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Homework 2.

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Abstract

The research within this lab report examines the core principles and real-world applications of digital communication strategies that incorporate Spread Spectrum together with FDMA and TDMA and OFDM protocols. The research starts by performing an investigation of spread spectrum system bandwidth needs in different Signal-to-Noise Ratio (SNR) circumstances compared to traditional systems. The analysis investigates LTE data streams by explaining subcarrier generation rates and technical requirements for orthogonality in signal transmission. A calculation of proposed TDMA cellular system efficiency takes place while the study determines how different bandwidth values affect efficiency levels. The report provides details on Frequency Hopping Spread Spectrum (FHSS) schemes through an explanation of how to calculate the minimum necessary PN bits needed for frequency hopping. The report describes how block interleavers team up with Hamming codes to correct transmission errors effectively. The analysis includes a MATLAB examination of a fundamental communication system using QPSK modulation with OFDM which subjects the signal to AWGN and Rayleigh channels. The simulation calculates Bit Error Rates (BER) among various modulation schemes for assessing performance under different wireless channel environments.

Introduction

The evolution of digital communication systems exists to create effective transmission methods which deliver reliable high-capacity data transfer operations. Modern wireless communication systems rely on Spread Spectrum combined with FDMA and TDMA but also utilize OFDM as a fundamental technology. Spread Spectrum demonstrates superior performance in interference and jamming which makes it exceptional for military and Wi-Fi and Bluetooth type commercial applications. The key elements of cellular networks depend on FDMA and TDMA because these methods split frequency range and timeslots between multiple users sharing the same band. The OFDM technology drives high-data-rate systems like Wi-Fi together with LTE because it enhances spectral efficiency and fights against multipath fading obstacles.

The purpose of this lab study is to analyze these technologies through theoretical methods and practical simulation processes to deliver complete understanding. The initial part of this report evaluates spread spectrum bandwidth use while it operates under various SNR levels to demonstrate bandwidth versus noise tolerance tradeoffs. The research shifts its focus to LTE devices where the generation process for subcarriers and orthogonality requirements are explained for minimizing interference in multi-carrier systems. The research analyzes TDMA system efficiency by studying bandwidth variations that affect system operation.

The assessment provides a detailed examination of FHSS by explaining the PN bit calculation method for frequency hopping because this ensures secure wireless communication while maintaining interference resistance. Block interleaving and Hamming codes are examined alongside their error correction methods that reduce burst errors and protect data integrity.

The report finishes with a MATLAB simulation demonstration of QPSK modulation and OFDM in a basic communication system. An evaluation based on BER takes place in this simulation where signals are sent through AWGN and Rayleigh channels while multiple modulation schemes receive comparisons. The practical analysis demonstrates how these modulation techniques function in different wireless channel conditions which serves as foundation research for digital communication system advancement.

Methodology

- 1. Research and Theoretical Foundation
  - Wireless Access Techniques:

    This report examined the essential wireless access techniques which include Spread Spectrum, FDMA, TDMA and OFDM. This review provided detailed descriptions about how these wireless access methods function in modern communication systems which include cellular networks (1G to 5G), Wi-Fi and satellite communications.

This report demonstrated Spread Spectrum functions as a security tool for communications alongside FDMA and TDMA systems in primitive cellular networks and its application in high-data-rate systems through OFDM in LTE and 5G networks.

- Fundamental Concepts:

  The study investigated core aspects of digital communication systems which include channel capacity alongside bandwidth optimization and orthogonality and error correction approaches. Definitions with explanations were provided for Signal-to-Noise Ratio (SNR) alongside frequency hopping together with interleaving.

  The research evaluated how different concepts enhance data transmission reliability and improve spectral efficiency and resistance against interference.

