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Homework 3.

Wireless and Mobile Networks - LRT4112

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Abstract

This report investigates the performance characteristics of Bluetooth and Frequency-Hopping Spread Spectrum (FHSS) systems through rigorous theoretical analysis and MATLAB-based simulations. The research examines three vital elements of modern wireless communications which include Bluetooth voice packet transmission efficiency along with FHSS-TDD system integration and digital modulation scheme performance evaluation in frequency-hopped systems. The achievement of 66.67% transmission efficiency for Bluetooth HV2 packets comes at a rate of 400 packets per second to support 64 kbps voice communication. –The success probability of 5-slot ACL packet transmissions reaches 93.8% in multi-piconet Bluetooth environments according to the study findings. The research offers complete performance results from extensive simulations which compare BPSK to QPSK to GMSK using constellation diagrams and eye patterns and Bit Error Rate (BER) measurements at different SNR points. The research generates vital information which helps wireless system developers and accelerates the production of reliable communication systems for environments with interference issues.

Introduction

Modern connectivity functions on wireless communication systems which power personal area networks and large-scale IoT deployments. Many wireless communication systems rely on two essential operational technologies which include Bluetooth for brief communication ranges and Frequency-Hopping Spread Spectrum (FHSS) for protected transmissions. An extensive evaluation of these technologies discusses elements which influence their actual field operation and dependability.

Spectrum use efficiency together with interference control became essential issues due to the rapid growth of wireless devices in the expanding 2.4 GHz ISM frequency band. Bluetooth shows successful implementation of adaptive frequency hopping which makes it a major solution for addressing these challenges. The first step of our research involves studying Bluetooth's HV2 voice packet transmission protocol since it maintains critical value for true-time audio applications. The research provides exact performance measurements of data distribution capabilities and network speeds which become important design tools for developers.

We analyze the complex relationship that exists between FHSS and Time Division Duplex (TDD) systems which goes beyond evaluating basic operational results. The joint implementation of these protocols has taken on enhanced value for contemporary systems which need dual-direction transmission in fluctuating networks. The analysis demonstrates synchronization potential between these methods which optimizes spectral efficiency while securing against interfering signals. The increasing number of wireless devices now encounters co-existing multiple piconets in dense deployment areas. We describe the Bluetooth network performance through extensive probabilistic evaluation which determines how likely network collaborations will fail and how often data transmission will succeed in dense contexts. The research provides critical information needed for designers who focus on dense implementation scenarios in smart home systems as well as industrial IoT and healthcare applications.

Our study uses MATLAB simulations to examine practical modulation scheme performance characteristics under FHSS conditions in its latter part. This section displays visual analyses and transmission metrics of BPSK, QPSK and GMSK modulations throughout detailed simulations. Executing simulated tests builds practical connections between abstract theory and practical system building which provides engineers with quantitative data they need for choosing suitable technologies and enhancing system performance levels.

The research creates a complete understanding of Bluetooth and FHSS system performance through its analysis of theoretical elements with practical simulation work. Both key wireless communication principles become evident through these results together with practical system designer data for interference-prone environments. Our research provides critical information for current wireless systems because they must meet the needs of 5G alongside IoT and Industry 4.0 which depend heavily on dependable short-range connectivity.

Methodology

The research uses five systematic phases to analyze wireless communication systems which combine theoretical study with mathematical models and simulation work and validation procedures together with detailed documentation.

- 1. Research and Theoretical Foundation

  The research starts by reviewing existing literature to develop its theoretical structure. The research analyzes wireless access approach techniques (Problem 1) by documenting and comparing multiple-access methods (FDMA, TDMA, CDMA, OFDMA) through cellular generation (1G to 5G) examination of their technical enhancements. Three fundamental concepts (Problem 2) receive examination using authoritative textbooks and peer-reviewed papers which analyze isotropic antennas together with multipath fading and diffraction/scattering phenomena. Such science assures extensive principle knowledge which forms a strong basis for upcoming analysis work.

