkin kullanmayı ele alan çok sayıda çalışma ve bu amaçla geliştirilmiş birçok protokol ve çözüm yer almaktadır. KAA'nın ömrü, düğümlerin kısıtlı güç kaynağının etkin kullanımına bağlı olduğundan enerji tüketimini azaltmak üzere önerilen çok sayıda ortam erişim kontrol (medium access control, MAC) protokolleri, kodlama teknikleri, çeşitli donanım ve yazılım geliştirme çalışmaları bulunmaktadır. Uygun stratejiler kullanılarak KAA'ların enerji verimliliği önemli ölçüde arttırılabilir ve böylece daha uzun ağ ömrü, daha düşük bakım maliyetleri ve daha iyi performans sağlanabilir.

KAA; güç, algılama, işlem ve haberleşme temel birimlerinin yanı sıra uygulama gereksinimlerine bağlı olarak konum izleme ve hareketlilik birimlerini de içerebilen çok sayıda algılayıcı düğümden meydana gelmektedir. Temel birimlerin enerji tüketimleri incelendiğinde en çok enerjinin haberleşmede harcandığı gözlenmektedir. Algılayıcı düğümlerin en fazla gücü haberleşme için harcadığı dikkate alındığında kullanılan modülasyon türünün önemi ortaya çıkmaktadır.

KAA protokol mimarisi; fiziksel, veri bağı, ağ, taşıma ve uygulama olmak üzere beş katman ile güç yönetim, hareketlilik ve görev yönetim olmak üzere üç düzlemden oluşmaktadır. Modülasyon, frekans seçimi, taşıyıcı frekans üretimi, işaret sezme ve veri şifreleme işlemleri fiziksel katmanda gerçekleştirilmektedir. Bu tez çalışmasında iki modülasyon türü (OOK ve BPSK) ele alındığından protokol yığının fiziksel katmanına yönelik bir çalışma sunulmaktadır.

OOK (On-Off Keying, Aç-Kapa Anahtarlama) ve BPSK (Binary Phase Shift Keying, İkili Faz Kaydırmalı Anahtarlama), çok sayıda modülasyon türü arasından basitlikleri ve düşük enerji tüketimleri nedeniyle KAA'larda tercih edilen iki sayısal modülasyon yöntemidir.

Taşıyıcı işareti açıp kapayarak (on ve off) ikili veriyi gönderen bir sayısal modülasyon yöntemi olan OOK modülasyonu, KAA gibi düşük güçlü kablosuz haberleşme sistemleri için kolay ve etkili bir modülasyon tekniğidir. OOK, taşıyıcı işareti açıp kapayarak (on ve off) ikili veriyi gönderen bir sayısal modülasyon yöntemidir. '0' biti taşıyıcı işaretin gönderilmemesi, '1' biti ise taşıyıcı işaretin gönderilmesi ile temsil edilir, kısacası taşıyıcı işaret ya iletilir (ON) ya da iletilmez (OFF). Birlikte çalışabilirliği, ekonomikliği ve basitliği sayesinde KAA'lar için arzu edilen bir alternatiftir. OOK, gürültü ve girişime duyarlı ve kısa iletim mesafesine sahip olmasına rağmen kullanımı kolay ve bant genişliği kullanımında etkindir.

BPSK, faz kaydırmayı kullanarak ikili veri ileten başka bir sayısal modülasyon yöntemidir. Faz Kaydırmalı Anahtarlamanın (Phase Shift Keying, PSK) bir türü olan BPSK'da tek bir bit iki farklı taşıyıcı işaret fazını göstermek için kullanılır. BPSK'daki '0' biti için faz kayması yokken, '1' biti için taşıyıcı işaret 180 derece faz kaydırılır. Basitliği ve düşük enerji tüketimi sayesinde KAA'lar için tercih edilmektedir. OOK ile karşılaştırıldığında BPSK, daha fazla iletim mesafesine sahiptir, gürültü ve girişime daha az duyarlıdır. Bununla birlikte OOK'dan daha fazla bant genişliği kullanır.

KAA'larda OOK ve BPSK her ikisi de uygulama ve özel gereksinimlere bağlı olarak sıkça kullanılmaktadır. Örneğin OOK, kısa pil ömürlü düşük güçlü cihazlar gibi enerji verimliliğinin önemli olduğu durumlarda kullanılabilir. Diğer yandan BPSK'nın kullanımı, kapsamlı endüstriyel izleme sistemleri gibi daha fazla iletim mesafesine ihtiyaç duyulan durumlarda uygun olabilir.

KAA'lar için önerilen çeşitli enerji modelleri vardır. KAA uygulamalarında enerji verimli sistem tasarlamak için algılayıcı düğümlerin RF mimarilerinin göz önünde bulundurulması gerekir. Literatürde KAA düğümleri için farklı sınıflı güç yükselteçleri (power amplifier, PA) olan dört RF mimarisi mevcuttur. Tezin konusu OOK ve BPSK modülasyonları olduğundan ilgili modülasyonlara dair enerji modellerine yer verilmektedir. Doğrusal ve doğrusal olmayan olmak üzere iki tür PA vardır. OOK ve BPSK doğrusal modülasyonlar olduğu için doğrusal PA mimarisi kullanılmaktadır. Bu tezde, 150 metreden fazla olmayan yayılma mesafeli, düşük bant genişlikli (< 50 kHz) ve düşük veri hızlı (< 50 kbps) KAA'lar için OOK ve BPSK modülasyonlarının bit başına enerji tüketimleri (E_{bit}) incelenmektedir. Bu amaçla literatürde daha önce yayınlanmış matematiksel denklemlere ve parametrelere yer verilmektedir. OOK ve BPSK modülasyonlarında üç farklı band genişliği (BW) değeri için (10 kHz, 25 kHz ve 50 kHz) bit başına enerji tüketiminin (E_{bit}) yayılma mesafesine göre (d) grafikleri elde edilmektedir. Sonuçların karşılaştırılmasından yayılma mesafesinin artışı ile, BPSK ve OOK enerji tüketim değerlerinin belirli bir noktada kesiştikten sonra BPSK'nın OOK'dan daha enerji etkin hale geldiği gözlenmektedir. Önceki çalışmalarda dar band genişlikli sistemlerde kısa mesafe haberleşme için OOK, uzun mesafe haberleşme için BPSK'nın optimal olduğu sonucuna varılmıştır. Fakat "kısa" ve "uzun" mesafe ile kastedilen belirli bir ölçü yoktur. Bu tez çalışmasında ise, band genişliği verildiğinde kısa-uzun mesafe ayrımının yapılabileceği sınır değer için kritik yayılma mesafesi tanımı önerilmektedir.

Bu tez çalışmasının amacı; her iki modülasyonun enerji tüketimlerinin aynı olduğu, diğer bir deyişle, kesişme noktasının olduğu yayılma mesafesi değerini belirlemektir.

Söz konusu yayılma mesafesi, kritik yayılma mesafesi (d_{kritik}) olarak tanımlanmakta ve matematiksel olarak ifade edilmektedir. Böylece düşük bant genişlikli (< 50 kHz) ve düşük veri hızlı (< 50 kbps) KAA'lar için yayılma mesafesinin altındaki ($d < d_{kritik}$) değerler için OOK'nın, yayılma mesafesinin üstündeki ($d > d_{kritik}$) değerler için BPSK'nın daha az enerji tükettiği sonucuna varılmaktadır.

OOK ve BPSK modülasyonları için veri hızları eşittir, band genişliği ve veri hızı arasındaki bağıntıdan hareketle ele alınan band genişliği değerleri (10 kHz, 25 kHz ve 50 kHz) için veri hızları hesaplanmakta ve kritik yayılma mesafeleri ile birlikte tablo biçiminde verilmektedir. Bu tablodaki sonuçlar incelenerek band genişliği ile yayılma mesafesi arasındaki ters orantılı ilişki ortaya koyulmaktadır.

Enerji etkin bir sistem tasarlarken uygulama gereksinimleri (band genişliği, veri hızı vb.) göz önünde bulundurulmalıdır. Yapılan teorik analize göre KAA uygulaması için band genişliği değeri verildiğinde OOK ve BPSK modülasyonlarının veri hızları aynı olmasına rağmen yayılma mesafesine göre daha az enerji tükettiği için hangisinin seçilmesi gerektiği tespit edilebilmektedir.