- 2. Mathematical Analysis and Calculations
  - Spread Spectrum Analysis
    * The Shannon-Hartley theorem was used to analyze the relationship between channel capacity, bandwidth, and SNR:

      $$C = Blog_2(1 + SNR) \tag{1}$$

      where C is the channel capacity, B is the bandwidth, and SNR is the signal-to-noise ratio.
  - LTE Subcarrier Calculation
    * The number of subcarriers in a 100 Mbps LTE data stream with a symbol time of 130 s was calculated using:

      $$N_{subcarriers} = \frac{Data\ Rate\ X\ T_s}{Bits\ per\ Symbol} \tag{2}$$
  - Orthogonality and Subcarrier Analysis
    * The orthogonality condition for OFDM subcarriers was defined as:

      $$\int_0^{T_b} b\cos(2\pi f_1 t)\cos(2\pi f_2 t)\, dt = 0 \tag{3}$$

      The minimum frequency spacing required to maintain orthogonality was derived as:

      $$f = \frac{1}{T_b} \tag{4}$$
  - TDMA System Efficiency
    * The efficiency of a TDMA system was calculated using the formula:

      $$Efficiency = \frac{Number\ of\ voice\ channels\ X\ User\ data\ rate}{Total\ bandwith} \tag{5}$$
  - FHSS Scheme Analysis
    * The minimum number of PN bits required for frequency hopping was calculated using:

      $$N = log_2 \frac{B_{ss}}{B_c} \tag{6}$$
  - Error Correction Techniques
    * The Hamming code was used to demonstrate error detection and correction. The number of parity bits r required for m data bits was calculated as:

      $$2^r \geq m + r + 1 \tag{7}$$

- 3. Computational Simulations
  - OFDM System Simulation

    * The researchers created a basic communication system simulation through MATLAB. The QPSK modulation preceded OFDM processing before the information went through AWGN and Rayleigh channels.
    * The simulation evaluated and compared BER calculations for BPSK, QPSK and 16QAM with theoretical predictions. The simulation process organized the following sequences of actions:
      1. The applied modulation technique for the signal input was QPSK.
      2. The IFFT operation split the signal into subcarriers while a cyclic prefix function was applied for OFDM implementation.
      3. The signal received AWGN and Rayleigh fading treatment through the channel model.
      4. The received signal passed through a demodulation process before the BER calculation took place.

- 4. Validation and Analysis
  - Cross-Verification
    * Simulation results together with mathematical calculations received verification through established benchmarks and theoretical models. The research compared spread spectrum bandwidth requirements against Shannon-Hartley limits as well as simulated BER values from MATLAB against theoretical BER graphs.
  - Performance Analysis
    * The OFDM system faced an evaluation for its performance characteristics when using both AWGN and Rayleigh channels. A performance evaluation of BER through different modulation techniques (BPSK, QPSK, 16QAM) determined optimal choices for wireless channel environments.
  - Efficiency Analysis
    * A performance evaluation based on different bandwidth levels occurred for the TDMA system and its outcomes aligned with cellular network implementation standards.
- 5. Documentation and Reporting
  - Structured Reporting
    * The results received structured organization which ensured both coherence and clarity of presentation. The report contained each section with thorough explanations together with mathematical proof and visual representations.
  - Graphical Representations
    * The report included visual plots that displayed theoretical along with simulated BER curves for BPSK, QPSK, and 16QAM modulation to show their performance characteristics.

Results and Discussions

Activity 1

Assume we wish to transmit a 56-kbps data stream using spread spectrum.

1. Find the channel bandwidth required to achieve a 56-kbps channel capacity when SNR = 0.1, 0.01, and 0.001.

$$C = Blog_2(1 + SNR) \tag{8}$$

For SNR=0.1

$$B = \frac{56 \ * \ 10^3}{log_2(1 + 0.1)} \tag{9}$$

$$B = \frac{56 \ * \ 10^3}{log_2(1.1)} \tag{10}$$

$$log_2(1.1) \approx 0.1375 \tag{11}$$

$$\approx 407.27kHz \tag{12}$$

For SNR = 0.01

$$B = \frac{56 \ * \ 10^3}{log_2(1 + 0.01)} \tag{13}$$

$$B = \frac{56 \ * \ 10^3}{log_2(1.01)} \tag{14}$$

$$log_2(1.1) \approx 0.0144 \tag{15}$$

$$\approx 3.89MHz \tag{16}$$

For SNR = .001

$$B = \frac{56 \ * \ 10^3}{log_2(1 + 0.001)} \tag{17}$$

$$B = \frac{56 \ * \ 10^3}{log_2(1.001)} \tag{18}$$

$$log_2(1.1) \approx 0.00144 \tag{19}$$

$$\approx 38.89MHz \tag{20}$$

2. In an ordinary (not spread spectrum) system, a reasonable goal for bandwidth efficiency might be 1 bps/Hz. In other words, to transmit a data stream of 56 kbps, a bandwidth of 56 kHz is used. In this case, what is the minimum SNR that can be endured for transmission without appreciable errors? Compare to the spread spectrum case