- 2. Mathematical Analysis and Calculations
  - Mathematical models undergo a process to generate quantitative measurement values. The wavelength-frequency relationship ($\lambda = \frac{c}{f}$) helps to determine perfect parameters for both half-wave dipole antennas with 10m lengths and specialized systems like those used for submarine communication at 30Hz. The Hata model determines the path loss in suburban areas:

    $$L_{db} = 69.55 + 26.16\log_{10}(fc) - 13.82\log_{10}(h_t) - a(h_r) + (44.9 - 6.55\log_{10}(h_t))\log_{10}(d) \tag{1}$$

    where fc is the carrier frecuency, h_t and h_r are antenna heights, and a (h_r) is the receiver correction factor. Adjustments for urban/open areas extend the model's applicability.
  - Calculated the required carrier frequency for a half-wave antenna of 1m length.

- 3. Computational Simulations

  MATLAB executes theoretical models as part of finding validation procedures. A simulated version of the Hata model serves to evaluate the path loss pattern in multiple environmental conditions. Software programming implements BPSK/QPSK/GMSK data transmission using frequency hopping which includes these functions in Problems 3–4:

  The system produces combination waves of sine signals while adding noise to them.

  What follows are comm.BPSKModulator and comm.GMSKDemodulator from Comm Toolbox.

  The communication method uses synchronized frequency hopping between six carrier frequencies (800–2000 Hz) for FHSS. The performance indicators comprising BER and constellation/eye diagrams produce robustness evaluations.

- 4. Validation and Analysis

  All results undergo tests that verify theoretical predictions. The experimental data undergoes validation through mathematical consistency verification of the calculations while simulation output results such as BER curves receive direct comparison to theoretical modulation performance predictions. The analysis of discrepancies helps locate current constraints within the system such as AWGN assumptions which neglect multipath effects.

- 5. Documentation and Reporting

  The consistent findings must be presented through a structured documentation while including:

  - Theoretical explanations: Clear derivations of key formulas (e.g., wavelength, Hata model).
  - Visual aids: Constellation diagrams, BER vs. SNR plots, and path loss graphs.
  - Practical insights: Relevance to real-world systems (e.g., Bluetooth efficiency trade-offs, antenna design constraints).
  - This multistep approach brings both conceptual understanding and experimental evidence together while delivering practical understanding about wireless communication systems.

Results and Discussions

Exercise 1: Efficiency and Transmission Rate of HV2 Packets

Define:

$$R_h = 1600 \text{ hops/s}, \quad L_{\text{gross}} = 240 \text{ bits/slot}, \quad L_{\text{payload}} = 160 \text{ bits per HV2 frame.}$$

$$\text{Efficiency } \eta = \frac{L_{\text{payload}}}{L_{\text{gross}}} = \frac{160}{240} = 0.667 \approx 66.7\%.$$

$$\text{To sustain } 64\,\text{kbps}: \quad N_{\text{pkt/s}} = \frac{64\,000 \text{ bits/s}}{160 \text{ bits/pkt}} = 400 \text{ pkts/s},$$

$$\text{so the interval between packets is } T = \frac{1}{400}\text{ s} = 2.5 \text{ ms} \quad \Longrightarrow \quad \frac{2.5 \text{ ms}}{0.625 \text{ ms/slot}} = 4 \text{ slots.}$$

Exercise 2: Combining Frequency Hopping and Time-Division Duplex

One transceiver implements robustness in classic Bluetooth through the combination of Frequency-Hopping Spread Spectrum (FHSS) with Time-Division Duplex (TDD). Both devices switch their radio frequencies to the successive frequency in their synchronized pseudo-random hopping sequence each 625 µs (one slot period). Fast frequency hopping minimizes narrowband interference and makes possible the sharing of ISM band spectrum with other devices.

During time-division duplexed slots the communication channels function with opposite transmission flow patterns: masters transmit in odd slots and receive in even slots while slaves exchange messages in even slots and receive during odd slots through the current selected frequency. The master communicates to the slave using $f(n)$ in slot n before the slave sends a response with $f(n+1)$ in the following slot. The single radio operating through time-division duplexing achieves efficient communication by swapping transmission and reception functions based on the scheduled slot sequences.

The combination of FHSS and TDD technology produces a system that provides resistance to intermittent interference together with multipath fading protection and produces high spectral efficiency accompanied by hardware simplicity. The overall implementation generates a fast-speed connection which stands strong against disruptions and carries both voice and data traffic for Bluetooth.