Bu tezin katkısı, BPSK'nın OOK'dan daha fazla enerji verimli olmaya başladığı yayılma mesafesi için krtitik yayılma mesafesi (d_{kritik}) olarak tanımlanan yeni bir kavram önerilmesi ve düşük bant genişlikli ve düşük veri hızlı KAA'lar için herhangi bir benzetim veya deney gereksinimi olmadan d_{kritik}'i göz önünde bulundurarak enerji tüketimini azaltmak için yayılma mesafesine göre BPSK ve OOK modülasyonlarından hangisinin tercih edilmesi gerektiğine ilişkin bir analitik ifade ortaya koyulmasıdır.

İleriki çalışmalarda dar band genişliği uygulamaları için yapılan bu analizler orta ve geniş band genişlikleri için de yapılabilir. OOK ve BPSK modülasyonlarının ele alındığı bu tez çalışması diğer modülasyon türlerini dahil ederek genişletilebilir.

1. INTRODUCTION

A novel type of wireless networks known as wireless sensing networks (WSNs) is quickly gaining popularity with both military and commercial uses. Several autonomous sensing devices are dispersed over a wireless network called a wireless sensor network (WSN) and are used to monitor environmental or physical variables. Small, linked sensing devices that may exchange data and communicate with one another make up a wireless sensor network (WSN). These sensors gather information about the surrounding environment, such as temperature, pressure, humidity, and pollutant levels, and send it to a base station. The latter either sends the information to a network that is linked or initiates an alarm or an action, depending on the kind and volume of data being observed.

Significant progress has been made in the field of wireless sensing networks over the past three decades. Diverse fields, including error-correcting coding, networked systems, and alternative modulation schemes, have made progress. Further consideration is given to the latest innovation aimed at enhancing the modulation approach that has been in use until recently. It includes aspects of the design of the WSN's environment, such as how to lower energy consumption using the modulation schemes for WSN communication.

In this thesis, an overview of OOK and BPSK are going to be studied and they are going to be compared in terms of energy consumption per bit. The approach used during the analytical study is described in detail and the results are obtained for OOK and BPSK modulations.

First of all the energy efficiency in WSN networks is mentioned during this thesis, how could it affect the quality of the network drastically, and how the modulation techniques are an essential part in any wireless sensor network. The literature review that is shown in chapter 2 expresses how the modulation schemes are studied in the literature while taking into consideration BPSK, OOK and other modulation techniques and why it's considered to be among the most crucial stages in creating a wireless sensing network. Then the BPSK and OOK are explained in detail in terms of their operating principles, the reason choosing them, their advantages and disadvantages, and their applications. The next part which is chapter 3 is aimed at the theoretical and practical side of the thesis it starts with explaining the energy model used in the analytical study and how the energy consumption might become a significant problem due to the low-battery power and how the suggested modulation schemes can help with this issue then, in order to choose the best modulation method to use between the suggested first of all some mathematical equations are investigated. The energy consumption per bit (E_{bit}) for OOK and BPSK modulations are examined for narrow band and low data rate WSN applications. The parameters used in the analytical study are shown using a table, then the numerical analysis and the theoretical calculations are done in scope of the parameters, the analytical study shows the energy consumption and which modulation technique is better for narrow band applications and low data rate WSN applications. Chapter 4 presents the conclusions of this dissertation and also points out some opinions to be considered in future research.

2. OOK AND BPSK MODULATIONS FOR WSNS

WSNs and wireless ad hoc networks have a similar autonomous network structure that allows sensor data to be sent wirelessly as well as wireless connection. WSNs really function as decentralized autonomous sensors that can keep an eye on or oversee environmental and physical conditions. In a fashion that transmits their data over a created network to a central place, they may all be natural phenomena, such as temperature, sound, pressure, etc. Instances of WSNs to serve as example is given in (Figure 2.1.)[1].

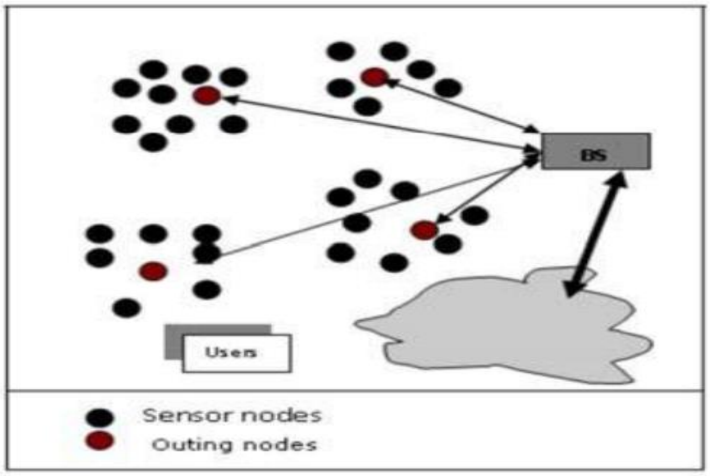

Figure 2.1. An illustrative structure of Wireless Sensor Networks [1].

One strategy to improve energy efficiency in WSNs is by optimizing the modulation scheme used for communication between sensors. Modulation schemes determine how information is encoded and transmitted over the wireless channel, and they significantly affect how much energy is used of WSNs. In this literature review, we will focus on two modulation schemes commonly used in WSNs: On-Off Keying (OOK) and Binary Phase Shift Keying (BPSK).

The choice of modulation scheme in WSNs depends on the specific application requirements and the trade-off between energy efficiency and data rate. OOK is a simple and energy-efficient modulation scheme for low data rate applications, while BPSK is a more spectrally efficient modulation scheme suitable for high data rate applications.

2.1. Energy Efficiency in WSNs

Since many strategies have been put out in recent years and there is a large number of current studies on how to save energy in WSNs. The application-specific details, however, are not systematically taken into account by these solutions. It is clear that the WSN services, some applications, such as those in agriculture, where the delay feature is less crucial, do not require quick and prompt reaction, for instance. According to our opinion, WSN energy-saving issues should be resolved by more systematically taking into account application requirements.

Due to its relevance in a broad range of situations, applications for traffic management, object tracking, environmental monitoring, and health applications, among others, wireless sensor networks (WSNs) have seen an increase in attention over the past ten years. Reducing the energy consumption in WSNs is crucial to increasing the network's lifespan since it is sometimes difficult and expensive to repair defective sensors once they have been installed [2]. The period of time before any or a specific number of devices in a sensor network expire is known as the "lifetime" of the network. Since the IoT (Internet of Things) has gained widespread acceptance for its enormous potential in many facets of contemporary life, modern agricultural infrastructure now includes vital and valuable components like sensors, wireless networks, and software applications. Strong analytical tools can provide details on the most effective agro-technical initiatives required for providing the best circumstances for production and quality based on the data acquired. When data analysis is paired with information from many sources, it is possible to predict potential dangers, offer a variety of explanations for what occurred, and make suggestions for how to proceed.

In several industrial and non-industrial application domains, such as industrial process monitoring and control, machine status monitoring, environment and habitat monitoring, wireless sensor networks (WSNs) are frequently employed, applications in healthcare, automation of homes, and traffic control, thanks to the quick development of wireless communication and low-power embedded techniques [3]. It is clear that the WSNs are becoming more common and they are going to change humans' lives.

It is crucial to create an energy-efficient system because the majority of wireless sensing nodes are powered by batteries, which have a finite amount of energy. For using wireless sensor networks (WSNs) of battery-powered nodes in particular, where energy efficiency directly impacts the network's lifetime, energy-efficient techniques are of utmost significance. This point becomes even more important when WSNs are used to monitor remote, challenging-to-access regions where battery replacement is prohibitive or impossible [4].

Wireless communication and mobile computing devices are widely used in everyday life. All of these devices are powered by batteries with a limited lifetime. Since the advances in battery technology have failed to keep up with increasing current consumption in mobile communication devices, aggressive techniques to reduce the power consumption of wireless communication devices have to be developed [5]. When communicating across short distances, OOK is the most energy-efficient modulation scheme. The long- and short-term objectives are not apparent, nevertheless.

According to (Figure 2.2.), a standart sensor node is shown as electronic device that consists of a computational component and a transmission mechanism, one or more sensing components, and a power unit. A mobility module or/and a location tracking module are examples of extra equipment that might be included [2] and [3].

A sensor node collects information about its surrounding circumstances using its sensing components. A sensor node also makes use of its communication module to wirelessly sharing data with the base station (BS) and other sensing networks, as well as its processing unit to manage the data it gathers. Usually, the power source is a battery. The sensor node's present location is tracked by the position tracking module. The mobility unit also enables portability.

