

Practical aspects of FHSS-based ISM band wireless telemetry system development

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Abstract – Development of an FHSS-based wireless telemetry system is a complicated process that involves evaluation of many trade-offs. This article delivers considerations on this process, describes criteria of efficient design, and analyzes existing solutions. The complex of techniques are suggested which allow improving characteristics of the FHSS-based wireless telemetry system compared to analogues.

I. Introduction

Wireless telemetry systems include burglar alarms, fire alarms, power utility meters, leak detectors, environmental monitoring, temperature control, etc. There are several basic concepts of wireless telemetry system structure. Speaking in terms of network topologies, usually centralized telemetry system structure has a star topology. Such system consists of a base station and independent numerous telemetry object devices (Fig. 1).

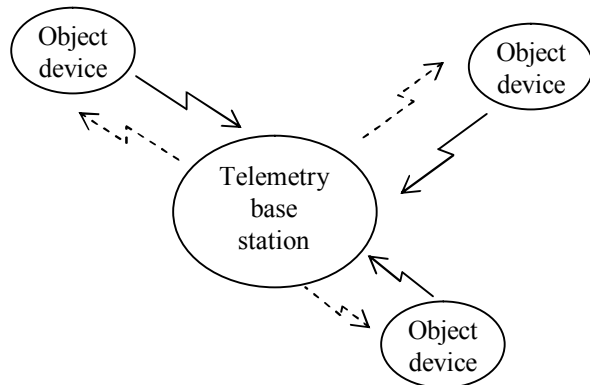


Fig. 1. Simplified structure of a wireless telemetry system with a centrally located base station.

Usually it is a two-way system in which a base station transceiver inquires each telemetry object transceiver using a specific algorithm (downlink) and the telemetry object transceiver sends an answer (uplink). This way of communication guarantees necessary sensing period of every object, allows to make an out-of-order check of any object upon an operator request.

Usage of Industrial, Scientific and Medical band (ISM band) is very attractive for commercial telemetry systems because of expense cuts as long as no license for a frequency range usage is needed. There are regulatory limits for ISM bands that restrict transmitter power and make a two-way system difficult to implement. The main problem is a downlink because a telemetry object device is often situated in a very inconvenient place (room of a multistoried building, cellar) and uses a simple cheap antenna (e.g. quarter-wave dipole). Also the telemetry object device cost should be as low as possible, so that a high quality receiver is difficult to implement. Such problem is usually solved by transmitter power increase, but this is not an option for ISM band.

An uplink path can always use an advantage of proper base station location, highly raised base station receiver high-gain antenna and high selectivity analog and digital signal processing. Significance of the base station cost decrease with increase of telemetry object devices amount. This allows making an optimal receiver to a high degree approximation that is able to provide a reliable uplink with a sufficient operating distance. Telemetry system without a downlink path is usually referred to as a passive or one-way system.

One-way wireless telemetry system comprises many objects with transmitters that periodically or sporadically transmit messages. A centrally located base station receiver receives messages from each transmitter.

Normally, the transmitters transmit messages that are as short as feasible and with the interval between the transmissions as long as feasible [10]. This is advantageous for two reasons. First, it minimizes the average current drain in the transmitters, which are typically battery operated. Second, short and infrequent transmissions lower the probability that data is lost as a result of collisions that occur when two or more transmitters transmit at the same time. However, if an urgency is detected by the sensor associated with the transmitter, the transmitter transmits immediately in order to notify the receiver of the urgency as soon as possible.

Telemetry system that transmits at a single frequency is susceptible to narrowband interference and signal loss due to a multipath fading. As a consequence, the reliability of such systems is compromised. The transmitted power has to be increased to overcome the fading, which results in larger power drain and shorter battery life. Again it can't be used in the ISM band because of transmitter power restriction. Because the multipath effect is highly sensitive to the frequency of the transmitted carrier, a system using multiple frequencies (e.g., a frequency-hopping spread spectrum system, etc.) has the potential to eliminate these drawbacks.

II. Problem statement

Frequency-hopping spread spectrum (FHSS) is a method of transmitting radio signals by rapidly switching a carrier among many frequency channels, using a pseudorandom sequence known to both transmitter and receiver. The method was originally designed for military use in order to prevent interception of radio transmissions. Today it is widely used in wireless data transmission protocols such as Bluetooth or Wi-Fi in order to reduce interference between the various stations of a cell. Due to both security and noise-immunity factors FHSS was adopted in wireless telemetry systems.