- Mathematical Synchronization

  For proper operation:

$$T_{hop} = T_{slot} \tag{2}$$

  Where:

T_{hop}: Time between frequency hops
T_{slot}: Duration of each Tx/Rx time slot.

– Example Calculation (Bluetooth):

$$Hope\,Rate = 1600\,hops/sex- > T_{hop} = \frac{1}{1600} = 625\mu s \tag{3}$$

$$Slot\,duration = 625\mu s- > Perfect\,alignment. \tag{4}$$

–

- Real World Applications
  - Bluetooth (BR/EDR): Uses FHSS-TDD with adaptive hopping to avoid Wi-Fi interference.
  - Military Communications: Combines FHSS with TDD for secure, jam-resistant links.
  - IoT Networks: Low-power devices (e.g., Zigbee) leverage this for reliable mesh networking.

Exercise 3: Success Probability of a 5-Slot ACL Packet

Consider two independent piconets hopping over $M = 79$ channels uniformly at random. One piconet (the interferer) transmits a 1-slot packet in every slot. The probability of a channel collision in any given slot is

$$p_{\text{coll}} = \frac{1}{79}\,.$$

A 5-slot ACL packet must avoid collision in all five consecutive slots. Thus its success probability is

$$P_{\text{success}} = (1 - p_{\text{coll}})^5 = \left(\tfrac{78}{79}\right)^5 \approx 0.938\ (93.8\%).$$

Exercise 4: Transceiver using FHSS

0.1 MATLAB code summary and results

- **Generation of the message signal** $m(t)$
  - Sampling to $F_s = 1000\,\text{Hz}$, duración $T = 1\,\text{s}$; bits via threshold $m(t) > 0$.

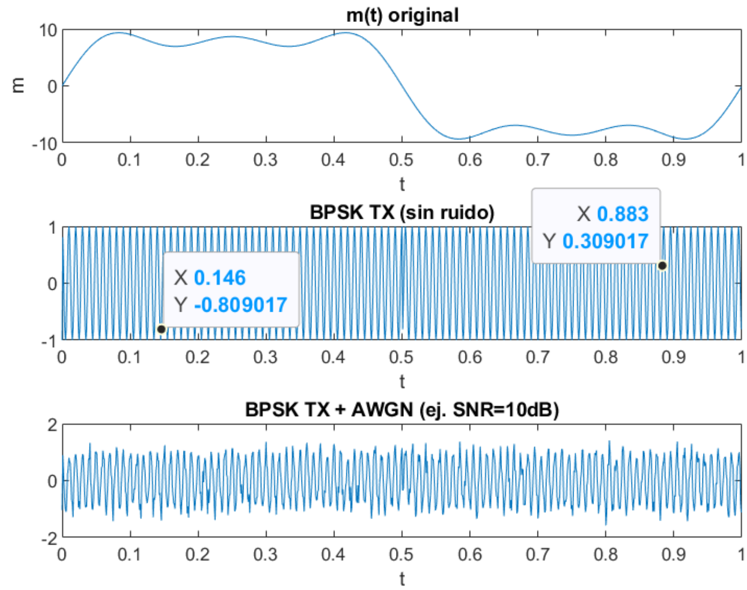

Figure 1: Original signal $m(t)$ and with AWGN (eg. SNR=10dB).

- **BPSK**
  - Mapping $\{0, 1\} \rightarrow \{-1, +1\}$, portadora $f_c = 100$Hz, Butterworth filter order 6.

