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SAKARYA UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

THE OPTIMAL VALUE DETERMINATION FOR ENERGY GAIN OF MME TO ME CODING IN WIRELESS SENSOR NETWORKS

MSc THESIS

Hisham IDKEIDEK

Electrical and Electronics Engineering Department

JULY 2023

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The thesis work titled "**THE OPTIMAL VALUE DETERMINATION FOR ENERGY GAIN OF MME TO ME CODING IN WIRELESS SENSOR NETWORKS**" prepared by Hisham IDKEIDEK was accepted by the following jury on **19/07/2023** by unanimously/majority of votes as a MSc THESIS in Sakarya University Graduate School of Natural and Applied Sciences, **Electrical and Electronics Engineering** Department.

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To those who believe that science is humanity's best hope to thrive and prosper.To those who take upon themself to live honestly, and those who take upon themselves to push themselves beyond their limits, break the cycle rise above, focus on science.

I would like to thank my Project supervisor, Dr. Nükhet SAZAK, for her continuous support and encouragement.

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Hisham IDKEIDEK

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ABBREVIATIONS

ADC	: Analog-To-Digital Converter
ASK	: Amplitude Shift Keying
BER	: Bit Error Rate
BPSK	: Binary Phase Shift Keying
CPSK	: Continuous Phase Shift Keying
DC	: Differential Coding
CDMA	: Code Division Multiple Access
DS-CDMA	: Direct-Sequence Code Division Multiple Access
FEC	: Forward Error Correction
LDPC	: Low-Density Parity-Check Code
LO	: Local Oscillator
LZW	: Lempel-Ziv-Welch
MAC	: Medium Access Control
MAI	: Multiple Access Interference
ME	: Minimum Energy
MME	: Modified Minimum Energy
OOK	: On-Off Keying
PA	: Power Amplifier
RF	: Radio Frequency
SNR	: Signal-To-Noise Ratio
VRAM	: Variable Rate Adaptive Modulation
WSN	: Wireless Sensor Network

SYMBOLS

k	: Number of Bits
$\mathbf{L_s}$	: Subframe Length
$\mathbf{T_{on,r_x}^{MME}}$	: Decoding Time for MME Coding
$\mathbf{N_s}$	: Number of Subframes
$\boldsymbol{\alpha}$	: Rate of High Bits
$\mathbf{L_{sopt}}$	: Optimal Subframe Length
$\mathbf{N_{sopt}}$	: Optimal Subframe Number
$\boldsymbol{\rho}$	: The Receive Energy Gain of MME To ME
$\mathbf{E_{r_x}^{ME}}$	: Energy for ME
$\mathbf{E_{r_x}^{MM_E}}$	: Energy for MME
$\mathbf{T_{on,r_x}^{ME}}$	: Decoding Time for ME Coding
BW	: Bandwidth
$\mathbf{L_0}$	: Original Codeword Length
n	: Number of Codewords

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THE OPTIMAL VALUE DETERMINATION FOR ENERGY GAIN OF MME TO ME CODING IN WIRELESS SENSOR NETWORKS

SUMMARY

Energy efficiency is essential in wireless sensor networks (WSNs), as the majority of sensor nodes run on little battery power. Enhancing energy efficiency in WSNs can lead to extended network lifespan, reduced maintenance expenses and improved overall performance. By implementing appropriate strategies and techniques, WSNs can optimize energy usage, thereby maximizing the utilization of available energy resources and minimizing energy wastage. This focus on energy efficiency is essential for ensuring sustainable and cost-effective operation of WSNs.

The manner of signal transmission has a considerable impact on the energy efficiency of wireless sensor networks (WSNs). In WSN applications, the choice of signal transmission technique is influenced by various factors, including energy consumption, transmission distance, interference, noise, and bandwidth efficiency. Finding the ideal balance between energy saving and performance enhancement is the objective. ME (minimum energy coding) and MME (modified minimum energy coding) are two coding techniques commonly employed in WSNs to achieve energy-efficient data transmission. These coding techniques are designed to minimize energy consumption during signal encoding and decoding processes, thereby contributing to improved energy efficiency in WSNs.

Minimum Energy (ME) coding reduces the amount of energy required during the encoding and decoding operations in wireless sensor networks (WSNs). It provides a number of advantages that lower energy consumption and improve the overall energy efficiency of WSNs. ME coding algorithms are created to reduce the energy needed for encoding and decoding processes. By optimizing the coding scheme, ME coding reduces the energy consumption of individual sensor nodes, resulting in longer network operation and greater battery life.

On the other hand, Modified Minimum Energy (MME) coding, as an enhancement to Minimum Energy (ME) coding, provides additional benefits to wireless sensor networks (WSNs) in terms of energy efficiency. Here are some ways in which MME coding benefits WSNs by improving energy savings. MME coding techniques built upon the principles of ME coding to further optimize energy consumption during encoding and decoding processes. MME coding delivers significantly larger energy savings than ME coding alone because of the coding scheme refinement. As a result, the battery life is increased, and the network's total energy efficiency is raised.

This thesis presents an investigation into the optimal value determination for receive energy gain of ME to MME coding in wireless sensor networks (WSNs). First of all, OOK modulation is going to be described and then the operation of ME coding and MME coding is going to be investigated in detail. Their advantages and drawbacks are going to be examined. The optimal value for receive energy gain of MME to ME coding is going to be determined. The receive energy gain of ME to MME coding

depends on the rate of high bits (α) and subframe length (L_s). The lower the rate of high bits (α), the more energy is saved. There is an optimal pair for the value of the rate of high bits (α) and subframe length (L_s). In this thesis study, optimality is going to be investigated and analyzed mathematically. Besides, the optimal subframe length (L_{sopt}) and optimal number of the subframes (N_{sopt}) that maximize receive energy gain of MME coding relative to ME coding in wireless communication systems are derived analytically.

KABLOSUZ ALGILAYICI AĞLARDA MME'NİN ME KODLAMAYA GÖRE ENERJİ KAZANCININ OPTİMAL DEĞERİNİN BELİRLENMESİ

ÖZET

Kablosuz Algılayıcı Ağlar (KAA'lar); çevresel olayları algılamak, veri toplamak ve kablosuz iletişim yoluyla bilgi paylaşmak için kullanılan bir teknoloji türüdür. KAA'lar genellikle küçük boyutlu ve düşük maliyetli algılayıcı cihazlardan oluşur ve çevre izleme, hava kalitesi ölçümü, akıllı tarım ve endüstriyel otomasyon vb. çeşitli uygulamalarda kullanılmaktadırlar. Bu uygulamaların bazılarında algılayıcı düğümlerin enerji kaynağı olan pillerini değiştirmek veya şarj etmek mümkün değildir. Bu yüzden KAA'ların enerji verimliliği, bu tür ağların sürdürülebilirliği açısından kritik öneme sahiptir. Bu nedenle, enerji tüketimini optimize etmek ve ağın ömrünü uzatmak önemlidir.

Çoğu algılayıcı düğüm sınırlı pil gücü ile çalıştığından enerji verimliliği kablosuz algılayıcı ağlarda (KAA'larda) önemli bir rol oynamaktadır. KAA'larda enerji verimliliğini arttırma; uzatılmış ağ ömrüne, azaltılmış bakım giderlerine ve iyileştirilmiş toplam başarıma yol açabilir. Uygun stratejileri ve teknikleri uygulayarak KAA'lar mevcut enerji kaynaklarının kullanımını maksimum ve enerji israfını minimum yaparak enerji kullanımını optimize edebilir. Enerji verimliliğine odaklanma, KAA'ların sürdürülebilir ve maliyet etkin çalışmasını sağlamak için esastır. Kablosuz algılayıcı ağların (KAA'ların) enerji verimliliği, işaret iletim yönteminden önemli ölçüde etkilenmektedir. KAA uygulamalarında işaret iletim tekniğinin seçimi; enerji tüketimi, iletim mesafesi, girişim, gürültü ve band genişliği verimliliğini içeren çeşitli faktörlerden etkilenir. Amaç, enerji korunumu ve başarım optimizasyonu arasındaki doğru dengeyi bulmaktır.

Tezin giriş bölümünde algılayıcı düğüm donanımına ilişkin bilgi verildikten sonra KAA mimarisi açısından enerji verimliliği ele alınmaktadır. Bir kablosuz algılayıcı düğüm mimarisi; fiziksel, veri bağlantı, ağ, taşıma ve uygulama olmak üzere beş katmandan oluşmaktadır. Hata kontrolü, güvenilir veri iletiminden sorumlu olan veri bağlantı katmanında (data link layer) gerçekleştirilmektedir. Literatürde birçok kodlama algoritması mevcuttur ancak karmaşık kodlar iyi performans sağlamalarına rağmen daha fazla güç tüketmektedirler. Kısıtlı güç kaynaklarına sahip algılayıcı düğümlerden oluşan KAA'lar göz önünde bulundurulduğunda daha az karmaşık kodların tercih edilmesi gerektiği açıktır. Literatür taramasında bir sayısal haberleşme sisteminde kodlamanın yeri açıklandıktan sonra kanal kodlama ve kaynak kodlama tekniklerinden kısaca bahsedilmektedir. Tezin odağını oluşturan Minimum Enerji (ME) kodlama ve adından da anlaşılacağı gibi ME kodlamanın modifiye edilmiş bir versiyonu olan Değiştirilmiş Minimum Enerji (MME) kodlama teknikleri ile ilgili yapılan çalışmalara ikinci bölümde yer verilmektedir.

ME (minimum enerji kodlama) ve MME (değiştirilmiş minimum enerji kodlama), enerji etkin veri iletimini başarmak için KAA'larda kullanılan iki kodlama tekniğidir. Bu kodlama teknikleri, KAA'larda işaret kodlama ve kod çözme süreçleri esnasında enerji tüketimini en aza indirmek ve böylece iyileştirilmiş enerji verimliliğine katkı sağlamak üzere tasarlanmıştır. Minimum Enerji (ME) kodlama, KAA'larda kodlama

ve kod çözme süreçleri esnasında enerji tüketimini en aza indirmek için kullanılan bir tekniktir. ME kodlama, mesajdaki ‘1’ bit sayısını en aza indirirerek enerji kazancı sağlamaktadır. ME kodlama algoritmaları, kodlama ve kod çözme işlemleri için gereken enerji miktarını minimuma indirmek için tasarlanmıştır. ME kodlamada yeni kod kelimesinin uzunluğu (L_{ME}), orijinal kod kelimesinden (L_0) daha fazla olmasına ($L_{ME} > L_0$) rağmen daha çok sıfır içermesi sayesinde enerji tasarrufu sağlamaktadır. ‘0’ biti iletilirken güç kuvvetlendiricisi (power amplifier, PA) kapatıldığından ve ME kodlama ile ‘1’den çok ‘0’ biti iletildiğinden toplam enerji tüketiminde kazanç elde edilmektedir. ME kodlama; kodlama şemasını optimize ederek bireysel algılayıcı düğümlerin enerji tüketimlerinin azaltılmasını, pil ömrünün arttırılmasını ve ağın daha uzun çalışmasını sağlamaktadır.