   We solve SNR:

$$SNR = 2^{C/B} - 1 \tag{21}$$

   Now we substitute

$$C = 56kbps = 56 \ * \ 10^3 bps \tag{22}$$

$$B = 56kHz = 56 \ X \ 10^3 Hz \tag{23}$$

$$SNR = 2^{(56 \ * \ 10^3/56 \ * \ 10^3)} - 1 \tag{24}$$

$$SNR = 2^1 - 1 \tag{25}$$

$$SNR = 1 \tag{26}$$

   Convert SNR to linear Scale

$$SNR(dB) = 10log_{10}(SNR) \tag{27}$$

$$SNR = (dB) = 10 \ * \ 0 \ = 0dB \tag{28}$$

   For data transmission at 56-kbps using a non-spread spectrum system with a 56 kHz bandwidth the needed SNR threshold equals:

$$SNR = 0dB \tag{29}$$

   Spread spectrum systems operate with substantially superior noise tolerance than the minimum required SNR values for ordinary (non-spread spectrum) transmission systems.

Activity 2

Assume a 100 Mbps LTE (Long-Term Evolution) data stream with a symbol time of 130µs, how many subcarriers are created? Assume 1-bit/symbol.

$$R_s = \frac{1}{T_s} \tag{30}$$

Substitute $T_s = 130 \times 10^{-6}\,\mathrm{s}$

$$R_s = \frac{1}{130\ *\ 10^{-6}} = 7,692.31\ symbols/second \tag{31}$$

We are given $R = 100 \times 10^6$ bps and $b = 1$ bit/symbol. Substituting these values:

$$100\ *\ 10^6 = 7,692.31\ *\ 1 \tag{32}$$

Now Substitute $R_s = 7,692.31\,\mathrm{symbols/second}$ and $b = 1\,\mathrm{bit/symbol}$.

$$R_{sub} = 7,692.31\ *\ 1 = 7,692.31bps \tag{33}$$

$$N = \frac{R}{R_{sub}} \tag{34}$$

$$N = \frac{100\ *\ 10^6}{7,692.31} \approx 13,000 \tag{35}$$

Activity 3

a) Find the relationship between subcarrier frequencies f1 and f2 that is required for two subcarriers to be orthogonal to satisfy the following orthogonality condition. Assume f1 and f1 are both integer multiples of 1/Tb. b) what is the minimum spacing that is possible to still maintain orthogonality?

To ensure orthogonality between two subcarriers with frequencies f_1 and f_2 the following condition must be satisfied by:

$$\int_0^{T_b} \cos(2\pi f_1 t)\cos(2\pi f_2 t)\,dt = 0 \tag{36}$$

Applying this identity to the integrand:

$$\cos(2\pi f_1 t)\cos(2\pi f_2 t) = \frac{1}{2}[cos(A+B) + \cos(A-B)] \tag{37}$$

Substitute the rewritten integrand into the orthogonality condition:

$$\int_0^{T_b} \cos(2\pi f_1 t)\cos(2\pi f_2 t) = \frac{1}{2}\int_0^{T_b} [\cos(2\pi(f_1\ +\ f_2)t) + \cos(2\pi(f_1 - f_2)t)]dt \tag{38}$$

a) For orthogonality, the frequencies f_1 and f_2 must satisfy:

$$f_1 = n\ *\ \frac{1}{T_b},\ f_2 = m\ *\ \frac{1}{T_b} \tag{39}$$

Where n and m are integers, and $n \neq m$.

b) Orthogonality demands the minimal difference between f_1 and f_2 frequencies to be Δ f to satisfy the orthogonality condition. From the relationship above:

$$\Delta f = |f_1 - f2| \tag{40}$$

The smallest possible difference occurs when $|n - m| = 1$

$$\Delta f = \frac{1}{T_b} \tag{41}$$

Activity 4

Prove if orthogonality holds for the following complex exponentials and verify if these two functions are periodic over T_s (symbol period).