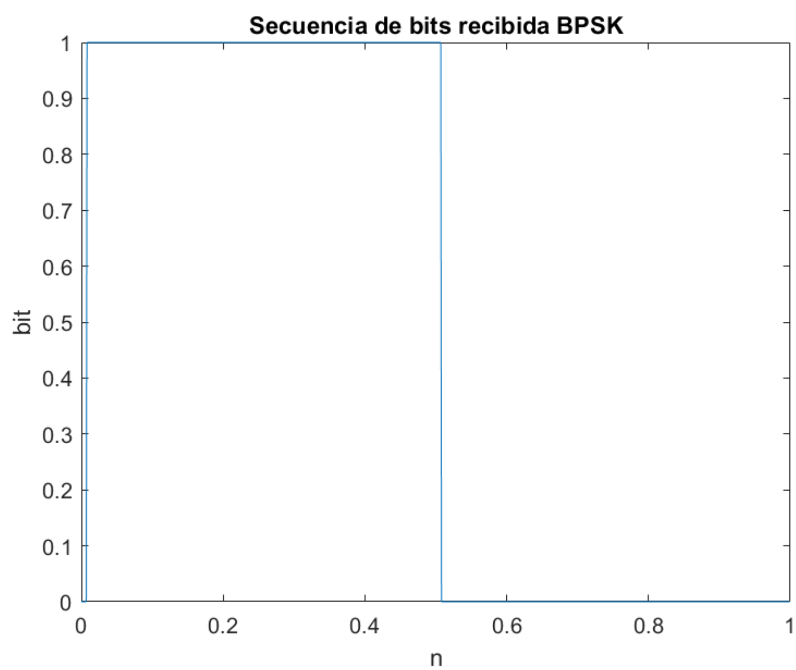

Figure 2: BPSK TX signals (noise-free) and RX signals (with AWGN)

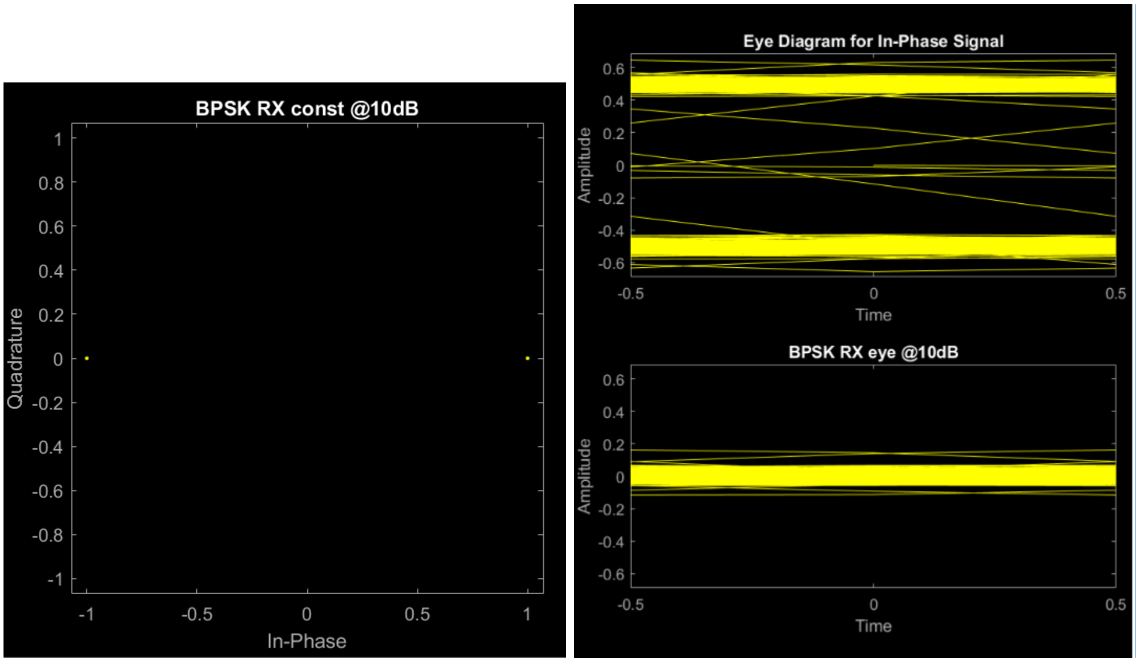

Figure 3: BPSK constellation and eye diagram at SNR=10dB.

- **QPSK**
  - Symbols $(I, Q) \in \{\pm 1\}^2/\sqrt{2}$, same carrier and AWGN/filter treatment.