Diğer yandan Değiştirilmiş Minimum Enerji (Modified Minimum Energy, MME) kodlama, Minimum Enerji (ME) kodlamanın geliştirilmişi olarak, enerji verimliliği bakımından kablosuz algılayıcı ağlara (KAA’lara) ek faydalar sağlamaktadır. MME kodlamanın enerji tasarrufunu iyileştirerek KAA’lara fayda sağladığı bazı yollar aşağıda verilmiştir. MME kodlama tekniği, kodlama ve kod çözme süreçleri sırasındaki enerji tüketimini daha fazla optimize etmek için ME kodlama üzerine inşa edilmiştir. MME kodlamadaki yeni kod kelimesinin uzunluğu ME kodlama ile aynıdır (L_{ME}=L_{MME}). ME’den farklı olarak MME kodlama, her birinde gösterge biti bulunan alt çerçevelerden oluşmaktadır. Bu her bir alt çerçevenin başında bulunan gösterge biti, o alt çerçevede bir veya daha fazla yüksek bit (“1” biti) olup olmadığını göstermektedir. Gösterge biti 1 ise yüksek bit yok, gösterge biti 0 ise yüksek bit (en az bir tane “1” biti) var anlamına gelmektedir. Yüksek bit olmayan çerçevenin kodunun çözülmesine gerek olmaması sayesinde MME kodlama, kodlama şemasını iyileştirerek tek başına ME kodlamaya göre daha fazla enerji tasarrufu elde etmektedir. Bu, uzatılmış pil ömrüne yol açmakta ve ağın toplam enerji verimliliğini arttırmaktadır.

Tezin üçüncü bölümünde ilk olarak bir genlik kaydırmalı anahtarlama (amplitude shift keying, ASK) modülasyonu olan OOK (On-Off Keying, Aç-Kapa Anahtarlama) modülasyonu anlatılmaktadır. Veri bitlerinin taşıyıcı sinyal varken (genellikle yüksek seviye) bit 1, taşıyıcı sinyal yokken (genellikle düşük seviye) bit 0 ile temsil edildiği, düşük veri hızlı kablosuz uygulamalar için tercih edilen bir sayısal modülasyon yöntemi olan OOK (On-Off Keying, Aç-Kapa Anahtarlama) modülasyonu anlatıldıktan sonra ME ve MME kodlama tekniklerinin işleyiş prensiplerinin ayrıntıları sunulmaktadır.

ME ve MME kodlamada alım enerji kazancı, veri iletimi esnasında tasarruf edilen enerji miktarının bir ölçüsüdür. MME’nin ME’ye göre alım enerji kazancı, ME kodlamanın enerjisinin MME kodlamanın enerjisine oranıdır, aynı zamanda ME kodlamanın kod çözme süresinin MME kodlamanın kod çözme süresine oranı şeklinde de ifade edilmektedir. Bu denklemlerden bulunan sonuca göre alım enerji kazancı, sadece yüksek bit hızı (α) ve alt çerçeve uzunluğuna (L_s) bağlıdır. Analitik çalışmanın yer aldığı dördüncü bölümde, ilgili matematiksel ifadeler ışığında MME’nin ME kodlamaya göre alım enerji kazancı, yüksek bit hızının (α) 0.1-0.9 aralığındaki değerleri için enerji kazancının alt çerçeve uzunluğuna (L_s) göre değişimi grafiği ile gösterilmektedir. Elde edilen grafikte bütün α değerleri için MME kodlamanın ME kodlamaya göre alım enerji kazancının yüksek olduğu ancak bir maksimum noktaya ulaştıktan sonra azalmaya başladığı gözlenmektedir. Alt çerçeve uzunluğu (L_s) arttıkça alım süresi uzadığı için enerji kazancı düşmektedir. Yüksek bit hızının (α) daha küçük değerleri ile daha yüksek enerji kazancı elde edildiği görülmektedir.

Bu tezin amacı, herhangi bir yüksek bit hızı (α) için bu maksimum enerji kazancının elde edildiği alt çerçeve uzunluğunu ve sayısını benzetim veya deney yapmaksızın doğrudan belirlemektir. Optimal alım enerji kazancını veren alt çerçeve uzunluğu, optimal alt çerçeve uzunluğu (L_{sopt}) olarak tanımlanmakta ve matematiksel hesaplamalar sonucunda elde edilen bir denklem ile bulunmaktadır. Çalışmanın bir sonraki adımı olarak optimal alt çerçeve sayısı (N_{sopt}) da analitik olarak elde edilmektedir. Türetilen formüllerin doğruluğu yapılan analiz sonuçları ile desteklenmektedir. Yüksek bit hızının (α) 0.1 olduğu durumda en yüksek enerji kazancına ulaşıldığı için bu değerden elde edilen sonuçlar ayrıca irdelenmektedir. α = 0.1 için alt çerçeve uzunluğunun iki katına çıkarılmasıyla enerji kazancında sağlanan artış (%31.92) hem grafik hem de tablo ile sunulmaktadır.

Bu tezde, kablosuz algılayıcı ağlarda (KAA'larda) kullanılan MME kodlamanın ME kodlamaya göre alım enerji kazancını maksimum yapan optimal alt çerçeve uzunluğu (L_{sopt}) ve optimal alt çerçeve sayısı (N_{sopt}) analitik olarak türetilmektedir. Verimli ve güvenilir kablosuz haberleşme sistemlerinin tasarımında yararı olabilecek; alt çerçeve sayısı, yüksek bit hızı ve alım enerji kazancı arasındaki ilişkiyi anlamaya yardımcı olan teorik bir yaklaşım ortaya konulmaktadır. Bu yöntem sayesinde herhangi bir yüksek bit hızı değeri için MME'nin ME'ye göre optimum enerji kazancının elde edilmesini sağlayan alt çerçeve sayısı benzetim veya deney gerektirmeksizin doğrudan belirlenebilmektedir. Bu sayede sistem tasarımındaki süre azaltılmakta ve tasarım süreci basitleştirilmektedir.

1. INTRODUCTION

A key factor in bridging the gap between the physical real-world and the digital virtual world is the use of wireless sensor networks (WSNs) [1]. A WSN is composed of multiple nodes, known as sensors which have minimal computational capabilities, sensing, and communication capabilities. These sensor nodes are distributed across a geographical region to observe various physical phenomena, such as temperature, humidity, and vibrations [2].

The sensor nodes are compact and contain crucial subsystems, including detection, processing, and communication systems, as well as a power supply unit, as demonstrated in figure 1.1.

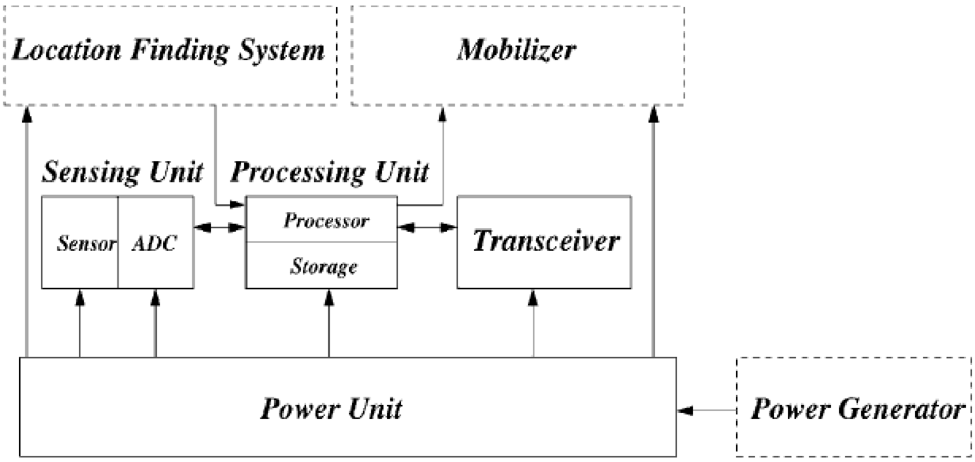


Figure 1.1. The components of a sensor node [3].

As depicted in figure 1.1, the node architecture is comprised of four crucial units. The sensing unit comprises sensors as well as an analog-to-digital converter (ADC), which changes the analog signals produced by the sensors into digital ones. The processing unit, which consists of a microprocessor or microcontroller with memory, is responsible for intelligently controlling the sensor nodes and processing the digital data received from the sensing unit. The communication unit is responsible for transmitting and receiving data via a radio frequency (RF) channel and for connecting the sensor nodes to the rest of the network. The power unit, containing a battery that provides power to all system parts, is the most crucial part of the node. These units are integrated into a compact module due to their low cost and energy consumption. Other sub-units such as a power generator, location finding system, and mobilizer that are shown in dotted-line blocks in figure (1.1) may be present in the node, depending on the application.

1.1. Energy Efficiency in WSNs

Energy efficiency is of significant importance for WSNs since sensor nodes have limited energy and changing or recharging their batteries is difficult in most of the applications. The protocol stack including five layers with three management planes for WSNs is shown in figure (1.2) Energy minimization can be achieved at every protocol stack tier. The overall energy consumption of the WSN may be decreased, which can aid in extending the network lifetime, by implementing energy reduction algorithms at each tier of the protocol stack.

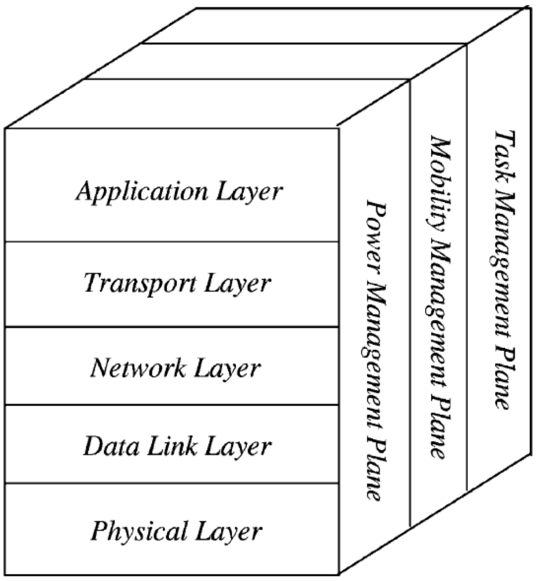


Figure 1.2. The protocol stack of WSN [3].

The requirements of the sensor node such as carrier frequency selection and generation, modulation, signal detection and reception are met at the physical layer. Medium access control (MAC) protocols and error control policies are covered at the data link layer.

Routing protocols and topology control are handled at the network layer. Flow control, congestion control and error checking at a higher level are performed at the transport layer. Data aggregation and compression are carried out at the application layer [3].

As discussed, earlier error control policies are considered at the data link layer which is responsible for reliable data transmission. Errors in WSNs cause data to get damaged because of the noisy channels and a few additional issues. In the literature, numerous different error control coding systems have been presented. Although complicated codes might provide better performance, more complex codes result in more energy consumption. Therefore, by taking into account the stringent energy constraint of sensor nodes the codes with low complexity are preferred while considering WSN applications. Two of them, ME and MME coding schemes, are the main subject of this thesis and are going to be investigated in detail later.