$$\int_0^{T_s} e^{-j2\pi mt/T_s} \cdot e^{j2\pi nt/T_s}\, dt = 0 \tag{42}$$

We have to combine the two exponentials

$$e^{-j2\pi mt/T_s} \cdot e^{j2\pi nt/T_s} = e^{j2\pi(n-m)t/t_s} \tag{43}$$

And we get:

$$\int_0^{T_s} e^{j2\pi(n-m)t/T_s} dt \tag{44}$$

This integral will be evaluated as:
If $n = m$:

$$\int_0^{T_s} e^{j2\pi(0)t/T_s} dt = \int_0^{T_s} 1\ dt = T_s \tag{45}$$

If $n \neq m$

$$\int_0^{T_s} e^{j2\pi(n-m)t/T_s} dt = \left[\frac{T_s}{j2\pi(n-m)} e^{j2\pi(n-m)t/T_s}\right]_0^{T_s} \tag{46}$$

$$= \frac{T_s}{j2\pi(n-m)}(1-1) = 0 \tag{47}$$

According to that,

If $n = m$, the integral evaluates to T_s

If $n \neq m$, the integral evaluates to 0

So The complex exponentials $e^{j2\pi mt/T_s}$ and $e^{j2\pi nt/T_s}$ are orthogonal over the interval $[0, T_s]$ when $n \neq m$. Both functions are periodic with T_s.

Activity 5

In a proposed TDMA cellular system, the one-way bandwidth of the system is 40MHz. The channel spacing is 30 kHz and total voice channels in the system are 1333. The frame duration is 40ms divided equally between six time slots. The system has an individual user data rate of 16.2 kbps in which the speech with error protection has a rate of 13 kbps. Calculate the efficiency of the TDMA system. What is the efficiency of the system with 20, 60, 80 and 100 MHz?

$$B_t = 40MHz \tag{48}$$

$$B_c = 30KHz \tag{49}$$

$$N_T = 1333channels \tag{50}$$

$$T_f = 40ms \tag{51}$$

$$M_t = 6timeslots \tag{52}$$

We prove the channel spacing formula.

$$B_c = B_t/N_T = 40 * 10^3/1333 = 30KHz \tag{53}$$

Total number of users supported in the total UL or DL bandwidth.

$$N = \frac{40 * 10^6}{(30 * 10^3)/6} = 8,000 simultaneoususers \tag{54}$$

Duration of time slot that carries data.

$$\tau = (\frac{13 * 10^3}{16.2 * 10^3})(\frac{T_f}{M_t}) = (.802Hz)(\frac{40ms}{6}) = 5.35ms \tag{55}$$

Multiple access spectral efficiency.

$$\eta a = \frac{\tau * M_t}{T_f} * \frac{B_c * N_t}{B_t} = \frac{5.35 * 6}{40} * \frac{30 * 1333}{40,000KHz} = .80 = 80\% \tag{56}$$

Overhead portion of the frame.

$$1.0 - .80 = 20\% \tag{57}$$

20MHz.

$$\eta a = \frac{\tau * M_t}{T_f} * \frac{B_c * N_t}{B_t} = \frac{5.35 * 6}{40} * \frac{30 * 1333}{20,000KHz} = 1.60 = 160\% \tag{58}$$

More data than the system can support using 20MHz.

60MHz.

$$\eta a = \frac{\tau * M_t}{T_f} * \frac{B_c * N_t}{B_t} = \frac{5.35 * 6}{40} * \frac{30 * 1333}{60,000KHz} = .53 = 53\% \tag{59}$$

Overhead portion of the frame.

$$1.0 - .53 = 47\% \tag{60}$$

80MHz.

$$\eta a = \frac{\tau * M_t}{T_f} * \frac{B_c * N_t}{B_t} = \frac{5.35 * 6}{40} * \frac{30 * 1333}{80,000KHz} = .40 = 40\% \tag{61}$$

Overhead portion of the frame.

$$1.0 - .40 = 60\% \tag{62}$$

100MHz.

