Abstract - This paper presents the implementation of Bluetooth Low Energy Controller (BTLE), Low Intermediate Frequency (IF), Gaussian Frequency Shift Keying (GFSK) Modulation and Demodulation technique. The GFSK modulation uses a bandwidth bit period product BT=0.5. The modulation index shall be configurable between 0.45 and 0.55. A binary one shall be represented by a positive frequency deviation, and a binary zero shall be represented by a negative frequency deviation.

The GFSK modulation uses quadrature or IQ based modulation and the two algorithm for GFSK demodulation presented in the paper seems better for low power design of BTLE. The choice of demodulation algorithm is by comparing the Bit Error Rate (BER) performance curve over Signal To Noise Ratio (SNR). The Receiver with the lower curve having better performance. A MATLAB simulation model was build for comparing BER performance of the two algorithms. The ultimate goal is obviously a BER of 0 but since this is difficult to achieve in a real receiver with realistic noise levels, the BTLE standard defines a target BER of $1e^{-3}$ (0.1%) at about 15dB SNR. This means that one bit in 1000 is wrongly received. Now, the simplest way to compare two receivers is to compare at which SNR this target BER is achieved. The lower the SNR the better the receiver. A more sophisticated way of comparing the SNR performance of two receivers is to compare the entire BER curves. The receiver with the "lower" curve wins.

Introduction

In BTLE controller project the hardware are focusing on the front end part of RF transceiver and software team developed the BTLE controller stack. The backend team was responsible for the all memories and analog part of RF transceiver. The front end part of RF transceiver was combination of IF GFSK modulator/demodulator.

This paper will discuss two demodulation algorithms for Bluetooth GFSK signals. In order to evaluate the performance of the algorithms, a Bluetooth simulation model has been built. In this model, Bluetooth packets are generated and transmitted and demodulated by different demodulation algorithms. First this paper will discuss the Bluetooth GFSK modulation technique. The demodulator can be split up into two parts, the demodulator and the decision function. The demodulator converts the incoming GFSK signal into a Non-Return-to-Zero (NRZ) signal.

GFSK Modulation

In normal continuous phase Frequency Shift Keying (FSK) a '0' is represented by an harmonic signal with frequency $f_0$ and a '1' by frequency $f_1$, both per interval of $T_s$. Continuous FSK uses an Voltage-Controlled Oscillator (VCO) that is driven by the bit signal. In this implementation no phase shifts occur between bit transitions, which explains the name continuous phase FSK. However due to the binary nature of the input signal, fast frequency transitions occur and therefore results in a large bandwidth. It is for that reason that GFSK uses a Gaussian pre-modulation filter. Fig shows a GFSK modulator. First the bits are converted to signal elements. A '0' is being represented by a signal with value -1 and a '1' by a signal with value 1, each with a duration of $T_s$ seconds.

The filter output is then connected to an Voltage Controlled Oscillator (VCO) that translates the amplitude of the filtered bit sin to an frequency shift. The Gaussian filter reduces the bandwidth of the input signal of the VCO. This reduces also the bandwidth of the output signal and therefore GFSK is more spectrum efficient compared to normal Frequency Shift Keying (FSK) at the cost of an increased BER, although the noise is also reduced by the smaller band. In Bluetooth systems, the modulation index $h$ may vary between 0.45 and 0.55. The modulation index $h$ is defined as:

$$h = 2f_dR = 2f_dT$$

where $f_d$ is the frequency deviation, R the bitrate and T the symbol time. The frequency deviation ($f_d$) is
the maximum frequency shift with respect to the carrier frequency, if a '0' or '1' is being transmitted.

GFSK Demodulation

The demodulation part of digital communication signals can be divided into two parts:

- demodulator
- decision block

The demodulation function converts the incoming GFSK signal into a NRZ signal. This can been seen as the digital equivalent of an analog demodulator. The second part, the decision block determines which bit was transmitted.

Demodulation Algorithms

As FM signals cannot be demodulated directly, several types of indirect FSK demodulation methods exists:

- FM-to-AM conversion, also called FM discriminator
- Phase-shift discrimination

the FM-to-AM conversion or FM discriminator allows the implementation for low-cost radio units, which is essential for Bluetooth units. It seems therefore appropriate to research the "cheapest" demodulator algorithm first. The second type of method we investigated is the phase-shift discrimination method. Both methods will be described shortly.

**FM discriminator algorithm**

Goal of the FM discriminator method is to translate a frequency shift into an amplitude change. A possible implementation is to use a time delayed version of the incoming (low Intermediate Frequency (IF)) signal.

This time-delayed signal is multiplied with the original, (not time-delayed) signal. The output of the FM-to-AM-conversion block with time delay τ depends on phase ($\phi(\tau)$), which is the phase difference between the original and time-delayed signal:

$$V_{out} = A(t)\cos(2\pi f + \theta) \cdot \cos(2\pi f + \theta + \phi(\tau))$$

where $A(t)$ is the amplitude, $f$ the frequency of the incoming signal, $\mu$ the initial phase and $\phi(\tau)$ the phase shift caused by the time delay. If a low-pass filter is used after the FM-to AM conversion block, the second term is assumed to be eliminated. So the output depends solely on $\tau$. The time delay $\tau$ is chosen in such a manner that it will produce for the central frequency, $f_c$, a phase shift of $\pi/2$, so $V_{out} = 0$. If $f_1 = f_c + f_d$ is being transmitted the phase shift will be more than $\pi/2$ and $V_{out}$ will be negative. For $f_0 = f_c - f_d$ the corresponding output will be positive. In order to retrieve the original bit sequence an inverter has to be placed after the FM discriminator. For Bluetooth signals the modulation index may vary between 0.45 and 0.55. As we want a phase shift of $\pi/2$ for $f_c$, the time delay must be:

$$\tau = \frac{1}{4f_c}$$

Furthermore, for a digital implementation with sample frequency of 80 MHz, we want $\tau$ to be an exact multiply of the sample time. There are several possible values for the time delay $\tau$. In general a large time delay has a larger amplitude at the output. On the other hand a larger time delay degrades the performance of the FM discriminator because the relation between the signal and the time-delayed signal becomes less.