Development of the FHSS-based wireless telemetry system is a complicated process that involves evaluation of many trade-offs and elaboration of critical features. The most important of them are:

- synchronization
- data rate
- spectrum
- energy efficiency

The features mentioned bring in conflicting demands to the developer. It is a complicated task to achieve long range robust data transmission using low-cost techniques and low power transmitters even in a dedicated radio channel. The same is even harder to implement in the ISM band which provides very noisy radio channel with unpredictable interferences.

III. Design considerations

A. Synchronization

Usually FHSS systems require a long acquisition time and are typically used in two way communication applications in which all the devices can be synchronized by continuously synchronizing with one master device or with each other using a variety of synchronization methods suitable for such case [1]. In other cases, to ease the synchronization problem, there are employed receivers that can simultaneously receive signals at many frequencies by making the receiver broadband [2] or by using several receivers at the same time. Usually, these receivers suffer from performance degradation or high cost or both which makes them undesirable for low cost applications that require high reliability such as security systems.

There is a method of implementing the multichannel broadband receiver using a fast Fourier transform (FFT) [2]. Every FFT bin is considered as a narrowband filter output thus it is possible to obtain several hundred or even thousands of channels using one digital signal processor. This method suffers from some limitations inherent to FFT, which result in insufficient selectivity of such filters [9].

As stated above the message length should be as short as possible to minimize collisions between different objects, thus the shortest preamble and synchronization pattern should be used. However, this condition makes it difficult for the receiver and the transmitter to become and stay synchronized. This problem is very critical in some systems, such as security alarms, that require some messages to be conveyed to the system immediately without waiting for the scheduled transmission time.

One of the methods that solve this problem is based on transmitting urgent messages on one of a plurality of transmission opportunities that allow the receiver to tune to the right frequency at the right time to check if there is any transmission pending from a transmitter. The urgent messages are, advantageously, synchronized to the routine messages, in effect, making the routine transmission an aid for the receiver in synchronization and tracking of the transmission opportunities [3]. This method requires usage of high-stability reference oscillators making the telemetry object devices very expensive.

There are some FHSS systems that use spectrum analysis techniques to recover frequency synchronization and detect the urgent message [4, 5]. This allows to use low cost reference oscillators and dispose of a burden to process unused channels. Unfortunately, this method works well only in an environment with a low interference level. Every irrelevant strong signal that falls in the system frequency range is determined as a message signal thus consuming receiver resources. ISM band is known to be a band with a

high level of different interferences. If there is a high-power irrelevant signal or irrelevant signals cover more than half of the frequency range, the spectrum analysis algorithm errors will heavily degrade system characteristics.

B. Data rate

Digital communication system error probability is dependent on E_b/N_0 ratio:

$$\frac{E_b}{N_0} = \frac{S/R}{N/W},$$

where E_b – bit energy, N_0 – noise power spectral density, S – signal power, N – noise power, W – bandwidth, R – data rate.

Assumed that noise power spectral density constant and maximum signal power limited, the only way to raise E_b/N_0 ratio is to lower the data rate R . Telemetry systems often do not require high data rate (remote sensing, temperature measurements, burglar alarm system, etc). This allows lowering the data rate of messages and thereby reducing the error probability of data transmission.

For example ADF7021 narrow-band transceiver IC supports data rates over the range 0.05 kbps to 32.8 kbps [6]. During field tests a telemetry object device based on ADF7021 showed the operating distance in a direct line of sight up to 20 km with data rate 160 bps and up to 16 km with data rate 1200 bps. The telemetry system uses 433 MHz ISM band, maximum transmitter power 10 dBm.

A REEF STRING 202 (LONTA 202) FHSS wireless security system uses 50 bps data rate and a broadband FFT-based receiver [2]. Manufacturer's performance ratings state the operating distance in a direct line of sight up to 50 km in the 433 MHz ISM band.

C. Spectrum efficiency

The FHSS system performance is strongly dependent on a spectrum efficiency of the signal during one hop. The less signal bandwidth during a hop the less probability of collisions between different object transmitters. The ADF7021 allows usage of shape filters (Gaussian, raised cosine) to reduce signal effective bandwidth. The spectrum efficiency can be further improved using low modulation indexes. Together with the low data rate it gives a narrowband spectrum efficient signal. The ADF7021 minimum frequency deviation is 56 Hz, but usage of low modulation indexes with low data rates degrades the transceiver sensitivity because of demodulator limitations. Experiments showed that the minimum frequency deviation of 1–3 kHz can be used without sensitivity degradation.