$$\eta a = \frac{\tau * M_t}{T_f} * \frac{B_c * N_t}{B_t} = \frac{5.35 * 6}{40} * \frac{30 * 1333}{100,000KHz} = .32 = 32\% \tag{63}$$

Overhead portion of the frame.

$$1.0 - .32 = 68\% \tag{64}$$

Activity 6

Assume a FHSS scheme with a hopping bandwidth, Bss, of 300 MHz and an individual channel bandwidth of 4 kHz. Compute the minimum number of Pseudo Noise (PN) bits required for each frequency hop?

$$Bss = 300MHz \tag{65}$$

$$B_c = 4KHz \tag{66}$$

$$B_c = \frac{Bss}{N_t} \tag{67}$$

$$B_c * N_T = Bss \tag{68}$$

$$N_T = \frac{Bss}{Bc} \tag{69}$$

$$N_T = \frac{300 * 10^6}{4 * 10^3} = 75,000 channels \tag{70}$$

$$K = \log_2(Nt) \tag{71}$$

$$K = \log_2(75,000) \approx 16.19 = 17 bits \tag{72}$$

Necesitamos un numero entero para representar todas las frecuencias posibles en el sistema FHSS.

$$2^{16} = 65,536 < 75,000 \tag{73}$$

Por lo que no es posible dejarlo en 16.

En cambio:

$$2^{17} = 131,072 > 75,000 \tag{74}$$

Un total de canales lo suficientemente grande para cubrir los 75,000 canales requeridos.

Activity 7

a) The sequence 1011000000000011 is the input to a 4 × 4 block interleaver. What is the output? Provide an example of burst errors using the same bit sequence. What is the output of the deinterleaved sequence at the receiver? b) Investigate and provide an example on how to correct errors using Hamming codes.

a)

Input: 1011000000000011

Interleaving:

1	0	1	1
0	0	0	0
0	0	0	0
0	0	1	1

Figure 1: Interleaving

Transmitting Data: 1000000010011001

Received Data: 1000000010011001

De-Interleaving:

1	0	1	1
0	0	0	0
0	0	0	0
0	0	1	1

Figure 2: De-Interleaving

Output Data: 1011000000000011

Burst Error example:

Suppose a burst error occurs where 4 bits in the sequence are flipped due to noise or interference. Let's assume bits 5-8 (0 0 0 0) become corrupted to 1 1 1 1:

1000 1111 10011001

At the receiver, the deinterleaver rearranges the bits back into a 4×4 matrix by filling the columns first:

1	0	1	1
0	1	1	1
0	1	0	0
0	0	1	1

Figure 3: De-Interleaving Burst Error

Reading row-wise, the deinterleaved sequence is:

1011011101000011

The burst error is now spread across different rows, making it easier for error-correcting codes to detect and correct.

b) 1. Encoding with Hamming (7,4) Code

The Hamming (7,4) code takes a 4-bit data word and adds 3 parity bits, forming a 7-bit codeword.

Example: Consider a 4-bit data: 1011

To compute parity bits p1, p2, p3.

$$p1 = d1 \oplus d2 \oplus d4 = 1 \oplus 0 \oplus 1 = 0 \tag{75}$$

$$p2 = d1 \oplus d3 \oplus d4 = 1 \oplus 1 \oplus 1 = 1 \tag{76}$$

$$p3 = d2 \oplus d3 \oplus d4 = 0 \oplus 1 \oplus 1 = 0 \tag{77}$$

Final Hamming code: p1 p2 d1 p3 d2 d3 d4

0110011

2. Simulating an Error

Suppose a transmission error flips the third bit:

0100011

3. Error Detection and Correction

To find the error, the receiver recalculates the parity bits and checks for inconsistencies:

Syndrome bits calculation:

$$S1 = p1 \oplus d1 \oplus d2 \oplus d4 = 0 \oplus 0 \oplus 0 \oplus 1 = 1 \tag{78}$$

$$S2 = p2 \oplus d1 \oplus d3 \oplus d4 = 1 \oplus 0 \oplus 1 \oplus 1 = 1 \tag{79}$$

$$S3 = p3 \oplus d2 \oplus d3 \oplus d4 = 0 \oplus 0 \oplus 1 \oplus 1 = 0 \tag{80}$$

Syndrome = S3S2S1= 011sub2=3sub10, meaning the 3rd bit is in error.
The receiver corrects it by flipping the 3rd bit back to 1, recovering the correct sequence:

0110011

This way, Hamming codes detect and correct single-bit errors effectively.