The rest of the thesis is organized as follows. Chapter 2 provides a literature review including coding processes in the digital communication system and two source coding schemes (ME and MME coding) which are the focuses of this thesis. The details of Minimum Energy (ME) coding and Modified Minimum Energy (MME) coding are explained in detail in Chapter 3. The analytical study for optimal receive energy gain is examined in Chapter 4. In Chapter 5 as conclusion, the results obtained from the mathematical computations are summarized and some research suggestions for further studies are pointed out.

2. LITERATURE REVIEW

2.1. Introduction

Wireless Sensor Networks (WSNs) have gained popularity in recent years, thanks to its potential to enable a wide range of applications in many domains including environmental monitoring, healthcare, and home automation etcThe . One of the main challenges facing WSNs is the limited energy resources of the individual nodes, which must be managed efficiently to extend the network lifetime.

Energy efficiency is a crucial concern in WSNs due to the restricted energy resources of the nodes. Researchers have proposed several approaches, including energy-efficient routing and MAC protocols, energy harvesting, data aggregation, and application-specific protocols, to address this issue and extend the network lifetime. Future research efforts are expected to focus on achieving energy-efficient information transmission over bandwidth-limited channels. These findings could be useful in the development of wireless communication systems that require energy-efficient and reliable data transmission.

WSNs are used in a variety of applications, including as home automation, healthcare, and environmental monitoring. The collected data from WSNs is typically transmitted wirelessly to a base station for processing and analysis. However, effective data transmission in WSNs is difficult owing to the sensor nodes' limited resources. Coding techniques have been proposed to address this challenge by reducing the amount of data transmitted while maintaining the integrity of the data. In this literature review, we will discuss some of the relevant research on coding techniques for WSNs.

2.2. Overview of Coding Techniques for WSNs

When an analog signal is produced by the original information source, such as in wireless applications, digital communication technologies are frequently employed. The block diagram shown in Figure (2.1) shows how a typical digital communication system operates.

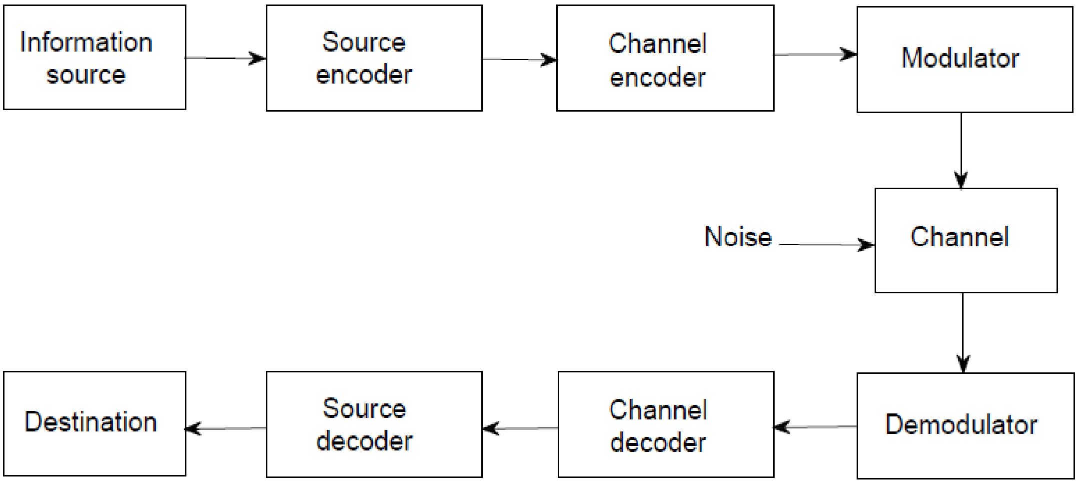


Figure 2.1. Block diagram of a typical digital communication system [4].

The source encoder, which compresses the digital data produced by the source to lower the number of bits needed for transmission, is the first. Various methods, including run-length encoding, arithmetic coding, and Huffman coding, are used to compress the data. The channel encoder then adds redundancy to the compressed data to guard against transmission problems. Convolutional or Reed-Solomon error-correcting codes, which are used by the modulator to transform the digital signal into an analog signal that can be broadcast across the communication channel, are used to add this redundancy. the channel represents the medium over which the modulated signal is transmitted, at the receiver end the demodulator extracts the modulated signal from the received signal, and converts it back into a digital signal, when it gets to the channel decoder the channel decoder decodes the received digital signal, and corrects any errors that may have occurred during transmission using the redundancy added by the channel encoder, Until it reaches its intended location, the error-free digital signal is decoded back into its original form, and any compression that the source encoder performed is erased by the source decoder.

Overall, the digital communication system processes the information signal through a series of encoding and modulation stages before transmitting it over the communication channel, and then decodes and reconstructs the original signal at the receiver end.

In mobile communication systems, transmission errors can happen due to various factors such as multipath fading, diffractions, scattering, restricted transmitting power and energy resources, poor signal-to-noise ratio. To address these errors, error coding is used in which mathematical formulas are applied to encode data bits into longer bit words for transmission. The encoded bit words, also known as codewords, contain additional bits that provide redundancy. At the receiving end, these extra bits are used to detect and correct any errors that might have occurred during transmission, thus ensuring accurate data retrieval without the need for resending the data [5].

Considering the limited computational and energy capacity of sensor nodes, simple coding schemes with low complexity might provide the best solutions for WSNs [3]. Source-channel coding in networks are crucial topic of study in the realm of digital communications. The subsections that follow provide explanations of them.

2.2.1. Channel Coding

In digital communication systems, channel coding (also called error-correcting coding) is a process used to add redundancy to the transmitted signal in order to combat the effects of noise and interference in the communication channel. The purpose of channel coding is to make it possible for the receiver to identify and fix transmission faults, enhancing the dependability and quality of the signal that is received. In order for channel coding to function, extra bits must be added to the broadcast signal, which are generated using complex mathematical algorithms. These additional bits are used to verify the accuracy of the received signal and, if necessary, to correct any errors that are detected. There are many different channel coding techniques, including block codes, convolutional codes, turbo codes, and LDPC codes. The choice of coding technique relies on the particular requirements of the communication system because each of these methods has strengths and limitations of its own [6].

Overall, channel coding plays a crucial role in ensuring the reliability and performance of digital communication systems. By adding redundancy to the transmitted signal, channel coding enables reliable communication over noisy and unreliable communication channels. Channel coding is widely used in many different types of digital communication systems, including wireless communication systems, satellite communication systems, and wired communication systems. It is an important component of modern communication technology, enabling reliable and efficient communication even in the presence of noise and interference.

As long as the code rate (the proportion of information bits to total bits transmitted) is below the channel capacity, Shannon's theorem, or the fundamental theorem of channel coding, states that information can be transmitted through a channel with an arbitrarily low probability of error for a given channel with a given capacity. In other words, the theorem guarantees the existence of channel codes that can approach the channel capacity as closely as desired, allowing for reliable communication over noisy channels. Channel coding techniques that approach the theoretical limits set by Shannon's theorem include low-density parity-check (LDPC), turbo, and convolutional codes [7].

One of the most well-known examples of channel coding is Convolutional Coding. Convolutional coding is a technique used in digital communication systems to protect against channel errors. It involves encoding the data stream using a convolutional encoder, which adds redundancy to the data by generating additional bits called parity bits. The parity bits are then used at the receiver end to detect and correct errors in the transmitted data [8].

2.2.2. Source Coding

In digital communication systems, source coding, commonly referred to as data compression or entropy encoding, lowers the amount of data needed to represent a signal or information source. The goal of source coding is to remove redundancy and irrelevant information from the source data, while preserving the essential information required for accurate reconstruction at the receiver. Source coding is widely used in various applications, including audio and video compression, image compression, and data storage [8]. It is also an important component of digital communication systems, when it is used to cut down on the quantity of data needed for transmission, increasing transmission effectiveness, cutting down on bandwidth needs, and cutting down on storage costs. Popular source coding algorithms include Huffman coding, arithmetic coding, and Lempel-Ziv-Welch (LZW) coding [8].

In conclusion, coding techniques are critical for efficient data transmission in WSNs due to the limited resources of the sensor nodes. Researchers have proposed several coding techniques, including FEC, network coding, CS, and distributed source coding, to address this challenge and improve the reliability and efficiency of data transmission in WSNs. In this thesis, ME and MME which are kinds of source coding are investigated and compared in terms of receive energy gain.

2.3. Minimum Energy (ME) Coding

Several significant contributions towards energy-efficient wireless information transmission were presented in [9]. The authors first formulate the energy-optimal coding problem for wireless communication systems, they propose a novel memoryless coding algorithm, called Minimum Energy (ME) Coding, that provides energy-optimal codes for sources with known statistics. Additionally, They present concatenation as a method that, by using a straightforward memory mechanism, improves the efficiency of memoryless coding. The data gathered from a finger ring sensor is used by the authors to illustrate possible energy savings achieved by ME Coding. They also combine existing error-correcting codes with ME Coding to provide energy-efficient and reliable information transmission. The study concludes that ME Coding, Concatenation, and ME error-correcting codes offer effective methods for dependable and energy-efficient information transfer via wireless channels with low power.

An investigation into energy-efficient source coding and modulation techniques for wireless communication applications is given in [10].The authors provide a literature review of existing energy-efficient coding and modulation techniques for wireless communication systems. They note that conventional coding techniques such as Huffman coding and arithmetic coding can achieve high compression ratios but require high energy consumption for encoding and decoding.

The authors [10] suggest using energy-efficient coding methods as Differential Huffman coding and Variable Rate Adaptive Modulation (VRAM) to overcome this issue. A source coding method called differential Huffman uses the correlation between consecutive symbols in the data stream to decrease the amount of bits needed for transmission. The VRAM is a modulation method that lowers the transmitter's energy consumption by adjusting the modulation scheme in accordance with the channel circumstances.

The study evaluates the performance of the proposed techniques using simulations. The results show that the Differential Huffman coding can achieve up to 50% reduction in the number of bits required for transmission compared to conventional Huffman coding, while maintaining a high compression ratio. The VRAM can achieve up to 50% reduction in the energy consumption of the transmitter compared to fixed modulation schemes, while maintaining a high bit error rate (BER) performance.

Overall, the study by [10] provides a valuable contribution to the literature on energy-efficient coding and modulation techniques for wireless communication systems. The results of this study might be used to the design and optimization of power-restricted wireless communication systems, such as wireless sensor networks, in particular.

An investigation into the minimization of energy consumption for an OOK (On-Off Keying) transmitter through the use of Minimum Energy (ME) Coding was presented to improve the energy efficiency of wireless communication systems in [11]. The authors start out by reviewing the research on strategies for wireless communication systems that are energy-efficient. They point out that traditional coding methods, such Convolutional and Turbo codes, are made to be very reliable at the price of energy use. Since wireless sensor networks are energy-constrained systems, these strategies are not appropriate for them.