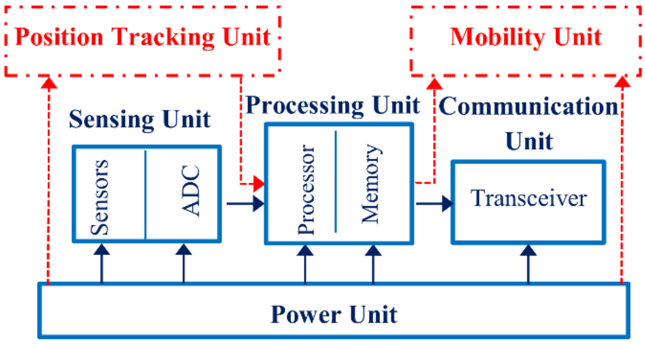

Figure 2.2. Typical architecture of a wireless sensor node [6].

In a WSN, the so-called protocol stack controls how both sensing nodes and the BS(s) operate. The protocol stack is made up of five layers, as depicted in (Figure 2.3.) the physical, data link, network, transport, and application layers [6].

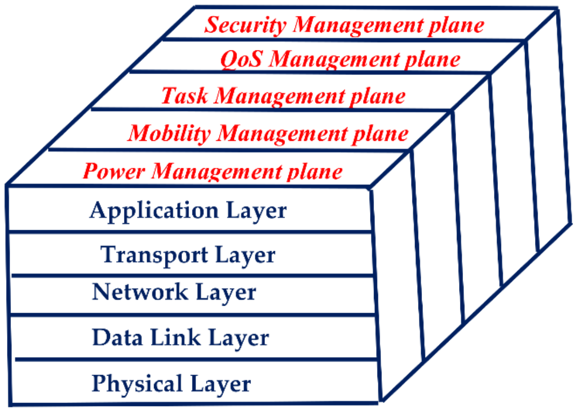

Figure 2.3. Protocol stack of a wireless node [6].

The physical layer specifically handles modulation, transmission, and receiving duties like choosing a communication frequency, producing a carrier frequency, detecting and modulating signals, and encrypting data. To accomplish reliable point-to-point and point-to-multipoint links, the data link layer takes care of data frame recognition, data stream merging, medium access, and error management. Data provided by the transport layer is routed by the network layer. The data movement retention is the responsibility of the transport layer. The layer that customizes its material to fit the requirements of each unique application is known as the application layer. The protocol stack also has five administration layers that aim to operate a WSN as efficiently as possible in terms of the related performance measures. Quality of service (QoS), security management plane, task management plan are specifically mentioned in [7].

2.1.1. The Impact of Modulation on Energy Efficiency for WSNs

Data is converted into radio waves by a process called modulation, which includes combining information into an electrical or visual carrier signal. A carrier signal is a steady pattern with a fixed height, or amplitude, and frequency. Information may be added to a carrier by altering its amplitude, frequency, phase, polarization for visual signals, and even quantum-level processes like spin. Low-frequency electromagnetic transmissions such as radio waves, lasers/optics, and computer networks may also be modulated. Even direct current, which may be used for telegraphy in Morse code or a digital current loop interface, can be modulated by turning it on and off. This direct current can be thought of as a degenerate carrier wave with a fixed amplitude and frequency of 0 Hz. Baseband modulation is the specific circumstance when there is no carrier a response message signaling an attached device is no longer linked to a distant system. As with powerline networking, modulation may also be used with low-frequency alternating current (50–60 Hz).

Radio frequency (RF) communications employ a carrier wave, which carries very little information by itself. The carrier wave must be overlaid with another wave in order to carry voice or data, modifying the carrier wave's structure. Modulation is the term used to describe this action. The audio signal must first be transformed into an electric signal using a transducer in order to convey sound. It is used to modify a carrier signal after conversion.

Wireless Sensor Networks (WSNs) are composed of energy-limited nodes that are deployed to collect and sense data from the environment. One of the fundamental challenges in WSNs is the limited energy available to each node, which constrains the network lifetime and reliability. The choice of modulation scheme used in WSNs has a direct effect on each node's energy use and, consequently, the total network lifetime.

The energy consumption of a node in a WSN can be divided into several components, including sensing, processing, communication, and idle listening. Modulation scheme impacts the energy consumption in the communication component of a node. In general, higher-order modulation schemes (e.g., 16-QAM) require higher signal-to-noise ratios (SNR) to achieve the same bit error rate (BER) as lower-order modulation schemes (e.g., BPSK). Therefore, higher-order modulation schemes generally require higher transmission power, which leads to higher energy consumption in the transmitter. Moreover, higher-order modulation schemes require more complex receiver circuits, which consume more energy in the receiver.

On the other hand, using lower-order modulation schemes like BPSK or OOK can reduce the energy consumption in both the transmitter and receiver of a node. However, using lower-order modulation schemes may result in lower data rates and lower spectral efficiency, which can affect the network performance.

In summary, the choice of modulation scheme in WSNs has a direct impact on the energy consumption of each node and thus on the overall network lifetime. The relationship between energy and modulation in WSNs is a trade-off between achieving higher data rates and spectral efficiency with higher-order modulation schemes, and reducing energy consumption and extending network lifetime with lower-order modulation schemes. The particular modulation method selected will rely on the particular application needs, such as data velocity, range, and energy economy.

Collection of nodes known as a wireless sensor network (WSN) can detect external occurrences and send the data they collect. Cluster head connects the sensing node to the base station.Both fixed and moving nodes are possible. It could or might not be aware of where they are. And they may or may not be homogenous. A lot of studies has gone into developing a transmission system that uses less energy and adjusting physical layer characteristics to lengthen the lifespan of sensor networks. The energy needed to transmit an event felt in order to examine the function of modulation and coding technique to increase the lifespan of sensor node.

Energy efficiency is a critical concern in Wireless Sensor Networks (WSNs) due to the limited energy resources of sensor nodes. On-Off Keying (OOK) and Binary Phase Shift Keying (BPSK) are two modulation schemes used in WSNs that can improve energy efficiency. One approach to improving energy efficiency in WSNs is to reduce the energy consumption during transmission. OOK modulation is a non-coherent modulation scheme that requires less energy for transmission than other modulation schemes, making it a popular choice in WSNs. However, OOK modulation is less robust in the presence of noise and interference, which can affect its reliability.

BPSK modulation, on the other hand, is a coherent modulation scheme that is more robust in the presence of noise and interference. BPSK requires more energy for transmission than OOK, but it can achieve higher data rates with improved reliability, making it a suitable choice for applications that require high throughput and reliable communication.

Another approach to improve energy efficiency in WSNs during idle listening is reduce the energy consumption. In OOK modulation, the energy consumption during idle listening can be reduced by using duty cycling techniques to turn off the radio when it is not needed. Duty cycling can significantly reduce energy consumption but can also affect network performance by introducing latency and reducing throughput.

In BPSK modulation, the energy consumption during idle listening can be reduced by using power management techniques to optimize the energy consumption of the power amplifier. Power management techniques can improve the energy efficiency of BPSK modulation by reducing the energy consumption during idle listening without affecting the network performance.

Overall, both OOK and BPSK modulations can improve energy efficiency in WSNs in different ways. The choice of modulation scheme depends on the specific requirements of the application, such as the data rate, reliability, and energy consumption. All of the sensor nodes in a cluster must employ the same power-efficient modulation algorithm in a sensor network for the cluster to operate with sufficient energy. The modulation and coding processes are crucial in increasing the bandwidth and energy efficiency of wireless networks. The lifespan of a sensor network is particularly dependent on the energy use of the transceivers.

It is crucial to create an energy-efficient system because the majority of wireless sensing nodes are powered by batteries, which have a finite amount of energy. Since wireless sensor networks consist of battery-powered nodes and the lifetime of WSNs are affected by the use of those limited energy resources, energy efficiency is crucial. This point becomes even more important when WSNs are used to monitor remote, challenging-to-access regions where battery replacement is prohibitive or impossible [4]. Since the battery technology could not satisfy the increasing current consumption demand of communication devices completely, novel and aggressive techniques are required to reduce power consumption of them [5].

Binary Phase Shift Keying (BPSK) modulation is considered the most energy-efficient modulation scheme for short-range communication. This distinction makes it stand in comparison to On-Off Keying (OOK) and other modulation techniques, particularly for narrow bandwidth systems. When the bandwidth is held constant, BPSK modulation outperforms OOK and maintains its efficiency. The definitions of long and short range are not clear enough.