Activity 8

Using the MATLAB code and the simulation parameters described in [2], simulate a basic communication system in which the signal is first QPSK modulated and then subjected to the Orthogonal Frequency Division Multiplexing (OFDM). A block diagram of the implementation of OFDM is shown in Figure 1 [1]. The signal is then passed through an additive white Gaussian noise (AWGN) channel to being demultiplexed and demodulated. Plot the theoretical and simulated data using BPSK, QPSK, and 16QAM on the same graph to compare results. Compare to the case of a Rayleigh channel. Compute the BER and conclude your results for both wireless channels [3]. Note that you can use the already defined MATLAB modulation system objects.

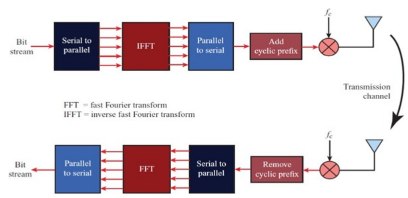

Figure 4: Implementation of OFDM [1].

Code in blackboard.

This MATLAB code simulates a basic communication system using Orthogonal Frequency Division Multiplexing (OFDM) with BPSK, QPSK, and 16QAM modulation schemes. The simulation evaluates the system's performance under both Additive White Gaussian Noise (AWGN) and Rayleigh fading channels by calculating the Bit Error Rate (BER) for each modulation scheme. The code begins by defining simulation parameters, such as the number of subcarriers, cyclic prefix length, and SNR range. It then generates random data bits, modulates them using the specified scheme, and applies OFDM modulation with a cyclic prefix. The signal is transmitted through AWGN and Rayleigh channels, and the received signal is demodulated to compute the BER. Theoretical BER values are also calculated and plotted alongside the simulated results for comparison. The code provides a comprehensive analysis of how different modulation schemes perform under varying channel conditions, highlighting the trade-offs between spectral efficiency and noise resilience.

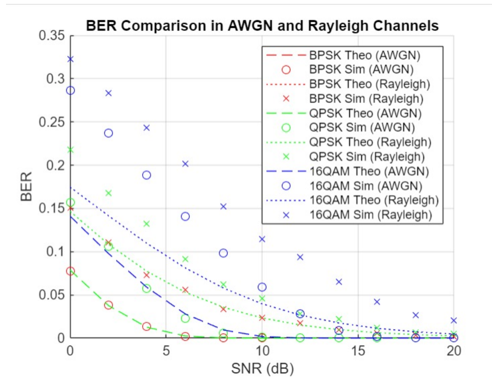

Figure 5: Code

Conclusions

The report provides a detailed exploration of key digital communication technologies, including Spread Spectrum, FDMA, TDMA, and OFDM, emphasizing their roles in modern wireless systems. Through theoretical analysis and practical simulations, the study highlights the trade-offs between bandwidth and noise tolerance in Spread Spectrum systems, demonstrating their superior performance in interference-prone environments. The investigation into LTE subcarrier generation and orthogonality requirements underscores the importance of minimizing interference in multi-carrier systems. Additionally, the efficiency analysis of TDMA systems reveals how varying bandwidths impact performance, with higher bandwidths leading to reduced efficiency due to increased overhead. The study also delves into Frequency Hopping Spread Spectrum (FHSS), calculating the minimum PN bits required for secure and interference-resistant communication. Error correction techniques, such as block interleaving and Hamming codes, are examined for their effectiveness in mitigating burst errors and ensuring data integrity. Finally, the MATLAB simulation of a QPSK-modulated OFDM system subjected to AWGN and Rayleigh channels provides valuable insights into the performance of different modulation schemes (BPSK, QPSK, and 16QAM) under various wireless conditions. The results confirm that higher-order modulations like 16QAM require higher SNR for reliable communication, especially in fading channels. Overall, the report bridges theoretical concepts with practical applications, offering a robust foundation for understanding and optimizing digital communication systems.

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