**Phase shift discrimination algorithm**

The phase-shift discrimination is a better demodulation method than the FM discriminator method because this method utilizes only the phase of the signal, the amplitude is not used. In the previous method however amplitude variations of the incoming GFSK signal are directly passed through the output (Eq. (2). A limiter could be used to overcome this problem.
Phase-shift discriminator

Fig shows a phase-shift discriminator. The first step is to down convert the incoming IF signal (Eq. (4)) to a complex Base Band (BB) signal (Eq. (5)).

\[ s(t) = A(t)\cos(2\pi f_c + \Delta\omega \int_{-\infty}^{t} m(\tau)\delta\tau) + n_1(t) \]  

where \( A(t) \) is the amplitude, \( f_c \) the carrier frequency, \( \delta! \) the deviation constant, \( m(t) \) the Gaussian filtered message bit at time \( t \) and \( n(t) \) noise.

\[ s'(t) = A(t)\cos(\Delta\omega \int_{-\infty}^{t} m(\tau)\delta\tau) + n'(t) \]  

The two paths, In-phase (I) and Quadrature (Q) path, are low-passed filtered to eliminate the high frequency products caused by mixing. Then the phase is extracted by the arctan block (Eq. (6)). In order to retrieve the NRZ signal, the output of the arctan block has to be differentiated (Eq. (7)).

\[ s''(t) = \Delta\omega \int_{-\infty}^{t} m(\tau)\delta\tau + n''(t) \]  
\[ s'''(t) = m(t) + n'''(t) \]  

Decision algorithms

This section describes two decision algorithms that have been investigated:

- The integrate-and-dump (IaD) algorithm
- The decision feed-forward and feed-back (DFF-DFE)

The first algorithm, the integrate-and-dump algorithm sums all samples of one bit period and decides on the output of the sum whether the incoming bit is an ‘0’ or ‘1’. So the algorithm does not take into account the influence of the Gaussian filter.

The second algorithm is more advanced and eliminates the influence of the Gaussian filter. For signals in the 800 MHz - 6 GHz band the maximum delay spread is 120 ns. The Gaussian filter has an impulse response of about 3 bit times (= 3000 ns). So the dominant distortion is caused by the Gaussian filter. We assume that multipath fading can be neglected. Therefore we can use the shape of the Gaussian filter to calculate and correct the influence of the previous detected bit on the samples of the current bit. Furthermore we can estimate the value of the future bit and calculate its influence on the samples of the current bit. After correction we can use the shape of the Gaussian filter for a matched filter to achieve best performance.

MATLAB Simulation Model

This section discusses the Bluetooth simulation model we used to evaluate the different GFSK demodulation algorithms. This model is packet based.

Fig shows the top view of the simulation model. The transmitter creates packets. Each packet consists of four fields: the preamble, the Access Address, the PDU, and the CRC. The preamble is 1 octet and the Access Address is 4 octets. The PDU range is from 2 to a maximum of 39 octets. The CRC is 3 octets.
The Preamble is transmitted first, followed by the Access Address, followed by the PDU followed by the CRC. The shortest packet is 80 bits in length. The longest packet is 376 bits in length. Then, the packet is transmitted according the Bluetooth specs using a carrier frequency of 2 MHz. To get realistic performances we assumed that the Bluetooth signal was sampled with a sample rate of 80 MHz. Noise is added and the distorted signal is filtered by an 512-taps Finite Impulse Response (FIR) bandpass filter which has a 1 MHz bandwidth with center frequency of 2 MHz.

```
function out = transmit(packet, ovs, IF)
    % apply gauss filter to input data
    % simulate phase accumulator (no overflow)
    % apply sin/cos lut
endfunction
```

In the receiver the signal demodulated by the FM or phase-shift discriminator. After demodulation the signal is down-converted with an factor $n$.

Finally, the decision block determines which bit was transmitted bits and the BER can be calculated. Bit synchronization is achieved by correlating the synchronization word of the packet with the incoming sample stream.

```
function [errs,len] = fm_discr(SNR,IF)
    % simulate transmission (only noise for the moment)
    % simulate 8 bit ADC
    % simulate FM to AM conversion block or phase shift discriminator(Demodulation)
    % simulate matched filter for decision algorithm
    % simulate synchronization algorithms
    % check for transmission errors
endfunction
```

**Conclusion**

In this paper we have analysed two implementations of an FSK demodulation algorithm, the FM discriminator algorithm and the phase-shift discriminator algorithm, for the use in Bluetooth systems. Furthermore we have analysed two decision algorithms, an integrate and- dump algorithm and a non-adaptive decision feed forward and feed-back (DFF-DFE) algorithm.

**References**