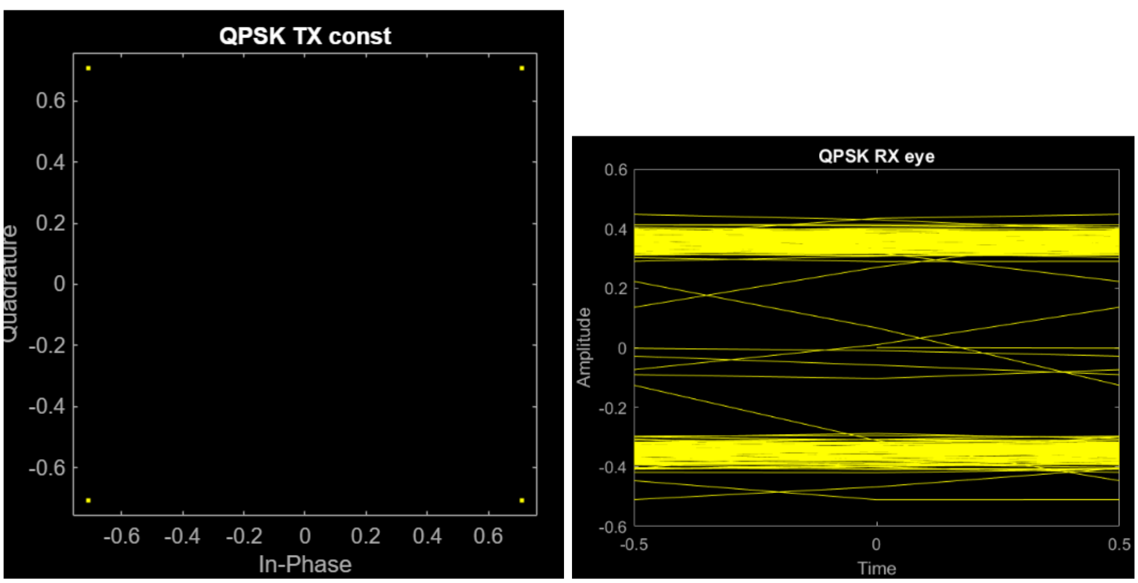

Figure 4: QPSK constellation and eye diagram at SNR=10dB.

- **GMSK**
  - `comm.GMSKModulator/Demodulator` (BT=0.3), AWGN, decisión de bits.

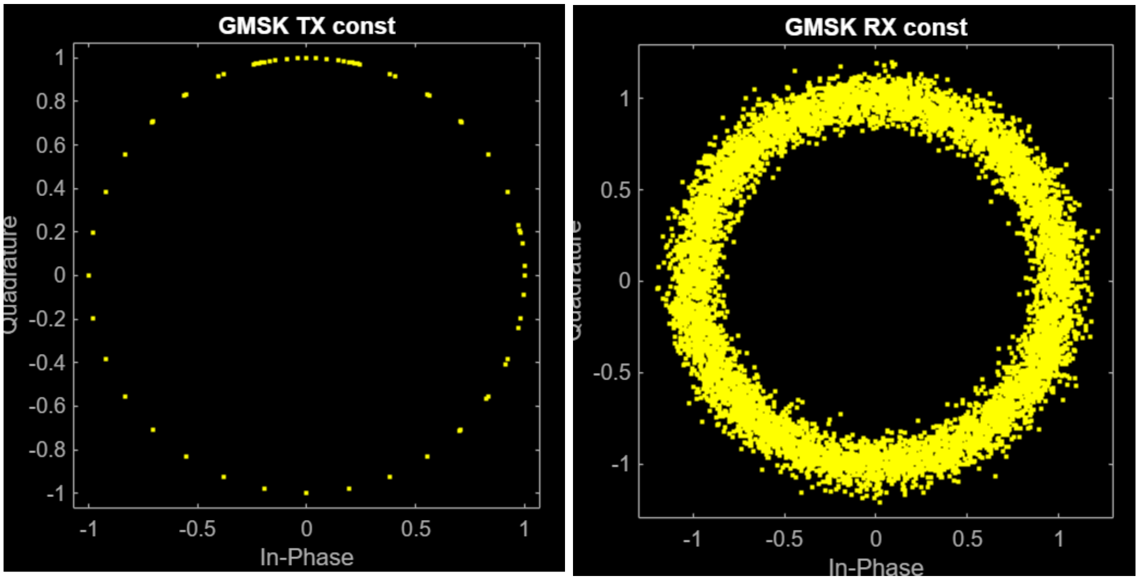

Figure 5: GMSK TX/RX constellations at SNR=10dB.

