Spectral Keying™: A Novel Modulation Scheme for UWB Systems

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Abstract. Spectral Keying (SK) is a novel UWB modulation scheme that combines properties of both Frequency Shift Keying and Pulse Position Modulation. An SK symbol consists of a number of pulses where each pulse is from a different frequency band. It relies on dividing the available spectrum into multiple bands. The information is encoded by the sequence of the sent bands. It is found that the SK available symbol set scales factorially with the number of frequency bands in use. Theoretical analysis and simulations of a five band SK system are provided. Measurement results from an experimental SK system are also included.

I. INTRODUCTION

Background

Recently, there has been growing demand for high bandwidth (>10 Mbps), short range (<30 m) wireless communications systems. Applications range from cable replacement for connecting personal computers and their peripherals, to wireless connections for home entertainment networks.

Adoption of the First Report and Order (R&O) by the FCC in February 2002 opened the door for unlicensed communication systems based on Ultra-Wideband (UWB) technology. These systems offer the promise of the aforementioned high bandwidth, short range wireless connectivity with low complexity, low cost, and low power. As a result, many workers are currently engaged in the development of UWB systems [1].

The FCC defines a UWB device as any device that uses at least 20% fractional bandwidth or occupies more than 500 MHz of spectrum [2]. Historically, UWB systems have relied on the transmission of a series of impulses whose frequency content meets this definition. Much of the early development concentrated on the concepts of impulse radio that relied on pulse position modulation (PPM) and time hopping sequences [3, 4]. Other modulation schemes include pulse amplitude modulation (PAM) [5], phase shift keying (PSK) [5], and direct sequence spread spectrum (DSSS) with polarity modulation [6]. More recently, the use of orthogonal frequency division multiplexing (OFDM) waveforms has been proposed [7].

Motivation for the Current Work

Key metrics for the evaluation of UWB modulation schemes include bit error rate, complexity, power consumption, data rate, and range. Evaluation of system performance against these metrics led to the development of multi-band UWB systems in which the available spectrum has been divided into multiple bands of >500 MHz each, as shown in Fig. 1.

This approach provides flexibility in selecting suitable bands based on the presence of interference or regulatory constraints. In addition, the use of multi-band modulation enables scalable systems that can optimize the tradeoff between system cost and performance.

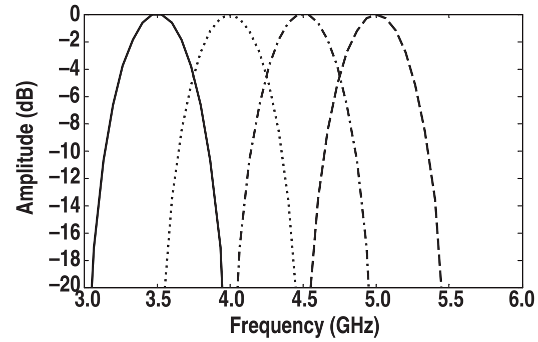

Fig. 1. Breaking the spectrum of 3.1–5.4 GHz into four bands.

The use of smaller UWB sub-bands of ~500 MHz has distinct technical advantages. One key advantage is that it will allow the collection of a high percentage of the available multipath energy. Fig. 2 compares the mean value of the energy that may be collected in a typical indoor multipath channel, as described in the channel report for IEEE 802.15.TG3a [8]. In this example, the channel has severe multipaths (a delay spread of 25 ns). Based on the usable bandwidth and the number of available Rake arms, this figure depicts an increase in the collected energy when using pulses of smaller bandwidth. More energy can also be collected by using separate independent receivers to capture multiple rays of the signal from the dominant multipaths.

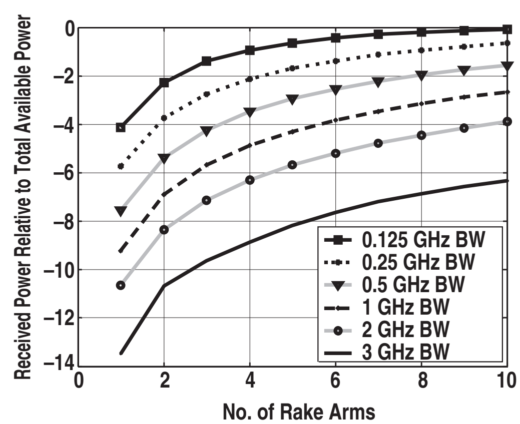

Fig. 2. Impact of pulse bandwidth and number of Rake arms on the amount of collected energy.