The authors suggest using ME Coding, a memoryless coding technique that attempts to reduce the energy consumption of wireless transmitters, to address this problem. They demonstrate that ME Coding can significantly reduce the energy consumption of an OOK transmitter without compromising the reliability of the system. In [11], the performance of ME Coding is evaluated by using simulations and experimental measurements. The results show that ME Coding can reduce the energy consumption of an OOK transmitter by up to 50% compared to conventional coding techniques. Moreover, ME Coding can achieve the same level of reliability as conventional coding techniques, demonstrating its effectiveness in energy-efficient wireless communication systems.

2.4. Modified Minimum Energy (MME) Coding

In order to lessen transmit and multiple access interference in conventional Direct-Sequence Code Division Multiple Access DS-CDMA systems, the usage of (DS-CDMA) with Modified Minimum Energy (MME) coding has been suggested and researched [12]. When compared to the previously recommended Minimum Energy (ME) coding method, MME coding achieves better energy savings at both the transmitter and the receiver by breaking a codeword into many subframes using indicator bits.

The results of the investigation show that MME coding leads to a significant improvement in Bit Error Rate (BER) performance due to the reduced Multiple Access Interference (MAI). The reduction in power consumption is achieved at the expense of codeword length or bandwidth. However, the power constraint in wireless sensor networks is more critical than the bandwidth constraint, making the increase in bandwidth acceptable. Therefore, the combination of MME coding and DS-CDMA is a desirable option for wireless sensor networks, considering the total system energy savings and the enhanced BER performance. This finding could be useful in the development of wireless sensor networks that require a reliable and energy-efficient communication system.

2.5. ME and MME Coding

Minimum Energy (ME) and Modified Minimum Energy (MME) coding techniques are energy-efficient coding techniques that can be used in Wireless Sensor Networks (WSNs). In ME coding, the symbols with minimum energy are assigned the shortest codewords to reduce the amount of energy used for data transmission. MME is an extension of ME, where the ME technique is modified by adding an error correction mechanism for improving the reliability of data transmission.

Numerous studies have been conducted to evaluate how well different coding techniques work in WSNs. For instance, [13] compared the performance of ME and MME coding techniques in terms of power use and packet loss percentage. According to the findings [13], MME coding beat ME coding in terms of energy usage and packet loss rate under various channel circumstances.

A new coding technique called Modified Minimum Energy Differential Coding (MME-DC) which is a combination of MME and Differential Coding (DC) was proposed in [14]. The authors evaluated the performance of MME-DC and compared it with ME and MME coding techniques. The results showed that MME-DC outperformed ME and MME in terms of throughput, packet delivery ratio, and energy use [14].

Another study by Thirumaran and Devi in 2020 compared the performance of ME and MME coding techniques with convolutional codes and Reed-Solomon codes in terms of energy consumption and error rate. The results showed that MME coding technique had lower energy consumption and higher error correction capability compared to ME and other coding techniques [14].

2.6. Optimal Receive Energy Gain in MME to ME Coding

There have been a number of research studies conducted on the optimal receive energy gain in MME to ME coding. One approach is the Minimum Energy (ME) coding, which aims to minimize the total transmission energy by utilizing the redundancy in the transmitted signals. ME coding assigns codes to each ME, such that the energy required for decoding is minimized. However, ME coding is limited in its ability to utilize the spatial diversity of the wireless channel, as it treats each ME as an independent entity.

To address this limitation, Modified Minimum Energy (MME) coding was proposed, which utilizes the spatial diversity of the wireless channel by considering the correlation between the signals received at different MEs. Each ME is given a code through MME coding, considering the correlation between the incoming signals, so as to reduce the overall energy needed for decoding. The effectiveness of MME to ME coding in terms of energy efficiency and throughput has been examined in a number of research investigations. For instance, MME coding significantly outperformed conventional ME coding in terms of energy efficiency and throughput in a research by [15]. A combined optimization method for MME coding was suggested in a different research by [16] that takes reliability and energy efficiency into account.

Furthermore, studies have been done to determine how channel circumstances affect MME to ME coding performance. For instance, the effect of fading channels on the energy efficiency of MME coding was examined in a research by [17]. The findings shown that when the channel state deteriorates, MME coding loses energy efficiency.

In summary, existing research on optimal receive energy gain in MME to ME coding has shown the potential for significant improvements in energy efficiency and throughput compared to traditional ME coding. In order to enhance the performance of MME coding even more, research is still being conducted on the effects of channel conditions and joint optimization frameworks. A detailed explanation of operation principles of ME and MME coding schemes is given in the next chapter.

3. ME CODING AND MME CODING

3.1. Introduction

In Chapter 2, the literature review for ME and MME is given. The technical details of these coding schemes, their operation principles are examined in this chapter. First of all, OOK modulation is addressed since it is applied with ME and MME coding.

3.2. On–Off Keying (OOK) Modulation

On-Off Keying (OOK) is a form of amplitude shift keying (ASK) modulation technique used to transmit binary data over a communication channel in digital communication systems. When using OOK modulation, the carrier signal's amplitude is changed to represent binary 1 and 0. When the carrier signal is present, it corresponds to a binary 1; while when it is absent, it corresponds to a binary 0 [18].

The efficacy of OOK modulation is dependent on a number of variables, including modulation depth, signal-to-noise ratio (SNR), bit rate, and transmitter-to-receiver distance. The modulation depth is the difference between the carrier signal's amplitude when it represents a binary 1 and the carrier signal's amplitude when it represents a binary 0. In a communication channel, the SNR is the ratio of signal power to noise power. Bit rate refers to the rate at which binary data is transmitted over a communication channel.

The benefit of OOK modulation in various communication systems has been extensively studied and analyzed. In [19], for instance, the usefulness of OOK modulation in optical communication systems is evaluated based on the bit error rate (BER) and the receiver sensitivity. The efficacy of OOK modulation in wireless communication systems is examined in [20] in terms of error probability and channel capacity.

In conclusion, OOK modulation is a basic and cost-effective technique for transmitting binary data in digital communication systems. Its performance in various communication systems has been extensively studied and analyzed, and it has been determined that it is suitable for applications requiring minimal complexity and cost-efficiency.

For low data-rate wireless applications, the use of fundamental digital modulation techniques like On-Off keying (OOK) can be contemplated. The working of OOK modulation is realized by modulating a higher-frequency carrier wave with the baseband signal and transmitting it as radio frequency (RF) waves. This means that a carrier signal is conveyed when bit-1 is to be transmitted, whereas no signal is transmitted when bit-0 is to be transmitted. Figure (3.1) illustrates the OOK signals transmitted for a sequence of bits [11].

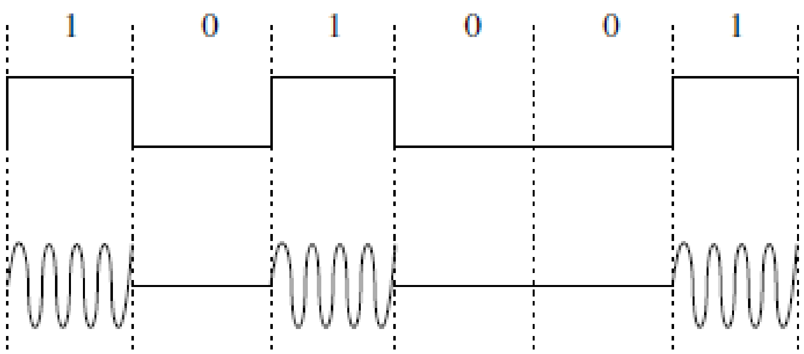


Figure 3.1. Typical OOK modulation scheme [11].

Since the transmitter does not transmit the bit 0, OOK modulation supplies energy saving. Besides, it is a good option for WSNs thanks to its properties like low complexity and cost efficiency [21].

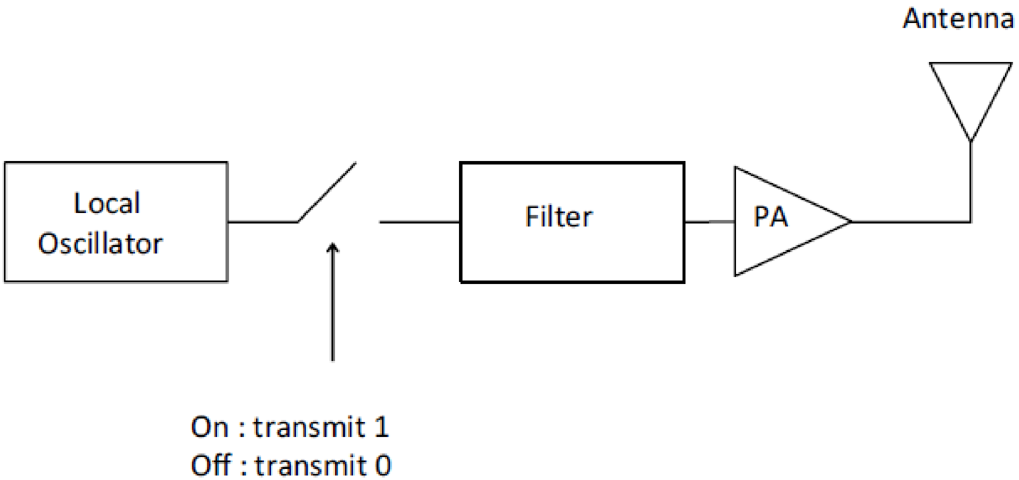


Figure 3.2. Energy consumption model of a realistic OOK transmitter [12].

[12] provides the energy consumption model of a realistic OOK transmitter. The transmitter and receiver circuit analog blocks are shown in Figure (3.2. and 3.3.), respectively. In Figure (3.2.) the transmitter consists of a local oscillator (LO) that produces the carrier wave. When a high bit is to be transmitted, a switch sends the signal through a filter to the power amplifier (PA) and the antenna. No signal is sent if a low bit is to be sent. Figure (3.2.), illustrates the receiver's components, which include a low noise amplifier (LNA), a frequency transposition connected to a local oscillator, and a detector that may be coherent or, more typically, non-coherent [12].

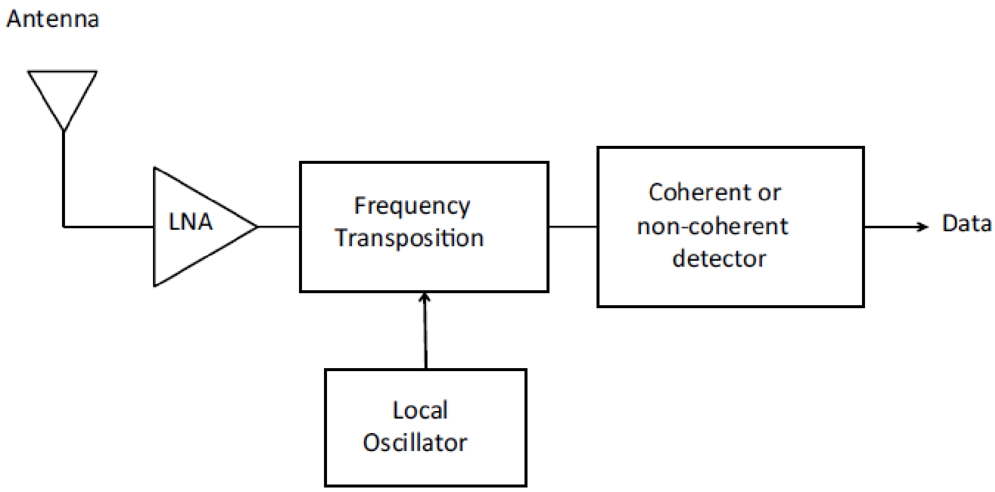


Figure 3.3. Energy consumption model of a realistic OOK Receiver [12].