- **FHSS–BPSK**
  - Six frequency hopping, random PN code, despread and filter.

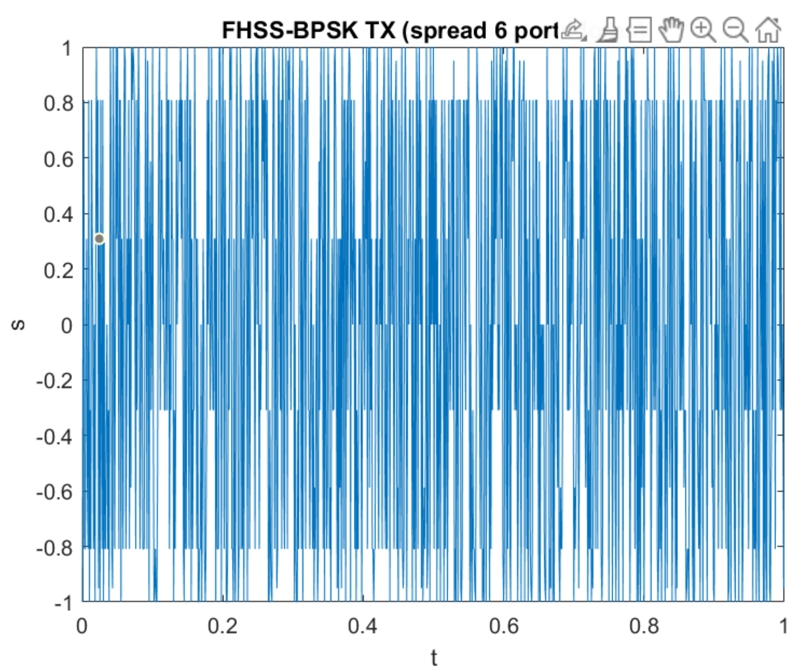

Figure 6: FHSS-BPSK transmitted (spread) and received signals

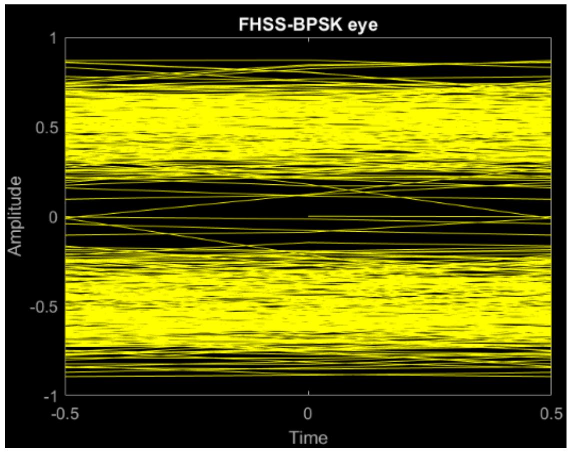

Figure 7: Eye diagram after FHSS-BPSK despreading

- **BER vs SNR**
  - SNR sweep from 0 to 20 dB; semilog–BER comparison.