2.2. Some Modulation Schemes in WSNs

Different facets of low-power approaches have been studied for WSN in recent years. These include an energy-efficient cooperative and a delay-controlled transmission method [8]. Communication in WSN [9], modulation scaling with low energy consumption [10–13], routing algorithms with low energy consumption [14–16], job scheduling for digital communication processors based on power management [17], and optimum cross-layer energy [18]. However, the majority of earlier research frequently ignores or oversimplifies the power wasted in RF and analog circuits to constant levels. Since the RF and the handling of high-frequency analog signals by analog components, which often use more energy than the digital component, might lead to erroneous energy estimates. According to [19], the RF front end dissipates around 75% of the overall power.

The literature presents several energy models that have been developed for WSNs [20–22]. To decrease a transceiver's total energy usage, precise energy models must be developed for each of the main signal processing steps. In [8], the energy models for RF front ends used in Wi-Fi applications are given by providing data about energy consumption of each component. There are four types of RF front-end architectures with different classes of power amplifiers for WSN nodes [23]. In this thesis, the linear power amplifier (e.g. Class A) is adopted in OOK and BPSK modulations which are both linear modulation systems.

OOK is the most fundamental digital modulation scheme. It provides energy efficiency by consuming energy only during ‘1’ bit transmission and switching off the transmitter while ‘0’ bit transmission. Addition to its efficiency, cost efficiency and low complexity makes it a good candidate modulation for WSNs [24].

Binary phase-shift keying (BPSK), a digital modulation method, conveys data by modulating two unique phases of a reference signal (the carrier wave). Normally, the constellation's points are positioned equally all around a circle. The maximum phase separation between neighboring locations is supplied by this, which offers the best corruption protection. They are organized in a circle so that they may communicate with one another using the same energy. The sine and cosine waves' needed amplitudes and the moduli of the complex numbers they represent will both be the same as a result of this [25].

As for [26] it concluded that when compared to narrow bandwidth modulation methods, the use of UWB modulation techniques is more appropriate for the WSN. After realizing a physical-layer basic, linear working model of the wireless sensor network using UWB modulation techniques, there is opportunity to further develop the WSN model by adding a fixed multidimensional structure.

To increase the energy efficiency, bandwidth efficiency, and lifespan of the sensor nodes under various channel circumstances, researchers examined the effectiveness of various encoding schemes and error correction codes for sensor networks.There are numerous academics working on innovations linked to various levels of the sensing network protocol right now. The need to consider more effective modulation and coding design and operation arises from the nature of energy constraints in the paper of [27] investigated the transmission method and modulation methods such BPSK, MSK, and QAM to increase bandwidth and energy efficiency in fault tolerant wireless sensor networks for landslide area monitoring. The total energy consumption includes both the energy that is transmitted and the energy used in circuits. On the basis of how much energy each modulation technique uses at the transceiver node, they are contrasted. The scientists also examined suitable homogeneous and heterogeneous modulation techniques to raise the wireless sensor network's energy and bandwidth effectiveness [28].

WSNs, or wireless sensor networks, are gaining popularity in a variety of uses, such as environmental tracking health care and industrial automation. In WSNs, the performance of the network is significantly influenced by the modulation method that is utilized for communication, especially in terms of energy consumption, data rate, and reliability. The review of the literature will look at some new studies on the application of modulation techniques in WSNs.

In another study, the performances of two modulation schemes, BPSK and OOK, were compared in a WSN used for indoor localization [29]. They evaluated the performance of each modulation scheme in terms of energy consumption, localization accuracy, and robustness to interference. The results showed that BPSK had lower energy consumption and higher localization accuracy than OOK.

An adaptive modulation scheme that can dynamically adjust the modulation scheme based on the channel conditions was proposed for WSNs [30]. The proposed scheme was designed to be energy-efficient while providing high data rates. The authors evaluated the performance of the adaptive modulation scheme in terms of energy consumption, data rate, and packet delivery ratio. The results showed that the adaptive modulation scheme outperformed other fixed modulation schemes regarding energy consumption and packet delivery ratio.

In [31], MATLAB SIMULINK was used to demonstrate the modulation and demodulation of BPSK technique. The information signal was defined as input binary bit sequence (ones and zeros), the carrier signal was generated randomly. The five kinds of bit sequences (two, four, six, eight and ten) were used and the BPSK modulated signal outputs were given with the input and carrier signals.

In conclusion, several recent studies have analyzed the performance of different modulation schemes in WSNs and proposed novel modulation schemes and adaptive schemes to improve the energy efficiency, data rate, and reliability of WSNs. The choice of modulation scheme in WSNs depends on several factors, including the data rate, energy consumption, and range requirements of the application. Therefore, choosing an appropriate modulation scheme is a critical design decision in WSNs, and more research is needed to explore new modulation schemes that can improve the network performance further.

2.3. Binary Phase Shift Keying (BPSK) Modulation

A digital modulation method called phase-shift keying (PSK) conveys data by changing (modulating) the phase of a reference signal with a predetermined frequency (the carrier wave). To create the modulation, the sine and cosine sources are altered at the ideal time. It is often used for wireless LAN, Bluetooth, and RFID transmission.

A limited number of unique impulses are used by every digital modulation method to symbolize digital data. PSK employs a limited number of stages, each of which is given a particular binary character sequence. Typically, an identical amount of bits are encoded in each step. Each bit sequence creates a sign that corresponds to a specific period. Determining the phase of the incoming signal and mapping it back to the symbol it symbolizes, the demodulator, which was created especially for the symbol-set used by the modulator, recovers the original data. This necessitates the receiver's ability to match the received signal's phase to a reference signal; such a system is known as consistent and referred to as Continuous Phase Frequency Shift Keying (CPSK).

Because it must take the reference wave from the received signal and keep note of it to compare each sample to, CPSK necessitates a complex demodulator. Instead, it is possible to gauge each symbol's phase change in relation to the one that came before it. This process is known as differential phase-shift keying (DPSK) because the signals are stored in the change in phase between subsequent examples. Due to the fact that DPSK is a "non-coherent" algorithm and does not require the demodulator to maintain track of a reference wave, it can be implemented much more quickly than conventional PSK. It has more demodulation mistakes as a trade-off.

BPSK, also referred to as phase reversal keying (PRK) or 2-PSK, is the most basic type of phase shift keying (PSK). Due to the fact that it uses two stages that are 180 degrees apart, it is also known as 2-PSK. Since their exact locations are not very significant, the celestial positions at 0° and 180° on the real axis. As a consequence, it can handle the most noise or distortion before the demodulator chooses incorrectly. It is the strongest PSK there is as a result. It cannot, however, be utilized for quick data-rate applications since it can only alter at 1 bit per character.

Despite this, it is still possible to enlarge this bit or symbol due to the modulators' symbol encryption and decoding logic design.

When the data path has included a random phase-shift, the demodulator (see, for instance, Costas loop) is unable to discriminate between two star points. As a result, differential encoding on the data is typically done before modulation.

Functionally equivalent, also BPSK and 2-QAM modulation are the same. Information is conveyed in terms of carrier phase in any phase modulation technique. The carrier signal's phase is adjusted in accordance with the binary input data. In the two-state phase shift keying (PSK), also known as BPSK, approach, the radio carrier's phase is either set to 0 or depends on the value of the incoming bit. The transmit symbol produced by each bit of the digital signal has a duration T_s equal to the bit duration T_b.

When two bits are concatenated and the radio carrier is phase-modulated using one of the four possible patterns for two bits, this is known as four-state or quadriphase PSK, or QPSK. The bandwidth efficiency of QPSK is twice that of BPSK because a symbol transmits twice as slowly as a bit ($T_s = 2T_b$).

The ratio of erroneous bits to the total number of bits is known as a communication system's bit error rate (BER). Independent of transmission rate, it is the probability that one or more received bits might contain an erroneous bit. BER can be decreased in a variety of methods. Figure 2.4 shows BER plot for BPSK modulation.