Figure (3.4.), shows the block diagram of the OOK transmitter with low energy consumption. Bit 0 is sent while the circuit shuts down fully. A speed-up strategy is used to achieve reduced wake-up times and large data rates [12].

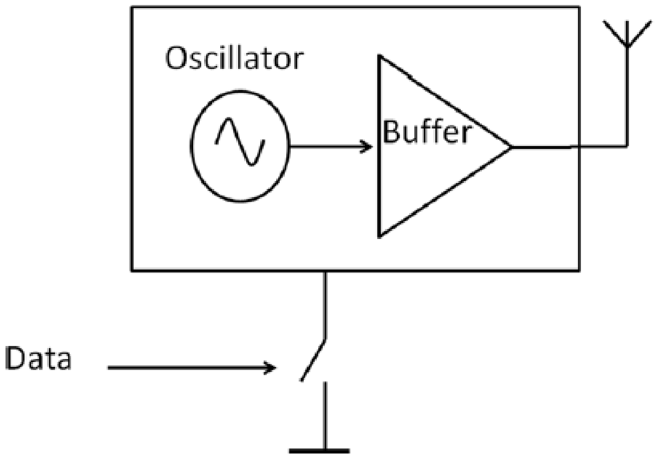


Figure 3.4. The block diagram of the OOK transmitter [12].

Due to its straightforward implementation at both the transmitter and receiver sides, OOK is a convenient modulation scheme for wireless communication. OOK, which has the benefit of utilizing less circuit power while sending bit 0 as opposed to bit 1, may be used to implement ME-Coding.

3.3. ME Coding

Minimum Energy (ME) coding [10] attempts to decrease the power consumption of digital RF transmitters, one of the sources of power that use the most in portable communication devices. Radio frequency signals are created from modulated binary codewords using a digital RF transmitter. To communicate with other devices, radio frequency vibrations can go through the atmosphere. One of the main reasons of energy consumption in sensor nodes is the amount of energy required to generate these signals.

Any attempt to formulate the power optimization problem must be based on a thorough comprehension of how these waves are generated; therefore, the modulation technique employed is of the utmost importance. Consideration is given to On-Off Keying (OOK) modulation for ME coding applications.

Despite of having limited performance of uncoded OOK when compared to other modulation schemes such as BPSK (typically 3dB worse due to a reduced minimum distance in the signal constellation) [11], the gain acquired when combined with ME is substantially more than enough to justify its existence.

ME coding combines these two techniques to produce the energy-optimal coding algorithm, which is founded on the two preceding bullet points. Codebook Optimality and Coding Optimality are the two phases involved. The first stage is to choose a codeword— a collection of bits with the fewest high bits—and the second is to pair words with fewer high bits with messages that have greater probability [21].

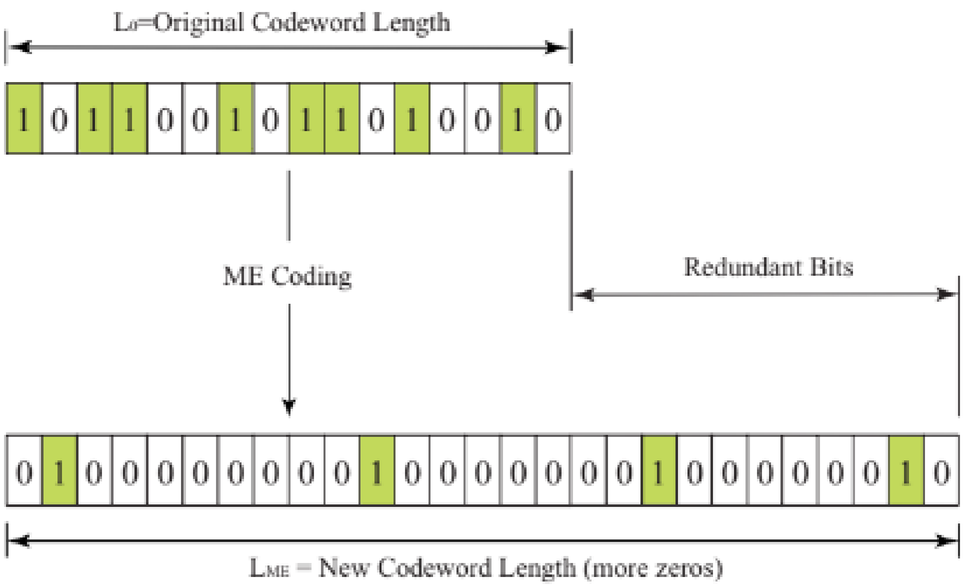


Figure 3.5. Principle of minimum energy coding [21].

With ME coding, each codeword from the codebook is mapped into a new codeword with larger length but including less number of high (1) bits. The original codeword length is L_0, the new codeword length is LME which is obtained by adding redundant bits as shown in Figure (3.5.). Although the length of the new codeword is longer than the one of the original (L_{ME}> L_0), it includes more zeros (or in other words less high bits) than the original codeword. Since only high bits (1's) are transmitted, ME coding provides energy saving when it is utilized with OOK modulation [21].

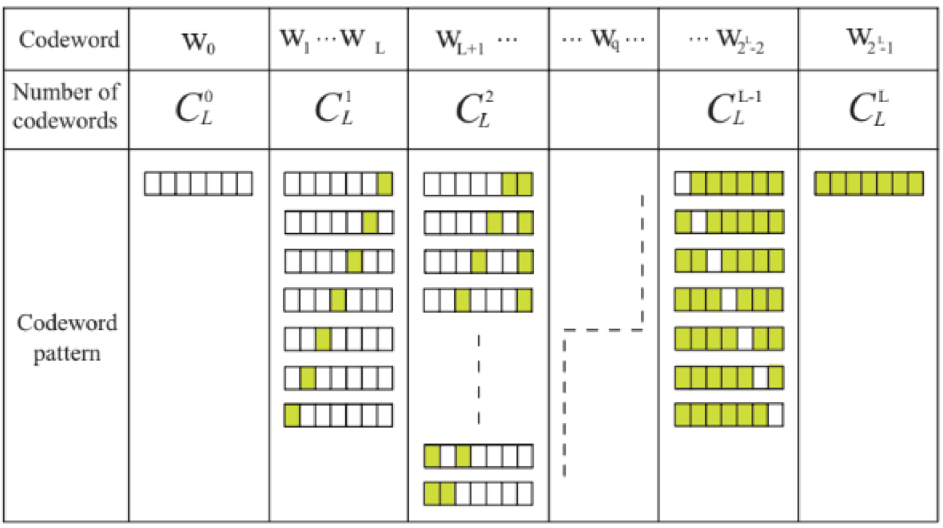


Figure 3.6. Fixed-length ME codewords [21].

All of the usable codewords with length L are sorted by the number of high bits as shown in Figure (3.6.). All the codewords in the i th column have i-1 high bits. All of the codewords ($w_1 \dots w_{2^L-1}$) are sorted in the ascending order of the number of high bits. The codeword in the first column (w_0) has no high bit and is represented by $C_L^0 = 0$. In the second column, there are C_L^1 codewords ($w_1 \dots w_L$) having one high bit and so on. The codeword w_{2^L-1} at the last column consists of all high bits and this means that it is the most energy consuming one. The remaining codewords after the first q codewords, as shown by broken lines, are abandoned and the optimal codebook is formed [21].

Every k bits of a source symbol are mapped into an n-bit ($n = 2^k - 1$) codeword represented by the standard form as ME [n, k]. The $2^k = n + 1$ codewords are composed of blocks of n bits. k is considered as a binary bit (1's and 0's, with k >1) from the source bits. These k bits are grouped and mapped into codewords with length n by the encoder [n > k] as shown in Figure (3.7.) [11].

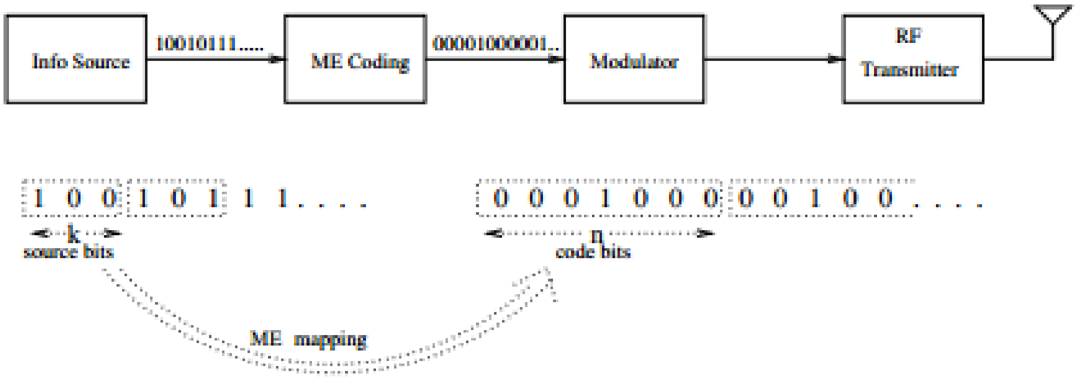


Figure 3.7. ME mapping scheme [11].

These codewords have a greater number of bits but a smaller number of high bits of them. Therefore, no codewords contain more than one high bit when compared to their original symbols. In the codebook, there are the $2^k - 1$ codewords with only one high bit and one all zero codeword. The source bits and their corresponding codewords for ME [3, 2] and ME [7, 3] are given in Table (3.1.) [11].

Table 3.1. Minimum energy codes for k = 2 and 3 [11].

Source bits	Codewords	Source bit	Codewords
ME [3 , 2]	ME [3 , 2]	ME [7 , 3]	ME [7 , 3]
00	000	000	0000000
01	001	001	0000001
10	010	010	0000010
10	100	011	0000100
		100	0001000
		101	0010000
		110	0100000
		111	1000000

The code rate is computed as $k/n=k/2^k-1$.The minimum Euclidean distance between any two ME codes is represented by dmin and since its value is 1, these codes cannot correct errors. If any codeword containing more than one high bit is detected, this means that there is an error. The bit-by-bit error detection process for ME [3,2] code is shown in Table (3.1.).