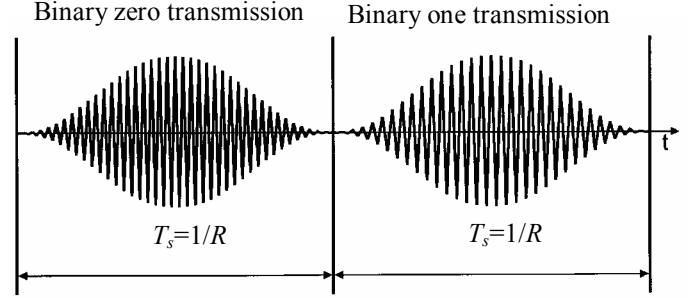


Fig. 2. Time diagram of amplitude-frequency modulated (AFM) signal

Some embodiments of the REEF STRING security system use a special combination of FSK and amplitude modulation. The time diagram (Fig. 2) of a FSK signal with 50 bps data rate and low frequency deviation is additionally modulated in amplitude with the modulation index $m=1$. Thus the signal amplitude falls down to zero during the transition between a frequency of binary zero F_0 and a frequency of binary one F_1 . This lowers the sidelobes of a signal spectrum at the expense of mean signal power drop.

D. Energy efficiency of modulation

The modulation type that is described above is sensitive to the non-linear distortions that may occur in both transmitter and receiver. Usage of highly linear amplifiers raises current drain and enlarges weight and dimensions of telemetry object transmitter. Constant envelope modulations are preferred which make power efficient nonlinear amplifiers suitable.

IV. Proposed system

The aim of current design is to improve main characteristics of existing FHSS-based wireless telemetry systems: raise sensitivity, enlarge the maximum allowable distance of data transmission, increase the maximum object amount of the telemetry system, improve the spectral efficiency of the telemetry objects transmitter signal, and lower power consumption.

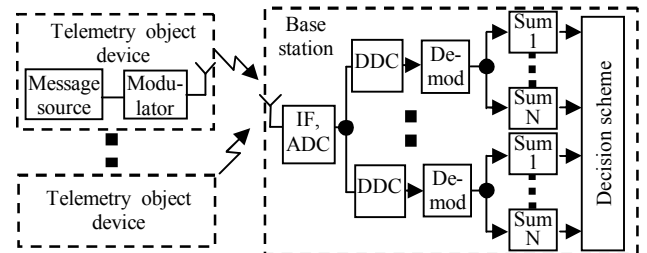


Fig. 3. Proposed FHSS-based wireless telemetry system block diagram

One implementation of a simple albeit efficient structure of FHSS-based wireless telemetry system is shown on figure 3. The system takes into account all the tradeoffs mentioned above. The diagram illustrates the principle of operation of data transmit/receive subsystem.

The signal received in base station is translated to analog intermediate frequency (IF) and digitized in analog-to-digital converter (ADC). Then it pass through the multistage digital downconverter (DDC) which provides high level of selectivity while separating individual narrowband signals of the wideband FHSS signal. The last stage of DDC contains finite impulse response (FIR) filter which passband width is set equal to the bandwidth of narrowband signal during one hop. Frequency spacing of the filters should be chosen as small as possible to provide reasonable value of maximum frequency error that is defined as difference between the central frequency of narrowband signal and the nearest filter central frequency.

After being filtered signals of all channels are demodulated separately. As all signals of telemetry object devices are transmitted asynchronously symbol and frame timing is unknown. Timing recovery circuit is substituted by a number of summators that sum demodulated signal on a symbol period $T_s=1/R$. Every narrowband receive channel has N summators. Input signal of N th summator is delayed from input signal of N th-1 summator on period of T_s/N . The amount of possible synchronization error vary as the inverse number of summators per channel. Since demodulator output signal has low sampling frequency, it is possible to use the maximum amount of summators with a delay between them equal to one sample of demodulated signal, thereby recovering exact symbol timing without heavy computational load growth.

Outputs of all summators are combined in sequences of information symbols are then analyzed in decision scheme which makes a correlation between sequences and a known synchronization word. Once this word is found in the output signal of a summator all following symbols are divided into words and decoded to get the message information. Depending on the message information base station indicates status or some parameters of telemetry object to the operator.