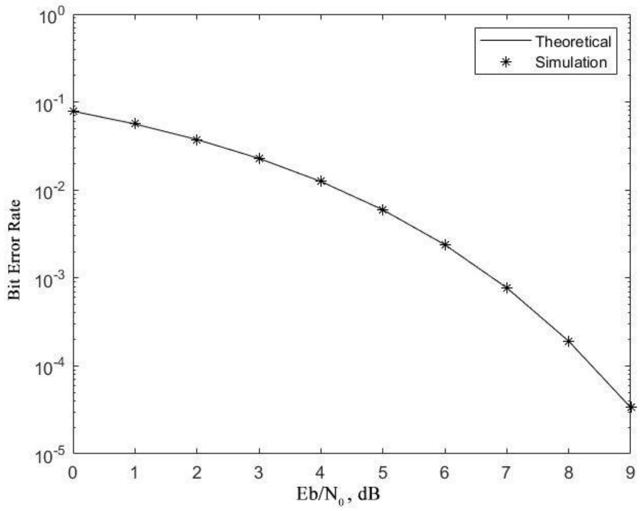

Figure 2.4. BER for BPSK modulation.

There are several approaches to imitate a channel in mobile communications. The impacts of multipath dispersion, fading, and Doppler shift brought on by the relative velocity of the emitter and the recipient are a few of the most important things to consider. The two most popular channels are the Additive White Gaussian Noise (AWGN) and the Rayleigh fading channel. In this thesis, the AWGN channel which disperses noise over the entire frequency range is assumed.

BPSK is the simplest variation of PSK. Figure 2.5. demonstrates how BPSK sends a binary (0 and 1) digital signal by setting the carrier phase to 0. (Figure 2.6.) depicts the BPSK modulator's configuration. One bit of data is sent per symbol in the BPSK system. BPSK is resistant to level fluctuation on the transmission line since information is sent by phase.

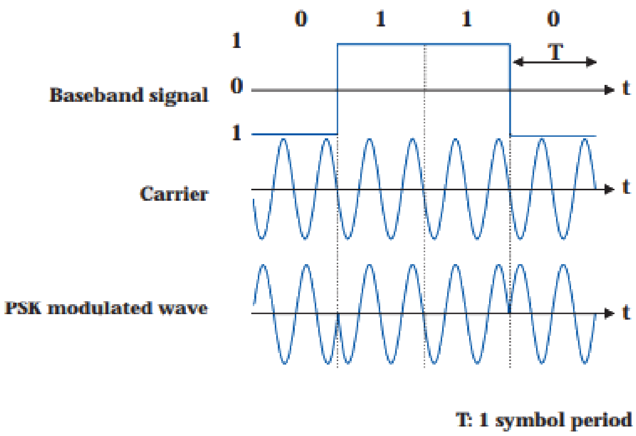

Figure 2.5. BPSK modulated waveform [32].

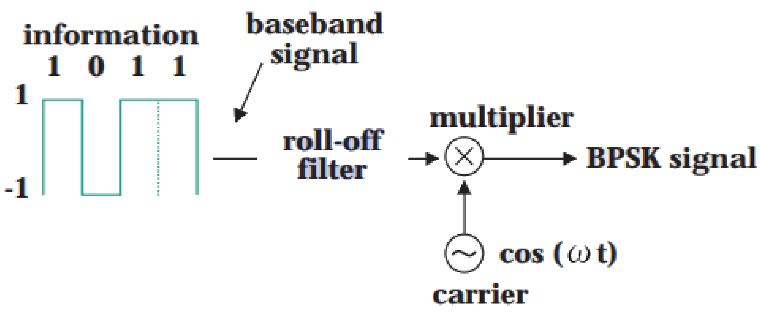

Figure 2.6. Depicts the BPSK modulation process [32].

The baseband signal's spectrum is equivalent to that of the BPSK signal, as illustrated in (Figure 2.7.), despite being shifted (minus side included) to the carrier frequency. Therefore, BPSK has a twice as wide bandwidth as baseband.

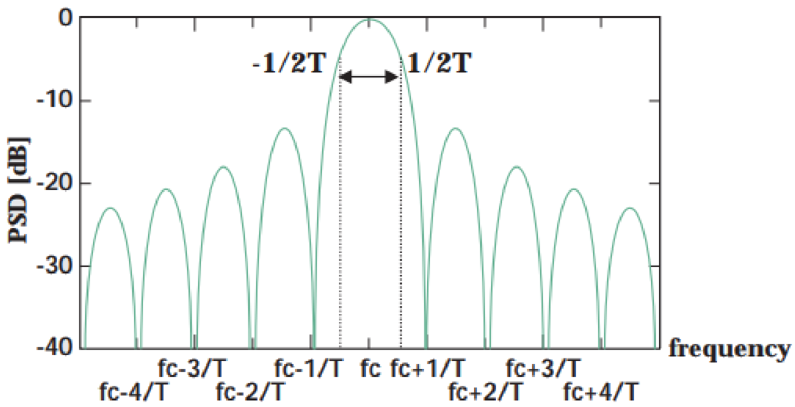

Figure 2.7. Power Spectral Density (PSD) of BPSK [32].

Observation shows that the carrier signal's initial shape and form are followed by the BPSK modulated signal. The BPSK modulated signal differs from the carrier signal in that the shape changes in response to the input binary bit response. The graphs in figures (2. 8., 2.9.) illustrate how the binary bit response goes from one to zero when the BPSK modulated signal exhibits a cut-off positive signal. On the other hand, when the binary bit response shifts from zero to one, the BPSK modulated signal exhibits a cut-off negative signal. It should also be observed that the carrier signal and the BPSK modulated signal are 180 degrees out of phase when the binary bit is 1. The two signals are in phase when the binary bit is zero.

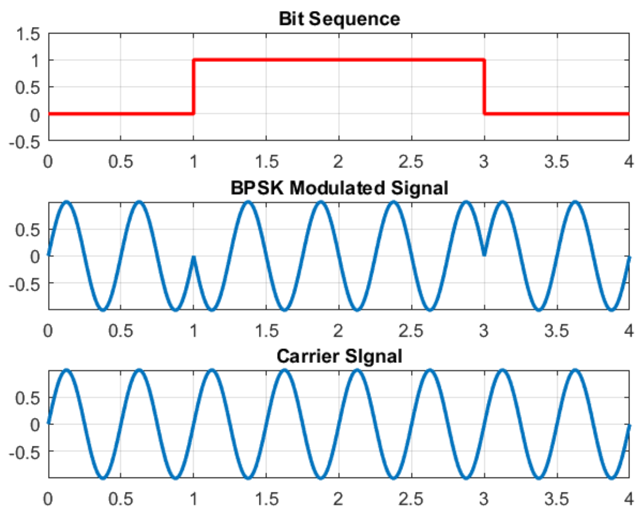

Figure 2.8. 4 bit binary sequence shown on a generated plot. Carrier and BPSK-modulated signals.

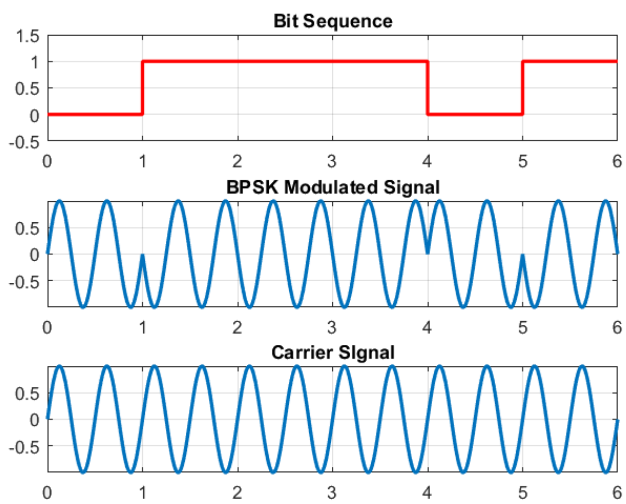

Figure 2.9. 6 bit binary sequence shown on a generated plot. Carrier and BPSK-modulated signals.

The BPSK bandwidth for a roll-off filter is (1+)r when the symbol rate is r (=1/T) and the roll-off rate is r. Demodulation by coherent detection just reverses the modulation process, as seen in the carrier recovery circuit recovers the carrier from the received signal after removing the modified and noise components. In order to retrieve the baseband signal, the system multiplies the received signal by this carrier. The baseband signal is then sent into a clock recovery circuit in order to recover the same clock as that on the modulator side. The system samples the baseband signal using this clock, determining if the symbols are 0 or 1, and then restoring the digital signal. As seen in (Figure 2.10.), demodulation by incoherent detection, on the other hand, uses the received signal that has been delayed by one symbol as the reference phase and multiplies the received signal by it to produce the baseband signal. Terrestrial mobile transmissions commonly employ incoherent detection because carrier recovery is challenging owing to significant amplitude changes brought on by fading effects. The bit error characteristics are worse than those of coherent detection in this case because the signal itself, which contains noise and distortion, is employed as the reference phase. Additionally, differential code conversion must be carried out on the transmit side prior to modulation since the information is conveyed as a phase difference in reference to the preceding signal.