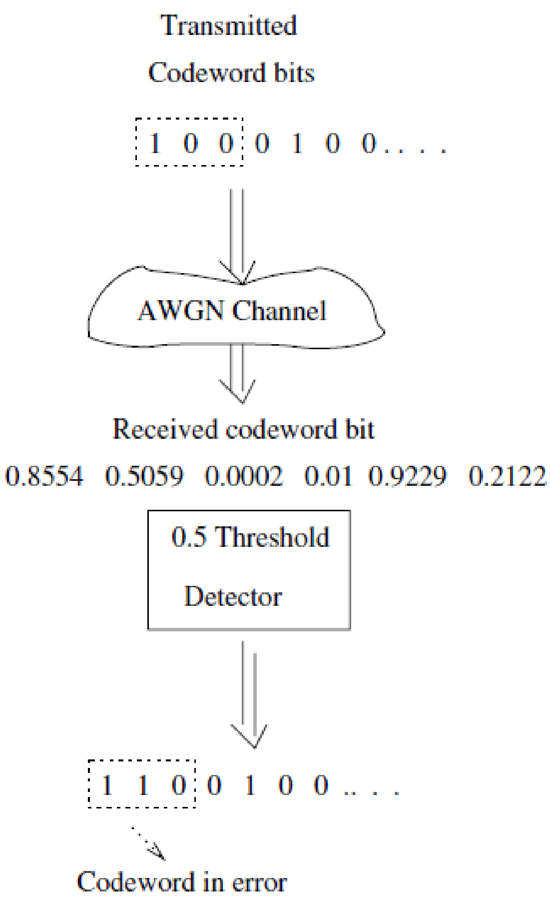


Figure 3.8. Flow of bit-by-bit detection process [11].

Any codeword with more than one high bit is considered to be compromised if the threshold for a bit-by-bit hard choice is 0.5. Any codeword with more than one high bit is deemed to be incorrect if the threshold for a bit-by-bit hard judgment is set to 0.5, as illustrated as an example in Figure (3.8.).

In summary, ME coding is an effective method for lowering energy usage in wireless sensor networks (WSNs), particularly for low data-rate applications. Significant energy savings may be gained during wireless transmissions by using straightforward modulation algorithms like OOK and adopting the ME Coding approach. Reduced circuit power consumption while transmitting bit 0 as opposed to bit 1 is another advantage of using ME coding with OOK modulation. This technique also allows for low wake-up times and high data rates, making it an ideal solution for low-power WSNs. As such, ME coding can potentially lead to significant improvements in the energy efficiency and overall performance of WSNs, making it a valuable area of research in the field of wireless communications.

3.4. MME Coding

As its name implies, Modified Minimum Energy Coding (MME coding) is a refined form of ME coding. A MME codeword is made up of several subframes, unlike ME encryption. Also, there is an indicator bit at the beginning of each subframe in MME coding scheme. The remaining part of the codeword is the same with ME coding [13].

The MME codeword consists of multiple subframes, each with its own indicator bit. If the indicator bit is high it implies that there are only zero bits in the subframe and so there is no need to decode the message so the receiver can be in the off state. If the indicator bit is low, it implies that there are high bits (1 bits) so the decoder has to be on and the receiver, too [21].

Actually the working principle of MME is not so different than ME except for the availability of the indicator bit and subframes. The working principle of MME coding is shown in Figure (3.9.). Similar to ME coding, the codeword has a fixed length [21].

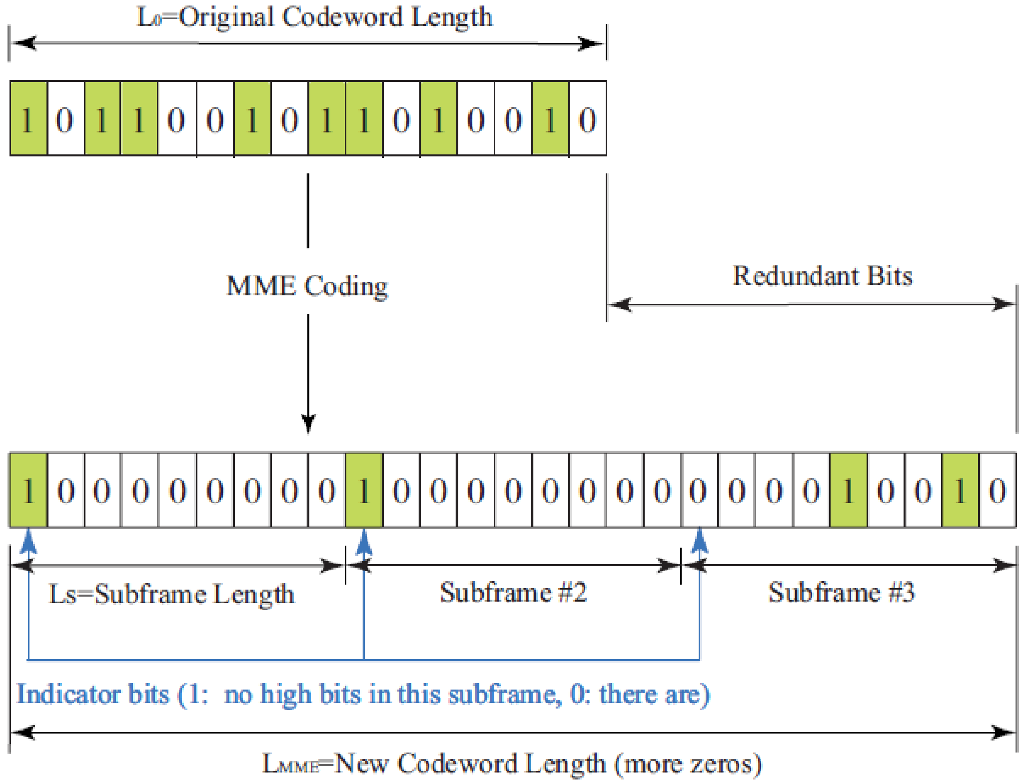
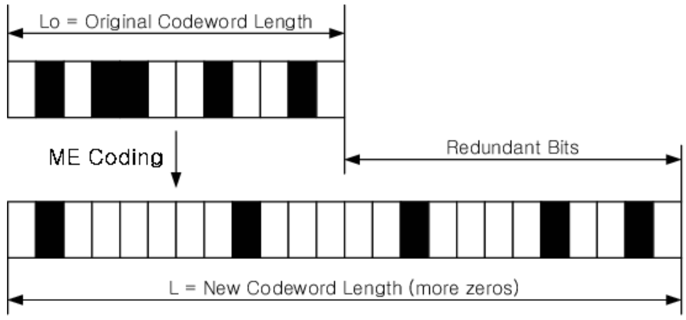


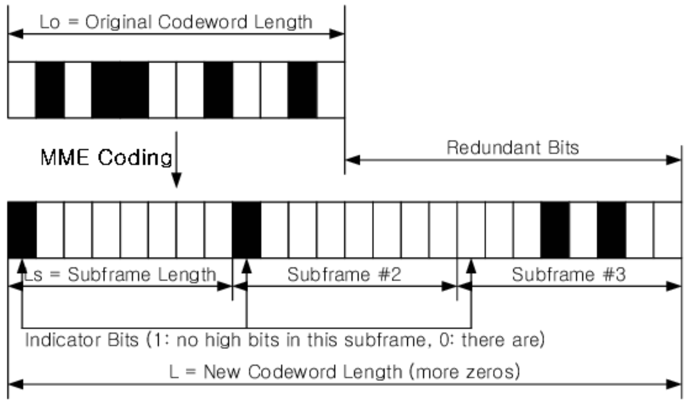
Figure 3.9. MME coding [21].

The first bit of every subframe, called as indicator bit, demonstrates whether that contains one or more high bits. If there is no high bit in the subframe, the indicator bit is 1. In this case the remaining subframe (L_s-1 bits) does not need to be decoded by the receiver. The indication bit is 0 if the subframe has at least one high bit. In that scenario, the receiver must decode the whole subframe. The essential differences between the ME and MME coding schemes are shown in Figure (3.10.)[13].

Because of the indicator bit, a codeword in MME coding can contain more high bits than in ME coding. Since the sensor node spends the most of its operating time to receive data rather than to send, MME coding offers energy savings. In addition to those energy savings, the indicator bit improves timing synchronization of the receiver [13].



(a) ME coding,



(b) MME coding

Figure 3.10. The principles of ME and MME coding schemes [13].

In conclusion, Modified Minimum Energy (MME) is a potential method that can raise the energy effectiveness of wireless sensor networks (WSNs) by cutting down on the energy used by nodes while transmitting data. The MME algorithm does this by maximizing each node's transmission energy and decreasing the network's overall energy usage. MME coding has been demonstrated to perform better in terms of bit error rate (BER) performance and energy efficiency than other coding methods, including BPSK and ME. The network architecture, the channel model, and the selection of suitable design parameters must all be carefully taken into account before MME coding can be implemented. The further study is required in order to determine the best design parameters for a given application and to evaluate the performance of MME coding under various circumstances.

4. ANALYTICAL STUDY

4.1. Introduction

The necessity for energy-efficient communication protocols has become a prominent subject of concern as wireless communication technologies have proliferated in today's society. Portable electronics like smartphones, tablets, and wearable technologies require battery power to function in many wireless communication protocols. As a result, power consumption must be carefully considered when developing wireless communication systems because it might shorten battery life and raise operating costs.

ME and MME coding algorithms have been created to address these problems by decreasing the amount of energy required to transmit signals while still ensuring reliable connection between devices. MME coding uses a modified form of ME coding that takes into account the wireless transmission's channel quality. Minimum Energy (ME) coding is a technique used in digital communication systems that minimizes the amount of energy required to transmit signals. Although ME and MME coding schemes have similar bit error probabilities, MME is superior to ME in terms of large codewords and low data rates [21].

The way that ME and MME coding function is by encoding the data to be communicated in a way that allows the signal to be reliably decoded at the receiver while consuming the least amount of energy. The channel quality, noise level, and other elements that may affect signal transmission must be carefully considered in order to do this.

ME and MME coding approaches employ a number of optimization strategies to meet this objective, including adaptive modulation and coding, transmit power control, and error correction coding. Together, these techniques reduce the amount of energy required to transport a certain quantity of data while maintaining dependable interoperability across devices.

ME and MME coding have many advantages. These methods can increase the battery life of portable electronics, save operating expenses, and boost the overall sustainability of wireless communication systems by reducing energy usage. Additionally, ME and MME coding can improve user experience and open up new applications that were previously not viable due to power limitations by increasing the reliability of wireless connection.

4.2. Receive Energy Gain

ME Coding is a coding scheme proposed to reduce power consumption in RF transmitters by decreasing the number of high bits ("1" bits) in the codewords. MME coding, on the other hand, is a modified version of ME coding that adds an additional bit known as the indicator bit.

In the case of ME coding and MME coding, the receive energy gain is a measure of the amount of energy saved during the transmission of data. This is because these coding techniques allow for more efficient use of bandwidth, reducing the overall energy consumption required for data transmission. The receive energy gain of MME to ME coding is computed by the following steps.

The decoding time for ME coding is [13]:

$$\mathrm{T}_{\mathrm{on,r_x}}^{\mathrm{ME}} = \mathrm{LT_b} \tag{4.1}$$

which is independent of the value of α.