The Gaussian frequency shift keying (GFSK) is proposed to be used as a spectral effective modulation technique. It allows forming a narrowband radio signal during transmission on one of the pseudorandom sequence frequencies. It minimizes interference between telemetry object transmitters and allows implementing narrowband filtering in the baseband station receiver. Frequency deviation is chosen equal or less than half of the data rate, so that low index of modulation additionally shrinks the spectrum. Another requirement that was stated above – power efficiency is inherent property of GFSK. As it is not sensitive to amplitude distortion [7], it enables usage of

nonlinear D-class high efficiency amplifiers in the telemetry objects transmitter. Data rate of 50 bps is considered to be minimum allowable for this design and can't be further optimized.

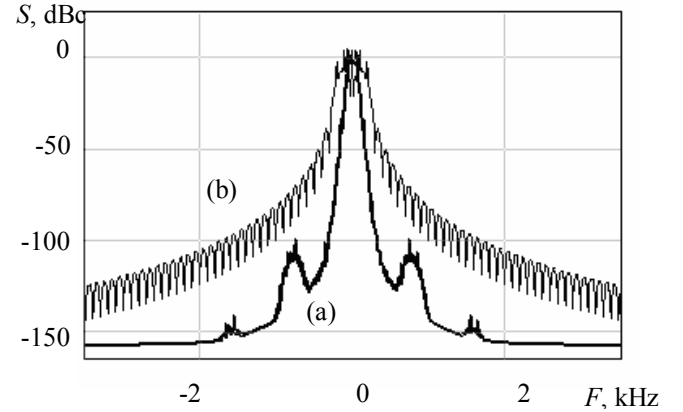


Fig. 4. Calculated spectrum of modulated signal (a) GFSK, $BT=0.5$, deviation 25 Hz; (b) AFM signal, deviation 50 Hz. Spectrums are calculated in MATLAB.

Figure 4 provides comparison of GFSK and AFM signal spectrums [2]. Spectrum of GFSK (Fig. 4a) has better roll-off factor, the sidelobes level is -100 dBc, main lobe width is 80 Hz at -40 dBc, while amplitude-frequency modulated signal (Fig. 4b) sidelobes level is -40 dBc, main lobe width is 140 Hz at -40 dBc.

V. Numerical results

Simulation of the above mentioned FHSS-based wireless telemetry system were conducted using Matlab Simulink.

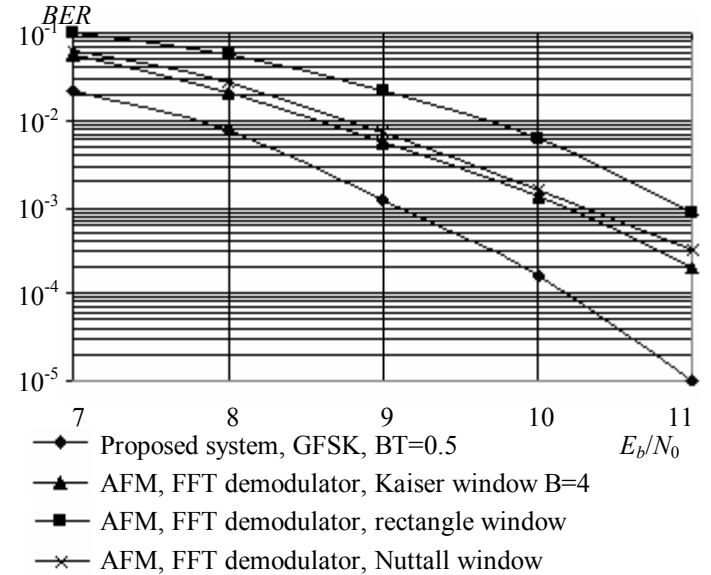


Fig. 5. Bit error rate vs. E_b/N_0 ratio graph

Bit error rate vs. E_b/N_0 ratio graph (Fig. 5) shows that the proposed system provides better BER compared to the closest analogue.

VI. Conclusions

The proposed FHSS-based wireless telemetry system provides robust operation in an ISM band with high operating distance. This task was achieved by means of:

- choice of spectral effective modulation technique with high level of power efficiency
- providing narrowband highly selective level of filtering
- providing robust algorithm of demodulation
- defining trade-off between baud rate of the system and spectrum width

Advantages of the proposed system:

- no frequency or symbol synchronization scheme is needed - as long as all possible signal positions are used to recover the message
- effective in the ISM band with high level of interference
- improved BER compared to closest analogues
- increased number of the telemetry objects
- FPGA-oriented algorithm

Further studies are needed to improve the computational efficiency of the filtering and demodulation. Particularly some techniques can be used to optimize multichannel DDC algorithm [8].

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