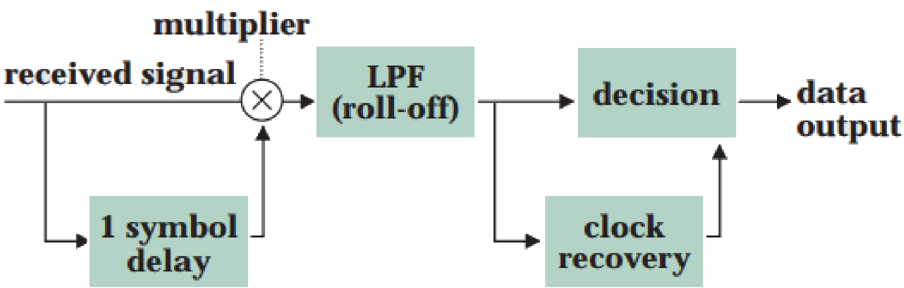

Figure 2.10. BPSK demodulation by incoherent detection [32].

In BPSK, binary data is expressed by two signals that have various phase differences. These two phases are typically 0 and π, and the signal are

$$s_1(t) = A\cos 2\pi f_c t, \qquad 0 \leq t \leq T, \qquad \text{for } 1 \tag{2.1}$$

$$s_2(t) = -A\cos 2\pi f_c t, \qquad 0 \leq t \leq T, \qquad \text{for } 0 \tag{2.2}$$

These signals are known as antipodal. They were selected because they have a correlation value of -1, which results in the least amount of inaccuracy for a given E_b/N_o. The frequency and energy of these two signals are identical.

The modulator that creates the BPSK signal is quite straightforward. A bi-polar data stream a(t) is first created. Deriving from the binary data stream

$$a(t) = \sum_{k=-\infty}^{\infty} a_k p(t - kT) \tag{2.3}$$

where $a_k \in \{+1, -1\}$, the rectangular pulse with unit amplitude specified on (0, T) is known as p (t). Then, A $\cos 2f_c t$, a sinusoidal carrier, multiplies a (t). The BPSK signal is the outcome [33].

A sinusoidal carrier is an example. Its polarity will be reversed each time the bit stream switches polarities if it is modulated by a bi-polar bit stream in accordance with the configuration shown in (Figure 2.11) below. This is comparable to a phase reversal for a sinewave (shift). BPSK is the signal output of the multiplier.

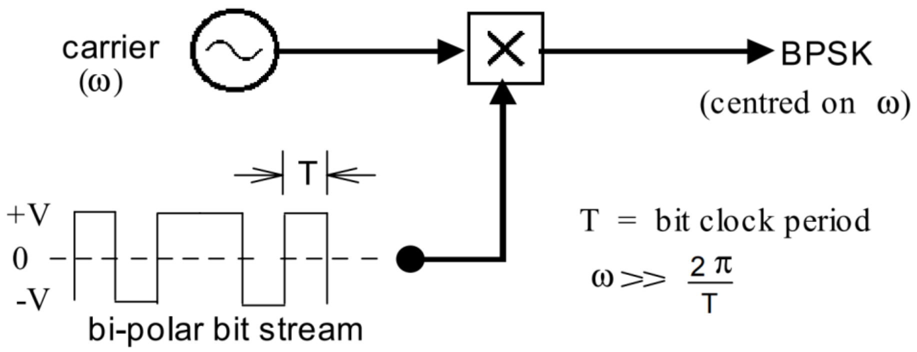

Figure 2.11. Generation of BPSK [34].

The transmitted signal's phase alterations hold the information about the bit stream. These phase reversals would be noticeable by a synchronous demodulator. In (Figure 2.12)'s lower trace, a BPSK signal can be seen emerging in the time domain. The binary message sequence is shown on the upper trace.

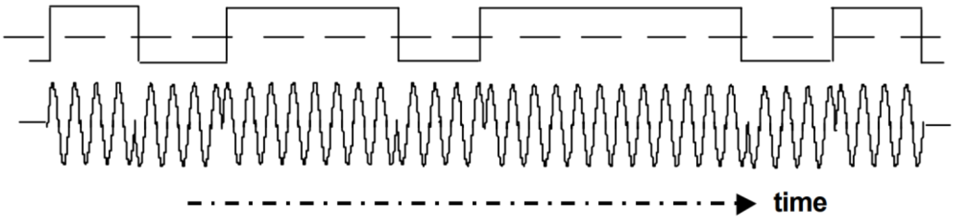

Figure 2.12. BPSK signal in the time domain [34].

2.4. On–Off Keying (OOK) Modulation

OOK is the simplest digital modulation scheme and it provides energy efficiency by switching off the transmitter while transmitting the ‘0’ bit. The energy is only consumed during the ‘1’ bit transmission. Besides its energy efficiency, OOK is cost efficient and less complex than the other modulation schemes. Thanks to these advantages, it is a good candidate as a modulation for WSNs [24].

OOK is a form of amplitude shifting key modulation the data are presented as present or absent the data are presented in binary 1 for present and 0 for absent, OOK is a modulation scheme that consists of keying a sinusoidal carrier signal on and off with a unipolar binary signal.

So OOK is used to limit the power consumption after using the ME coding because the ME increases number of transmitted bits which uses more power and that contradicts with the purpose of out algorithm, OOK came to reduce power consumption by transmitting only when there is high bits 1 and not transmitting when there are low bits 0 hence the On-Off name which means that when 0 = low bits = off

1 = high bits = on.

The OOK signal set is:

$$s_1(t) = A\cos 2\pi f_c t, \qquad \text{for } a = 1, \qquad 0 \le t \le T, \tag{2.4}$$

$$s_2(t) = 0, \qquad \text{for } a = 0, \qquad 0 \le t \le T, \tag{2.5}$$

where a is the binary data, which are considered equally probable and uncorrelated. Across the full time axis, the OOK signal's complex envelope is:

$$\dot{s}\,(t) = \sum_{k=-\infty}^{\infty} A_k p(t - kT) \quad -\infty < t < \infty \tag{2.6}$$

where $A_k \in \{O, A)$, p(t) is a rectangular pulse with unit amplitude. Since m_A= A/2 and $\sigma_A^2 = A^2$ /4. P($\frac{k}{T}$) = 0 except for k = 0.

The symbol error probability for coherent demodulation of OOK can be obtained with $E_{avg} = E_b$, the BER expression for binary signaling. That is

$$P_b = Q\left(\sqrt{\frac{E_b}{2N_0}}\right) \tag{2.7}$$

This modulation decreases the power used in the device significantly that is the reason why it is preferred.

3. THE COMPARISON OF ENERY CONSUMPTION FOR OOK AND BPSK

Various energy models can be used to evaluate and improve a variety of transmission systems, including digital encoding methods like OOK (On-Off Keying) and BPSK (Binary Phase Shift Keying). In this chapter the energy model used for OOK and BPSK modulation schemes are going to be explained with their mathematical equations and the parameters used in the analytical analysis. The detailed diagrams produced by the analysis are also presented in this chapter.

3.1. Energy Model

At the moment, homes, buildings, parks, and cities as a whole all have many electronic gadgets that utilise various wireless technologies. The right set of standards and protocols to be utilized depends on the kind of application. The energy requirement is one of these wireless gadgets' key qualities.

Devices used in Wireless Sensor Networks (WSNs) have compact nodes, low energy consumption, short battery life, minimal job processing, and little storage space. The deployment and implementation of these self-configuring networks are simple. Communication across channels with many interferences and computation power requirements are analyzed in these networks. In order to utilize the least amount of energy and offer meaningful information for a long time, sensor networks should execute optimally with fewer delays and trustworthy information [35].

However, due of the limited battery power, energy consumption might become a significant concern. Due to the harsh environment of certain of their applications, such as in the study of natural behavior, danger regions, medical sector, demotics, agriculture, battlefields, and home networks, the nodes' life cycle should be as long as possible in order to reduce unnecessary human participation [36].

The deployment of sensor networks must be straightforward, long-lasting, and adaptable to topology or configuration changes, therefore energy consumption considerations are crucial. These elements, which are all represented by a network's performance metrics, have a substantial impact on how much energy it uses.