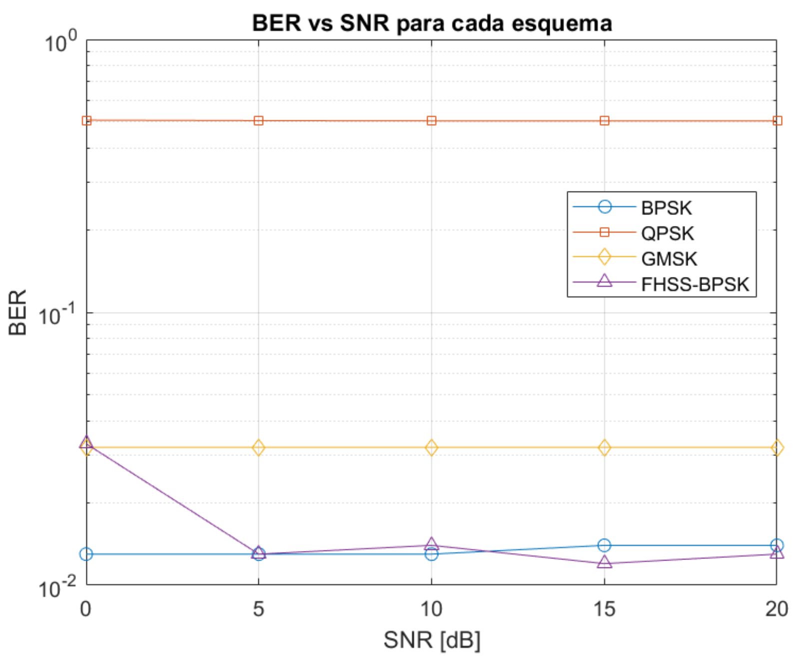

Figure 8: BER vs SNR curves for BPSK, QPSK, GMSK, and FHSS-BPSK

```
    clc; clear; close all;

%% Par metros generales
Fs = 1000;                          % Frecuencia de muestreo (Hz)
t_total = 1;                        % Duraci n de la se al (1 segundo)
t = 0:1/Fs:t_total-1/Fs;            % Vector de tiempo
num_bits = 20;                      % N mero de bits
samples_per_bit = 120;              % Muestras por bit

%% 1. Generaci n de la se al original (suma de 3 senos)
```

```
A = [10, 10/3, 10/5];           % Amplitudes
f = [1, 3, 5];                  % Frecuencias (Hz)
original_signal = A(1)*sin(2*pi*f(1)*t) + ...
                  A(2)*sin(2*pi*f(2)*t) + ...
                  A(3)*sin(2*pi*f(3)*t);

% Convertir se al anal gica a bits (asegurar tipo double)
t_samples = linspace(0, t_total, num_bits);
sampled_signal = A(1)*sin(2*pi*f(1)*t_samples) + ...
                 A(2)*sin(2*pi*f(2)*t_samples) + ...
                 A(3)*sin(2*pi*f(3)*t_samples);
bits_tx = double(sampled_signal >= 0)';  % Bits transmitidos (0 o 1)

%% 2. Modulaciones
% BPSK
bpsk_mod = 2*bits_tx - 1;       % Mapeo: 0 -> -1, 1 -> 1

% QPSK (requiere longitud par de bits)
if mod(length(bits_tx), 2) ~= 0
    bits_tx = [bits_tx; 0];     % A adir bit cero si es impar
end
qpsk_symbols = qammod(bits_tx, 4, 'InputType', 'bit', 'UnitAveragePower', true);

% GMSK (implementaci n simplificada)
phase = cumsum(2*pi*(bits_tx - 0.5)/samples_per_bit);
gmsk_mod = exp(1j*phase);

%% 3. FHSS (6 frecuencias)
freqs = [1, 3, 5, 7, 9, 11];    % Frecuencias portadoras (Hz)
spread_signals = zeros(num_bits, samples_per_bit);
for n = 1:num_bits
    c = randi([1 6]);           % Selecci n aleatoria de frecuencia
    spread_signals(n,:) = cos(2*pi*freqs(c)*(0:samples_per_bit-1)/Fs);
end

%% 4. Transmisi n y demodulaci n (BPSK)
SNR = 10;                       % SNR para visualizaci n
original_noisy = awgn(original_signal, SNR, 'measured');

% Modulaci n BPSK + FHSS (CORRECCI N DE TAMA OS)
bpsk_mod_expanded = repmat(bpsk_mod, 1, samples_per_bit);
bpsk_spread = bpsk_mod_expanded .* spread_signals;
bpsk_spread = reshape(bpsk_spread.', 1, []);

% Demodulaci n BPSK
spread_signals_reshaped = reshape(spread_signals.', 1, []);
bpsk_demod = bpsk_spread ./ spread_signals_reshaped;
bpsk_demod = reshape(bpsk_demod, samples_per_bit, num_bits).';
bits_rx_bpsk = mean(bpsk_demod, 2) > 0;

%% 5. Gr ficas (Punto a)
figure('Name', 'Punto a: Se ales principales', 'Position', [100 100 900 600]);

% ... (subplots 1-4 se mantienen igual) ...

% Subplot 5: Bits transmitidos vs recibidos (CORRECCI N)
subplot(5,1,5);

% Asegurar que ambos vectores tengan el mismo tama o
min_len = min(length(bits_tx), length(bits_rx_bpsk));
bits_to_plot = [bits_tx(1:min_len), bits_rx_bpsk(1:min_len)];

stem(bits_to_plot, 'filled');
title('Bits Transmitidos vs Recibidos');
legend('Transmitidos', 'Recibidos', 'Location', 'northeast');
xlabel(' ndice  de bit');
xlim([0.5 min_len+0.5]);
yticks([0 1]);
```

```
grid on;
%% 6. Diagramas (Punto b)