Although multi-banded UWB systems improve the collection of multipath energy, issues arise when the delay spread in the propagation channel exceeds the quiescent time (often referred to as the guard time) between successive pulses. In this case, an equalizer is required to detect the pulses, increasing system complexity and cost. It is desirable to utilize a low enough Pulse Repetition Frequency (PRF) to provide sufficient guard time between successive pulses so that no significant inter-pulse interference is encountered. The sparse nature of the transmission due to the low PRF allows additional power saving, when the receiver is turned off during the guard time. In this paper, we discuss a new modulation scheme that enjoys the advantages of multi-band UWB spectrum use, while minimizing PRF to avoid inter-pulse interference.

II. DESCRIPTION OF SK

Overview of SK

As mentioned earlier, SK is a specific variation of a multi-band UWB system. In SK, a symbol is made up of a number of pulses and each of these pulses is sent using a different frequency band. Information is encoded in a symbol by the order of the frequencies sent, where each frequency is usually used only once during a symbol period. This limitation mitigates the effect of multipath delay on the system, since all pulses in a symbol have orthogonal frequencies and the spacing between symbols exceeds the maximum expected delay spread of the channel. This will eliminate the need for an equalizer for the signal, trading receiver simplicity for data rate.

There are dual interpretations for SK. We can think of SK modulation as a modified m-ary frequency shift keying (M-FSK) with an internal code, or as a multiband PPM that reuses the time slots. In the remaining part of the paper, we will analyze SK using the first interpretation, where each M frequency is transmitted only once in T time slots.

Fig. 3 describes the simplest form of SK. Each SK symbol is comprised of several pulses at different frequencies. A guard time with no signal always follows the SK symbol. In the example shown, three pulses are sent in three time slots. In the first SK symbol, frequency 1 is sent at time slot 1, followed by frequency 3 in time slot 2 and frequency 2 in time slot 3. In the second SK symbol, frequencies 2, 1, and 3 are sent in time slots 1, 2, and 3 respectively. The sequence 2,1,3 defines one symbol while 1,2,3 defines another. The available symbol set for this simple case is factorial of 3.

Note the above example gives a simple SK definition. There is no need to restrict the number of transmitted pulses to the number of bands or time. In a time slot, zero or multiple pulses may be transmitted. Also the phase of the sent pulses may be used to encode information. Generally, assume an SK system with M frequencies, T time slots, and B sent pulses. We define an input symbol, X, to be an MxT matrix with exactly B non-zero entries, and at most one non-zero entry in any row or column. A non-zero entry at position *k*, *l* represents a pulse of frequency *k* at time *l*, and the sign of entry represents the phase of the burst. We use the variable P to represent the number of phase bits. Each non-zero entry can be a binary $X_{k,l} \in \{-1,1\}$ or quaternary $X_{k,l} \in \{\pm 1 \pm \imath\}$ phase-shift-keying signal. Fig. 4 depicts an SK symbol with three frequencies (M=3) transmitted over four time slots (T=4).

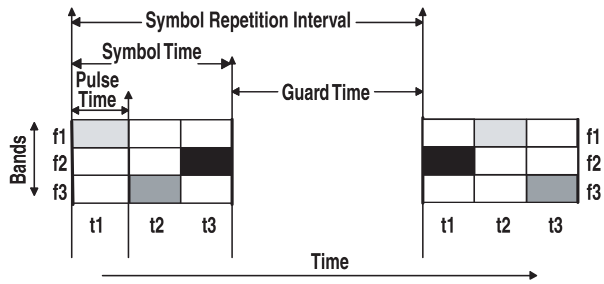

Fig. 3. Definitions for SK.

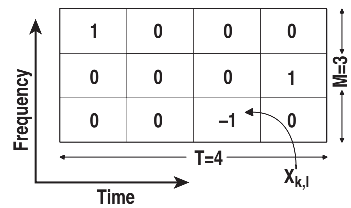

Fig. 4. An example SK symbol in 2D.

For the scenario where we use M frequencies, T time slots, and B frequency pulses, the size of the input alphabet is the product of the number of ways to choose the B frequencies from the possible M, the number of ways to choose the B time slots from the possible T, and the number of ways of ordering the B frequencies in time. Using the phase of the burst to transmit information also multiplies the number of symbols by 2^{PB}. This means the number of symbols is given by

$$N(M,T,B,P) = \binom{M}{B}\binom{T}{B} B! 2^{BP}, \binom{M}{B} = \frac{M!}{M!(M-B)!} \tag{1}$$

This explains the primary feature of SK. It is a high order modulation that can provide a large number of bits per symbol. In fact for P≠0, the size of SK symbol set increases exponentially as the number of frequencies used; and for P=0, the number of SK symbols increases factorially as the number of frequencies used. An example implementation of an SK symbol can be thought as a sequence of independent frequency choices: for time 1, we have M independent choices, for time 2 we have M-1 independent choices, and so on. In the example of M=5, T=5, B=5, and P=0, we get N(5,5,5,0)=5*4*3*2. The maximum number of bits per symbol is then given by $\log_2 120$ = 6.907 bits. For the same example with P=1, we have N(5,5,5,1)=3840 symbols and 11.907 bits per symbol!