OOK (On-Off Keying) and BPSK (Binary Phase Shift Keying) are two commonly used digital modulation techniques in communication systems. In this study, these two modulation techniques for sensor networks are compared with the aim of quantifying energy consumption during the execution of the main tasks of a node within a network. The energy models for OOK and BPSK are given in the following subsections, respectively.

3.1.1. Energy model for OOK

In OOK, the amplitude of the carrier signal is varied between two levels to represent digital information. It is assumed that the bit duration is T. In OOK, there are two possible signal levels: a high-level signal with amplitude A and a low-level signal with amplitude 0. Thus, the average power of the transmitted signal can be expressed as:

$$\mathrm{P_{avg}} = \frac{\mathrm{A^2T}}{2} \tag{3.1}$$

The energy per bit (E_b) can be calculated by dividing the average power by the bit rate (R_b):

$$\mathrm{E_b} = \frac{\mathrm{P_{avg}}}{\mathrm{R_b}} = \frac{\mathrm{A^2T}}{\mathrm{2R_b}} \tag{3.2}$$

3.1.2. Energy model for BPSK

To represent digital information in BPSK, the carrier signal's phase is 180 degrees shifted. It is assumed that the carrier signal has a power of P_c and the bit duration is T. In BPSK, there are two possible phase shifts: 0 degrees and 180 degrees. Thus, the average power of the transmitted signal can be expressed as:

$$\mathrm{P_{avg}} = \frac{\mathrm{P_c\,T}}{2} \tag{3.3}$$

The energy per bit (E_b) can be calculated by dividing the average power by the bit rate (R_b):

$$E_b = \frac{P_{avg}}{R_b} = \frac{P_c T}{2R_b} \tag{3.4}$$

Note that these energy models assume ideal channel conditions, i.e., no noise or interference. In practical systems, the actual energy per bit might probably be higher due to the presence of noise and other impairments in the communication channel.

3.2. Numerical Study

In this section, energy consumption per bit (E_{bit}) for OOK and BPSK modulations are evaluated for narrow bandwidth and low data rate WSN applications. The low data rate is less than 50 kbps, while the narrow bandwidth is less than 50 kHz. In this thesis, the propagation distance (d) is assumed to be no more than 150 meters.

To compare those modulation schemes, the mathematical expressions for E_{bit} are given below. The energy per bit consumed by the RF front end is represented as E_{bit}. The energy per bit for OOK, BPSK can be stated ,as:

$$E_{bit_{OOK}} = \frac{(1+\alpha)\ \cdot\ P_{E_{OOK}}}{BW} + \frac{32\pi^2 d^2 L}{G_t G_r \lambda^2 K}\ \cdot\ PAR\ \cdot [Q^{-1}(BER)]^2 \tag{3.5}$$

$$E_{bit_{BPSK}} = \frac{(1+\alpha)\ \cdot\ P_{E_{BPSK}}}{BW} + \frac{8\pi^2 d^2 L}{G_t G_r \lambda^2 K}\ \cdot\ PAR\ \cdot [Q^{-1}(BER)]^2 \tag{3.6}$$

where $Q^{-1}(\cdot)$ is the inverse function of Q $(\cdot)$ and $Q(\cdot)$ function is given by :

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-y^2/2} dy \tag{3.7}$$

The difference between the energy per bit values for OOK and BPSK modulations is obtained from (3.5) and (3.6) as:

$$F_1(d^2, BW) = E_{bit_{BPSK}} - E_{bit_{OOK}} \tag{3.8}$$

$$= \frac{(1+\alpha).(P_{E\_BPSK} - P_{E\_OOK}}{BW} - \frac{24\pi^2(1+\alpha).L.d^2.BW.N_0}{BW.G_t.G_r.\lambda^2.K}\ .PAR\ .[Q^{-1}(BER]^2$$

If $F_1(d^2, BW) < 0$, it means $E_{bit\text{-}BPSK} < E_{bit\text{-}OOK}$, then the propagation distance[2].bandwidth (d^2.BW) inequality is obtained as in [3]:

$$d^2.\,BW > \frac{(P_{E\_PBSK} - P_{E\_OOK}).\,G_t.\,G_r.\,\lambda^2.\,K}{24\pi^2 L.\,N_0.\,PAR.\,[Q^{-1}(BER)]^2} \quad (3.9)$$

After these equations, the energy consumption for OOK and BPSK per bit (E_{bit}) for narrow band and low data rate WSN applications can be considered by using the parameters given in Table 3.1 as in [23], [37]. AWGN channel is assumed.

Table 3.1. Parameters.

PARAMETERS			
f = 2.4GHz	$G_r = G_t = 1$	L = 1.25	K = 0.5
$PAR_{roll\ off}$ = 5dB	BER = 1e – 3	α = 0.2	N_0 = 2e − 16 W/Hz
$P_{E\text{-}BPSK}$ = 126.85e −3W			$P_{E\text{-}OOK}$ = 72.35e −3W

After solving the inequality (3.9) using the parameters shown in the Table 3.1.:

$$d^2.\,BW > 2.1844e + 8 \quad (3.10)$$

If $F_1(d^2, BW) = 0$, it indicates that the energy consumption per bit values of the OOK and BPSK modulation schemes are equal, and the answer is d^2.BW=2.1844e+8. This outcome and its equivalent comparison graph for only 25 kHz bandwidth. It is concluded that the OOK modulation scheme is more energy efficient than BPSK when d^2. BW <2.1844e + 8; when d^2. BW < 2.1844e + 8 < d^2. BW 1.125e + 9, BPSK is a more energy efficient one.

In our study, it is mentioned that BPSK is more energy efficient for large values of d^2. BW, BPSK and OOK are both energy efficient for medium values of d^2. BW and OOK is more energy efficient for small values of d^2. BW. Since energy consumption from analog circuits dominates for low values of d^2. BW, OOK provides the lowest energy consumption. On the other hand, PA consumes more energy by the increment of propagation distance. Therefore, BPSK becomes providing the better energy performance.

Li et al. express that BW is fixed and cannot be changed for the most communication systems. Therefore, the most energy efficient modulation scheme could be determined according to the system restrictions such as data rate or bandwidth [23].

In this thesis, energy consumption values versus propagation distances are calculated and the exact value of the propagation distance is determined at which each modulation becoming more energy efficient. The energy per bit values (E_{bit}) versus propagation distance (d) are obtained for 10 kHz, 25 kHz and 50 kHz BW and shown in (figures 3.1., 3.2., and 3.3.), respectively.

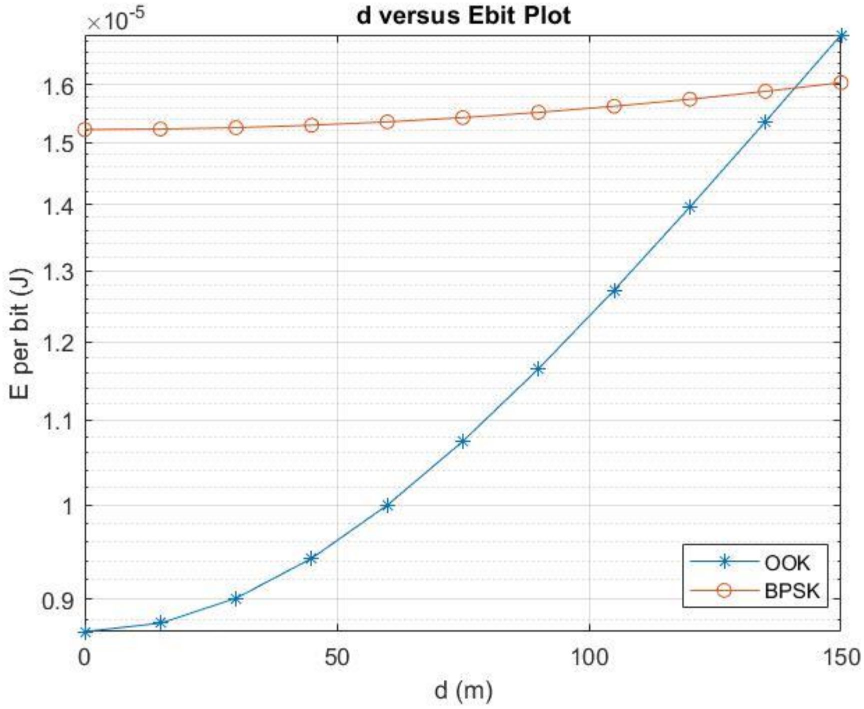

Figure 3.1. Energy per bit for various RF front-end architecture with Class A PA in narrow-bandwidth applications, BW= 10 kHz and d = (0 150] m.