For MME coding, the average receiver on-time $\mathrm{T}_{\mathrm{on,r_x}}^{\mathrm{MME}}$ is computed by the equation (4.2) [13]:

$$\mathrm{T}_{\mathrm{on,r_x}}^{\mathrm{MME}} = N_s[L_s(1-(1-\alpha)^{L_s-1}) + (1-\alpha)^{L_s-1}]\mathrm{T_b} \tag{4.2}$$

The receive energy gain of MME to ME coding is calculated by putting the equation (4.1) and (4.2) into the equation (4.3) [13]:

$$\rho = \frac{\mathrm{E}_{\mathrm{r_x}}^{\mathrm{ME}}}{\mathrm{E}_{\mathrm{r_x}}^{\mathrm{MM_E}}} = \frac{\mathrm{T}_{\mathrm{on,r_x}}^{\mathrm{ME}}}{\mathrm{T}_{\mathrm{on,r_x}}^{\mathrm{MME}}} = (1 + \frac{1-\mathrm{L_s}}{\mathrm{L_s}}(1-\alpha)^{\mathrm{L_s}-1})^{-1} \tag{4.3}$$

It is seen that, the energy savings of MME Coding is dependent on L_s and α, Figure (4.1.) shows the relationship between those parameters. With respect to subframe length (L_s), the energy gain of MME Coding over ME Coding is determined for various values of the coefficient (0.1-0.9) with 0.1 increment, as shown in Figure (4.1.) α and L_s are the two variables that have an impact on the receive energy gain of MME Coding in comparison to ME coding. Because of the longer reception time as Ls rises, the energy gain drops. Additionally, higher energy gain is produced by smaller values of α.

In order to determine the best design parameters for a given application and to evaluate the performance of MME Coding under various circumstances, more research is necessary. The BER performance boost for MME Coding diminishes as drops (and low bits become more frequent), yet the power savings grow. In any case, for all conceivable values of α the suggested MME Coding scheme performs better than the original ME system under both measures.

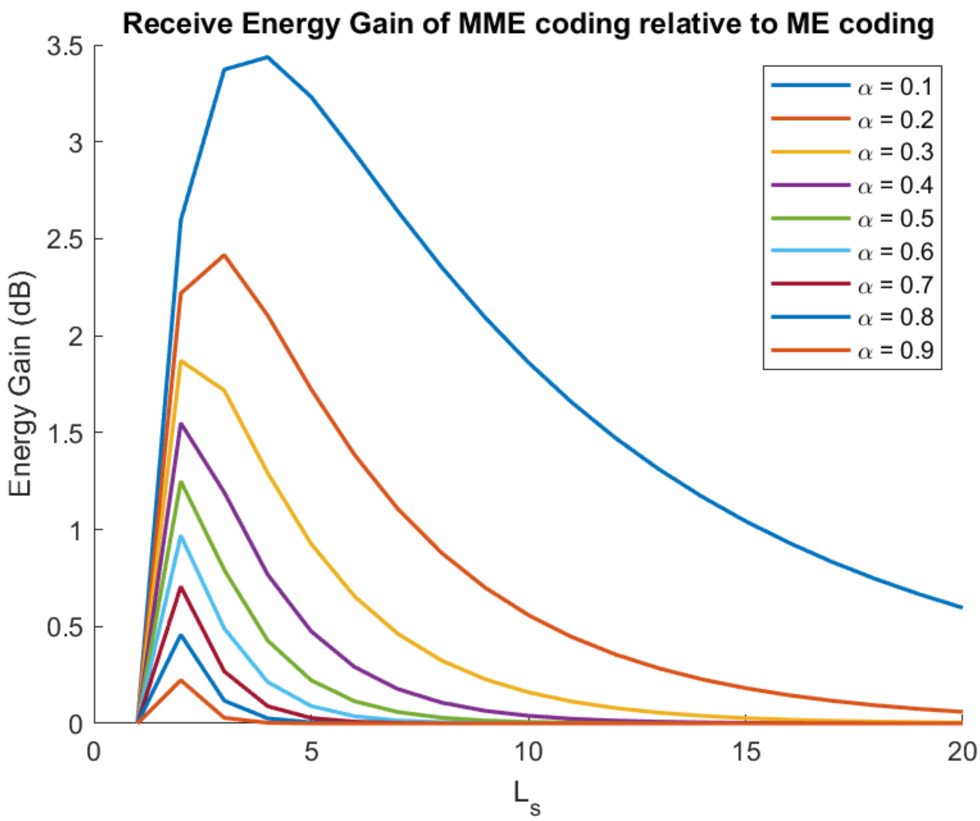


Figure 4.1. Receive energy gain of MME Coding relative to ME coding.

It is observed that the receive energy gain of MME to ME coding depends on the rate of high bits (α) and subframe length (L_s). As such, we will examine how the lower the rate of high bits (α), the more energy is saved. In this study, we will determine the optimal pair for the value of the rate of high bits (α) and subframe length (L_s), analyzing it mathematically.

In wireless communication systems, the energy gain plays a crucial role in determining the efficiency and reliability of the communication link. Energy gain is dependent on various factors such as the subframe length, transmit power, and channel characteristics. In particular, it has been observed that the energy gain reaches a maximum value and then starts to decrease as the subframe length is increased for a given α value.

4.3. Optimal Receive Energy Gain in MME to ME coding

MME Coding further lowers energy use at the receiver in addition to the transmit power savings illustrated in the preceding subsection. Assume that both the ME and MME systems use the same amount of power for CDMA decoding. However, the problem of determining the optimal receive energy gain arises when balancing energy efficiency with reliable data transmission. The main aim of this thesis is to determine the ideal receive energy gain value for MME to ME coding. This involves finding the best values for the rate of high bits (α) and subframe length (L_s) that minimize energy consumption while maintaining reliable data transmission.

The trade-off between energy consumption and data transmission reliability is analyzed mathematically to tackle this problem. By determining the optimal receive energy gain, we can optimize the design and implementation of communication systems, particularly in low-power applications such as the IoT and sensor networks. This can help to minimize energy consumption and prolong the lifespan of devices, ultimately leading to a more sustainable and efficient communication system.

The optimal receive energy gain as a function of L_s for each value of α is important in determining the maximum efficiency of the communication system. However, determining the subframe length that provides the maximum energy gain for any given α value directly, without the need for simulation or experimentation, is a challenging problem.

L_s appears as a parameter in equation (4.3), which is the expression for energy gain. By taking the derivative of this equation with regard to L_s, we obtain an optimal value expression for L_{sopt} that maximizes the energy gain.

$$\frac{d\rho}{dL_s} = -L_{s^2} \ln(-\alpha + 1)(-\alpha + 1)^{L_s - 1} L_s \ln(-\alpha + 1) * (-\alpha + 1)^{L_s - 1} - (-\alpha + 1)^{L_s - 1} = 0 \tag{4.4}$$

Now to find the maximum point, we should make this equation equal to zero the common terms are taken into parentheses:

$$(1 - \alpha)^{1 - L_s} * ({L_s}^2 \ln(1 - \alpha) + L_s \ln(1 - \alpha) - 1) = 0 \tag{4.5}$$

$$({L_s}^2 - L_s + \frac{1}{\ln(1 - \alpha)}) = 0 \tag{4.6}$$

After inserting α values as α =0.1, α =0.5 and α =0.9 we get the roots of the second order equation in (4.6) in Table (4.1.) below:

Table 4.1. Roots for α =0.1, 0.5 and 0.9

L_{s1}	-2.62109	-0.80104	-0.32722
L_{s2}	3.621093	1.801036	1.327221
α	α= 0.1	α=0.5	α=0.9

The optimal value of the L_s equation has two roots, but only the positive root has physical significance because L_s represents the length of a subframe, which must be positive. Therefore, we only need to contemplate the equation's positive root. Therefore, the optimal subframe length (L_{sopt}) is obtained as:

$$L_{s_{opt}} = 0{,}5(1 + \sqrt{1 - \frac{4}{ln(1 - \alpha)}} \tag{4.7}$$

L_{sopt}, denoting the optimal value of L_s, can be computed directly without simulations or iterative calculations. Therefore, for any given value of, we can directly compute L_{sopt} using equation (4.7), without the need for simulations. This analytical method facilitates the rapid and accurate calculation of the optimal value of L_s for a range of values, which is useful for the design and optimization of energy harvesting systems.

Without simulations or iterative calculations, we can directly determine the optimal value of L_s for any given value of, as mentioned. This is a potent instrument for the design and optimization of energy harvesting-based wireless communication systems.

In addition, the energy gain of MME Coding in comparison to ME coding can be calculated using the optimal value of L_s (Ls_{opt}) for a given value. This can be accomplished by substituting the optimal value of L_s into the expressions for the energy gain of MME and ME Coding and calculating their ratio. This ratio provides the energy gain of MME coding in comparison to ME Coding, which can be used to evaluate the system's efficacy and make design decisions.

After finding the L_s value now the optimal number of subframes (N_{sopt}) can be found using equation (4.7) [13]:

$$N_s = L/L_s \tag{4.8}$$

Substituting Ls_{opt} into (4.8), the optimal number of subframes is calculated as:

$$N_{s_{opt}} = L/0{,}5(1 + \sqrt{1 - \frac{4}{\ln(1-\alpha)}} \tag{4.9}$$

MME Coding allows for an increase in the number of high bits in a codeword up to a certain limit, denoted as N_{sopt}, due to the insertion of an indicator bit. This increase in the number of high bits can improve the reliability of the communication system and enhance its error correction capability.

However, the use of MME Coding also results in a decrease in the time-on ($T_{on,rx}$) of the system, which is proportional to 1/ L_s where L is the length of a subframe. As a result, if we design the subframe length such that L_{sopt} is less than L_s the total energy consumption of the system, denoted as E_{total}, is reduced.

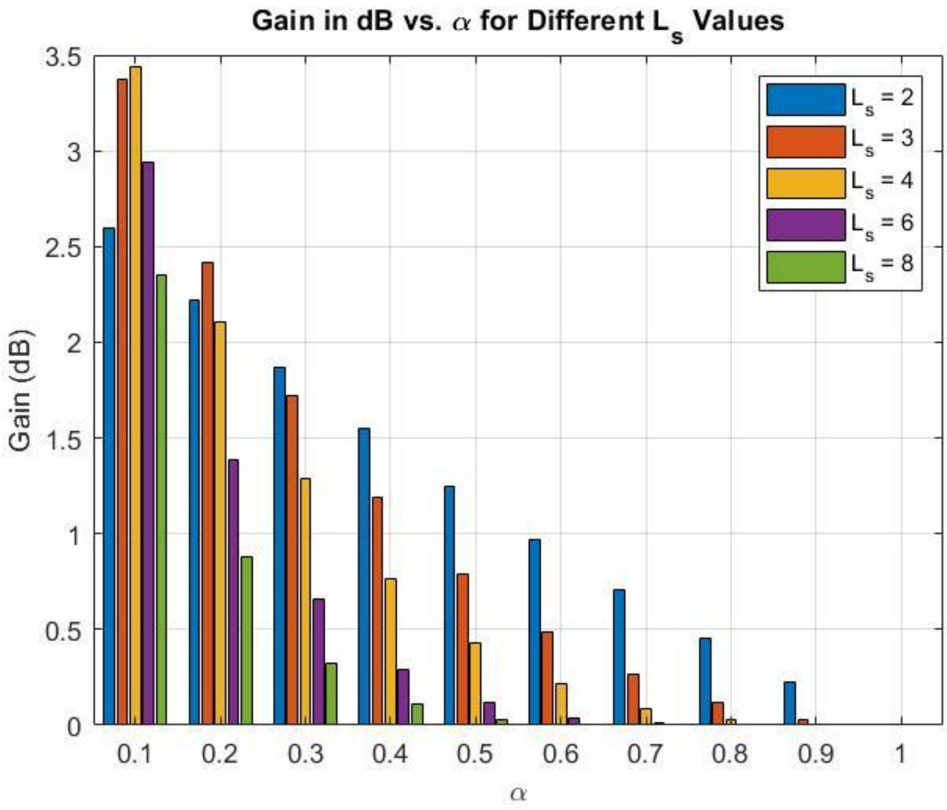


Figure 4.2. Energy gain of MME to ME coding versus the rate of high bits (α) between 0.1 and 1.