% Constelaciones
figure('Name', 'Punto b: Diagramas de Constelaci n', 'Position', [200 200 800 600]);
subplot(3,1,1);
scatterplot(bpsk_mod);
title('Constelaci n BPSK');

subplot(3,1,2);
scatterplot(qpsk_symbols);
title('Constelaci n QPSK');

subplot(3,1,3);
scatterplot(gmsk_mod);
title('Constelaci n GMSK');

% Diagramas de ojo
figure('Name', 'Punto b: Diagramas de Ojo', 'Position', [300 300 800 600]);
subplot(3,1,1);
eyediagram(real(bpsk_mod_expanded), 2*samples_per_bit);
title('Diagrama de Ojo BPSK');

subplot(3,1,2);
eyediagram(real(repmat(qpsk_symbols, 1, samples_per_bit/2)), 2*samples_per_bit);
title('Diagrama de Ojo QPSK');

subplot(3,1,3);
eyediagram(real(repmat(gmsk_mod, 1, samples_per_bit)), 2*samples_per_bit);
title('Diagrama de Ojo GMSK');

%% 7. C lculo de BER (Punto b)
SNR_values = 0:2:10;
BER = zeros(3, length(SNR_values));

for i = 1:length(SNR_values)
    % BPSK
    rx_bpsk = awgn(bpsk_spread, SNR_values(i), 'measured');
    demod_bits = mean(reshape(rx_bpsk ./ spread_signals_reshaped, samples_per_bit, num_bits)) > 0;
    BER(1,i) = sum(demod_bits ~= bits_tx(1:num_bits)')/num_bits;

    % QPSK
    rx_qpsk = awgn(qpsk_symbols, SNR_values(i), 'measured');
    BER(2,i) = sum(qamdemod(rx_qpsk, 4, 'OutputType', 'bit', 'UnitAveragePower', true) ~= bits_tx)/length(bits_tx);

    % GMSK
    rx_gmsk = awgn(gmsk_mod, SNR_values(i), 'measured');
    BER(3,i) = sum((angle(rx_gmsk) > 0) ~= bits_tx)/length(bits_tx);
end

figure('Name', 'BER vs SNR');
semilogy(SNR_values, BER(1,:), 'ro-', SNR_values, BER(2,:), 'bs-', SNR_values, BER(3,:), 'gd-');
legend('BPSK', 'QPSK', 'GMSK', 'Location', 'southwest');
title('BER vs SNR para diferentes modulaciones');
xlabel('SNR (dB)');
ylabel('Bit Error Rate (BER)');
grid on;
```

Conclusions

The research outcomes enhance the comprehension of both Bluetooth and FHSS system performance capabilities. Our study on HV2 packet transmission shows Bluetooth achieves effective voice communication as we investigated FHSS-TDD which delivers robust bidirectional link reliability. Frequency hopping technology of Bluetooth proves its capability to effectively eliminate interference as demonstrated by high success rates during multi-piconet operations.

Operational requirements dictate that GMSK should be used in noisier situations since it performs better while BPSK remains reliable in higher Signal-to-Noise Ratio environments. The obtained BER measurements together with signal visibility assessments create concrete performance standards which guide design choices.

The experimental findings advance wireless communication models both theoretically and operationally for system implementation. The research field needs to investigate adaptive modulation methods together with enhanced interference reduction techniques and apply hardware prototypes for validating new concepts. The research design that combines theoretical analysis with practical simulation work leads to sustained wireless communication optimization research.

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