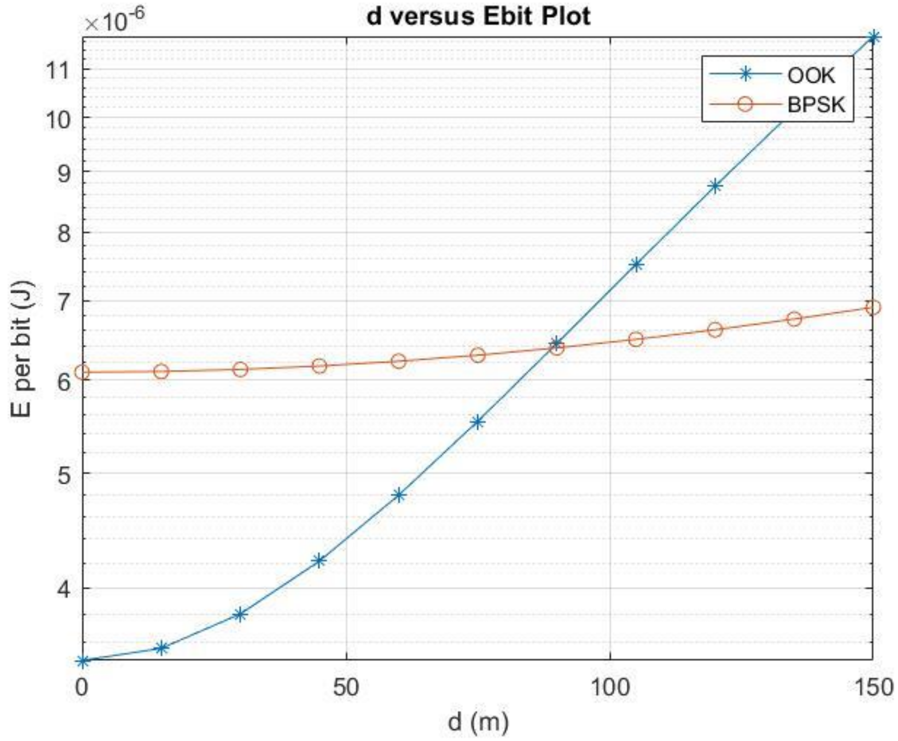

Figure 3.2. Energy per bit for various RF front-end architecture with Class A PA in narrow-bandwidth applications, BW= 25 kHz and d = (0 150] m.

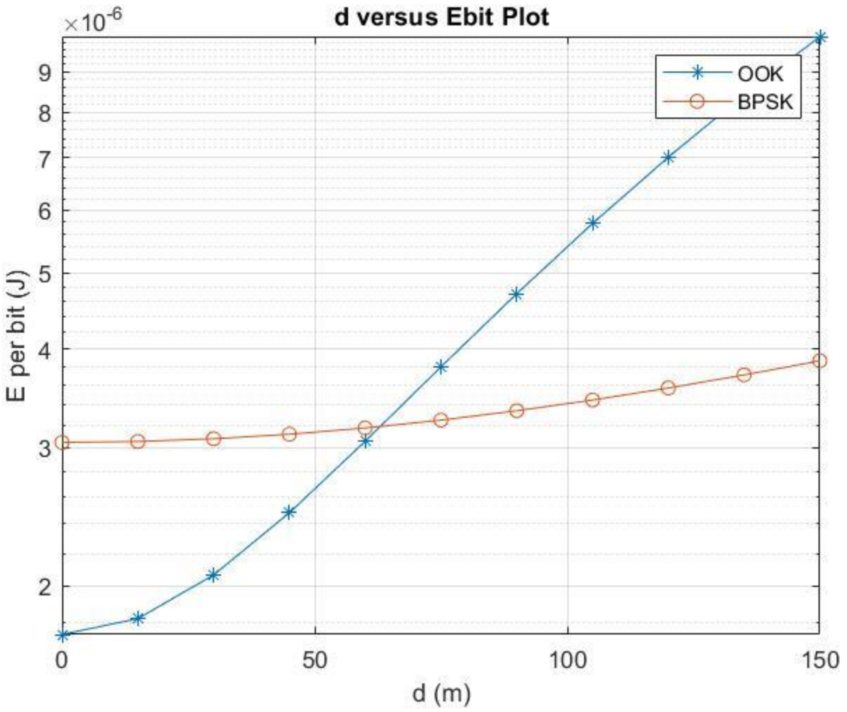

Figure 3.3. Energy per bit for various RF front-end architecture with Class A PA in narrow-bandwidth applications, BW= 50 kHz and d = (0 150] m.

The propagation distance value at which energy per bit of BPSK becomes superior to that of OOK is calculated. The critical propagation distance ($d_{critical}$) at which OOK and BPSK modulations intersect is computed as:

$$d_{critical} = \sqrt{\frac{2.1844e+8}{BW}} \quad (3.11)$$

For OOK and BPSK modulation schemes, the relations between bandwidth (BW) and data rate (R_b) are given as:

$$R_{b_{OOK}} = R_{b_{BPSK}} = \frac{BW}{1+\alpha} \quad (3.12)$$

For each BW value considered, the data rate values (R_b) are also given in Table 3.2.

Table 3.2. Propagation distance (d) and data rate (R_b) for narrow BW.

BW (kHz)	R_b (kbps)	$d_{critical}$ (m)
10	8.333	147.7
25	20.833	93.47
50	41.666	66.09

The $d_{critical}$ values are calculated by using equation (3.11) for narrow BW values (10 kHz, 25 kHz and 50 kHz) shown in Table 3.2. When the BW is increased k times, the propagation distance decreases $1/\sqrt{k}$ times because of the inverse relationship between the bandwidth and propagation distance. In other words, the propagation distance at which BPSK becoming more energy efficient than OOK decreases by the increase of BW.

In this chapter, the energy models and energy consumption per bit (E_{bit}) calculations for OOK and BPSK modulation techniques are given. The energy consumption per bit values (E_{bit}) versus propagation distance (d) plots are obtained for narrow bandwidth as 10 kHz, 25 kHz and 50 kHz. It is observed that energy consumption per bit values of those two modulations intersect in the graphs. The aim of this thesis is to determine that intersection point without any simulation or experiment. For this purpose, the difference of the energy consumption per bit (E_{bit}) expressions of OOK and BPSK modulation schemes is obtained and the critical propagation distance ($d_{critical}$) at which OOK and BPSK modulations intersect is computed. Besides data rate (R_b) values are also calculated for those narrow BW values considered and all the computations are summarized in the table. Thanks to this analytical study, it is determined directly which of the two modulation schemes (OOK and BPSK) should be preferred for any given propagation distance value in narrow bandwidth and low data rate WSN applications.

4. CONCLUSION

The efficient use of limited energy has a more crucial impact than the other networking systems in wireless sensor networks since they consist of many battery powered sensor nodes and recharging or replacing the batteries of the nodes is not possible for most of WSN applications. Therefore energy efficient solutions are one of utmost significant design considerations for WSNs. The most energy consuming operation is communication in sensor nodes so the kind of modulation types has a crucial impact on energy efficiency.

OOK and BPSK modulation schemes were considered and their energy consumption per bit values were compared for narrow bandwidth and low data rate WSNs in this thesis. From the energy consumption per bit versus propagation distance graphs, it was observed that OOK is more energy efficient than BPSK until a particular distance and BPSK becomes superior in terms of energy efficiency after that distance. In this study, that particular propagation distance was defined as the critical propagation distance ($d_{critical}$) and its mathematical expression was derived. Thanks to this equation, critical propagation distance ($d_{critical}$) was obtained directly without the requirement of simulation or experiment. As a result, the energy efficient modulation type could be determined in case of given propagation distance for narrow bandwidth and low data rate WSNs. It is concluded that OOK should be preferred for the propagation distance below $d_{critical}$ and BPSK is preferred for the propagation distance above $d_{critical}$ in terms of energy consumption.

In further studies, the simulations might be used and the results might be compared with the ones obtained from the analytical study. This analysis realized for narrow bandwidth and low data rate WSNs might be extended for medium and large bandwidth applications. Furthermore, the similar analyses might be done on other modulation types.

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