The energy gain of MME to ME coding versus the rate of high bits (α) between 0.1 and 1 is obtained for the subframe lengths (L_s) 2, 3, 4, 6 and 8 as shown in figure 4.2. When the rate of high bits increases, the value of subframe length for optimal energy gain decreases. As it is seen from the graph, the gain values for α=0.1 are higher than the other ones. The highest energy gain of MME to ME coding is obtained at the L_s=4 value. L_{sopt} is calculated by the derived formula and the result is given in table 4.2. Since the subframe length has to be integer, the result (3.6) is rounded to 4 which is the same in the figure 4.2. This verifies the derived formula of L_{sopt} given in equation (4.7).

Since the maximum energy gain value is reached for α =0.1, the energy gain values of subframe lengths 2 and 4 are compared by focusing on that rate in figure 4.3. It is observed that the energy gain is increased by 31.92 % when the subframe length is doubled.

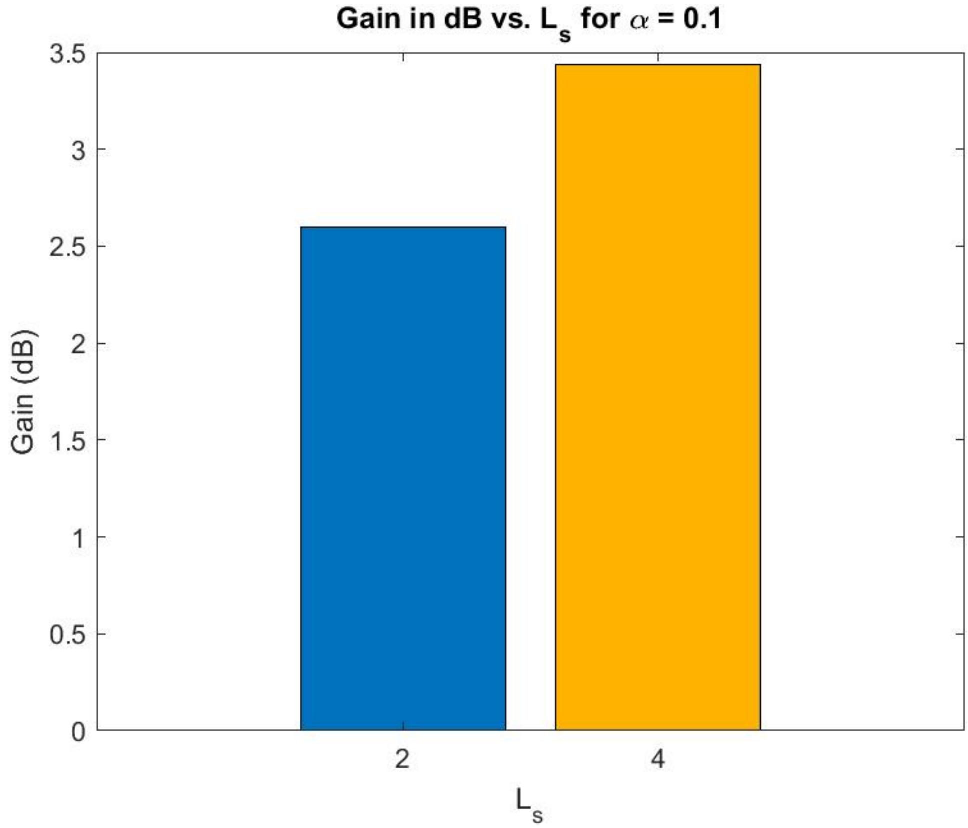


Figure 4.3. The energy gain values of subframe lengths 2 and 4.

The subframe lengths, number of subframes and gain values are computed for α=0.1 and given in table 4.2. The new codeword length (L) is assumed as 24 bits as in [13].

Table 4.2. Number of subframes and gain values for α=0.1.

L_s	2	3	4	6	8
N_s	6.627833	6.627833	6.627833	6.627833	6.627833
Gain (dB)	2.596373	3.372422	3.436622	2.942004	2.354576

By using equation (4.7) and (4.9), optimal subframe length and optimal number of subframes are calculated as follows:

$$L_{s_{opt}} = 0,5(1 + \sqrt{1 - \frac{4}{ln(1-\alpha)}} = 3.6 \approx 4 \quad (4.10)$$

$$N_{s_{opt}} = L/0,5(1 + \sqrt{1 - \frac{4}{ln(1-\alpha)}} = 6 \quad (4.11)$$

When the results in table 4.2 and in equations (4.10), (4.11) are compared, exactly the same results are obtained. As a result, this is a proof of the derived formulas.

Furthermore, since the majority of the operating time of a sensor node is used for receiving data rather than transmitting, the use of MME Coding can save power efficiently. Additionally, the insertion of indicator bits in MME Coding can improve timing synchronization at the receiver, which is an important consideration in wireless communication systems.

In this context, the analytical approach that we have developed for computing the optimal subframe length for MME Coding can be a valuable tool for designing and optimizing energy harvesting systems that employ wireless communication. By using this approach, we can directly compute the optimal subframe length for any given value of α and evaluate the energy gain of MME Coding relative to conventional maximum entropy (ME) Coding. This can help us make informed design decisions that optimize the energy efficiency and performance of the system.

4.4. Analysis of the Obtained Results

Significant implications and prospective applications are associated with the proposed method for determining the optimal receive energy gain in Minimum Energy (ME) and Modified Minimum Energy (MME) Coding techniques in the design and operation of wireless communication systems.

MME Coding provides benefits in terms of enhancing the communication system's reliability. In addition, it can conserve energy and enhance timing synchronization at the receiver. It also decreases the system's time-on, which can be compensated for by designing the subframe length so that N_{sopt} is less than L_s, thereby reducing the system's total energy consumption, denoted by E_{total}.

The proposed method has several advantages. Firstly, it provides a simple and efficient way to determine the subframe length that maximizes energy gain. Secondly, it is a computationally efficient method that can be applied in real-time systems. Finally, it provides a theoretical foundation for understanding the relationship between subframe length, α value, and energy gain, which can be useful for designing efficient and reliable wireless communication systems.

Overall, the analytical method that we have developed enables us to directly determine the optimal subframe length for any given value and evaluate the energy gain of MME Coding in comparison to ME coding. This provides a potent instrument for designing and optimizing wireless energy harvesting systems.

This method eliminates the need for simulation or experimentation to determine the subframe length that provides the optimum energy gain for a given value of, which is one of its primary advantages. This is a significant advantage because it simplifies the design process and reduces the time and resources needed to optimize the effectiveness and dependability of wireless communication systems.

In addition, the method is computationally efficient and applicable to real-time systems, making it a feasible solution that can be applied to a variety of wireless communication applications. The direct solution to the problem of determining the subframe length that maximizes energy gain, denoted as L_{sopt}, is a straightforward and efficient method for enhancing the performance of wireless communication systems.

This study also provides the theoretical basis for comprehending the relationship between subframe length, value, and energy gain in wireless communication systems, which is an important implication. This knowledge can be used for designing and optimization of communication systems in order to enhance their efficacy and dependability.

The proposed method for determining the optimal receive energy gain in ME and MME Coding techniques has significant implications for the design and operation of wireless communication systems. This method can improve the efficacy and dependability of wireless communication systems, resulting in a better user experience and lower operational costs, by providing a straightforward and efficient method for optimizing energy gain.

5. CONCLUSION

The need for energy efficient communication protocols has become crucial due to the proliferation of wireless communication technologies in portable electronics. ME and MME Coding algorithms have been developed to reduce the amount of energy required to transmit signals while ensuring reliable connection between devices. These methods encode data in a way that allows the signal to be reliably decoded at the receiver while consuming the least amount of energy. ME and MME Coding approaches employ optimization strategies like adaptive modulation and coding, transmit power control, and error correction coding to reduce energy consumption. ME and MME Coding can increase battery life, save operating expenses, and improve overall sustainability while increasing the reliability of wireless connections.

Modified Minimum Energy (MME), as its name suggests, is a modified version of Minimum Energy (ME) Coding. MME Coding further reduces energy usage at the receiver in addition to the transmit power savings. In wireless communication systems, energy gain is important for achieving efficiency and reliability. The energy gain is affected by various factors, including subframe length, transmit power, and channel characteristics. The energy savings of MME Coding is dependent on α and subframe length (L_s), and there is an optimal pair for the value of α and L_s. The MME Coding scheme outperforms the original ME scheme under both metrics for all possible values of α. The energy gain of MME coding over ME Coding was given for various values of the coefficient (α) and subframe length (L_s). It was observed that the energy gain begins to increase with the increment of subframe length for all α values and it decreases after reaching its maximum value. The optimal subframe length (L_{sopt}) was defined as the value providing the maximum receive energy gain of MME relative to ME coding.

In this thesis, the aim was to determine optimal subframe length (L_{sopt}) directly for any given the rate of high bits (α) to obtain the optimal value for the receive energy gain of MME to ME coding. The analytical expressions were derived for computing the optimal subframe length (L_{sopt}) and optimal number of subframes (N_{sopt}) length that maximize energy gain of MME Coding relative to ME Coding in wireless communication systems. This simple and efficient approach developed provides a theoretical foundation for understanding the relationship between subframe length, α value, and energy gain, which is useful for designing efficient and reliable wireless communication systems. Thanks to this analytical approach proposed, optimal subframe length (L_{sopt}) and optimal number of subframes (N_{sopt}) length values are computed directly without simulation or experimentation requirements, saving time and resources during the design process.

This thesis gives a theoretical basis for understanding the relationship between subframe length value and energy gain of MME Coding used in wireless communication systems, which can enhance their efficacy and dependability. And also it provides a straightforward and effective method for determining the optimal receive energy gain in wireless communication systems, which is the main contribution.

This thesis concentrates on the energy efficiency aspect of MME Coding in wireless communication systems and ignores other performance metrics. In addition to energy efficiency, future research can expand the proposed method to include other performance metrics such as throughput and latency. This may entail incorporating these metrics into the optimization problem and developing novel methods for determining the optimal subframe length that balances multiple performance objectives.

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