Transmit Pulse Description

Let $x_{m,n,i}$ be the n^{th} ordering of the i^{th} symbol at the m^{th} chip time, *p(t)* be the pulse-shaping function with duration less than T_c seconds, $\omega_1, \omega_2, ..., \omega_{n_f}$ and $\theta_1, \theta_2, ..., \theta_{n_f}$ be the respective frequency and phase components of the sinusoid, and n_f be the total number of frequencies. The i^{th} transmit symbol can be written as

$$s_i(t) = \sum_{m=1}^{n_f}\sum_{n=1}^{n_f} x_{m,n,i}\, p[t-(n-1)T_c]\cos(\omega_m t + \theta_m) \quad . \tag{2}$$

The overall transmit signal is

$$s(t) = \sum_{i=-\infty}^{\infty} s_i(t - iT) \quad , \tag{3}$$

where T is the symbol period and T=1/PRF. Here, $p(t)$ is selected to minimize adjacent band interference and to satisfy the FCC spectral mask requirement. Possible pulse shapes include Gaussian, rectangular, and raised cosine. Fig. 5 depicts a transmit pulse waveform in both the time and frequency domain. The pulse is generated using a 2 ns rectangular pulse that is shaped by a second order low pass filter. The pulse is modulated at 4 GHz, and has a 10 dB bandwidth of 700 MHz.

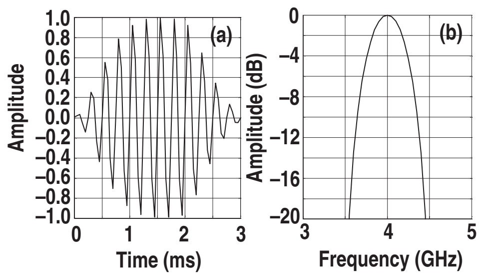

Fig. 5. Gaussian transmit pulse shaping of a 4 GHz pulse. (a) Time and (b) frequency domain representation.

Optimum Receiver for SK

As shown earlier, SK may be represented as T time slots of M-FSK with an input restriction. Many receiver architectures are possible. In an optimum configuration, the first step in demodulation is done by a bank of M correlators or matched filters, sampled at T time slots. We denote the output of the matched filters as Y_{ij} for the i^{th} frequency during j^{th} time slot. Picking the most likely input symbol given Y will require calculating N decision variables, one for each of the possible sent symbols, and selecting the peak given by

$$\max_n \left(\sum_B Y_{ij} \right) \tag{4}$$

where $n \in$ N, $i \in$ M, and $j \in$ T. Y_{ij} is based on the restriction placed on the choices in combination of the frequencies and time slots within a symbol. A block diagram for such a receiver is shown in Fig. 6 for the case of 4 bands.

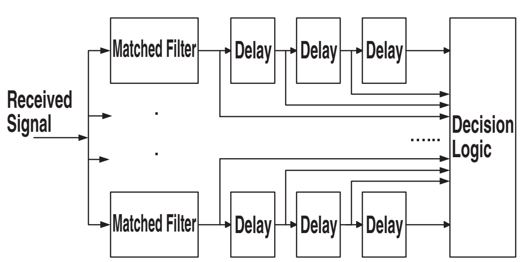

Fig. 6. Optimum SK receiver.

Performance Prediction

To predict SK performance, bounds are derived for its performance under soft decision decoding. These bounds are based on representing SK as a nonlinear code over T time slots of M-FSK. SK is a symbol-wise geometrically uniform code, meaning that the probability of symbol (or frequency) error is independent of the transmitted symbol frequency [9].

Let x_0 and x_1 be 2 constellation points, and let d, be the squared Euclidean distance (SED) between them. The probability that the receiver chooses the symbol x_1 when x_0 was actually sent is given by Q(sqrt(d/(2σ^2))), where σ^2 is the variance of the noise and the Gaussian tail integral is given by

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt \quad . \tag{5}$$

The probability of error for the optimal noncoherent detector is a function of the correlation coefficient ρ between x_0 and x_1 and can be written in terms of the Marcum Q function [10].

The error bound will be derived for the case where M=T=B and no phase bits are used. Each symbol in the SK constellation can be associated with a permutation of the integers {1,…,M}. The SED between 2 constellation points which differ in f frequencies will be $2f$ irrespective of the sent symbol. It is noted that any 2 constellation points will differ by a minimum of 2 frequencies giving a minimum SED of 4. Let X_0 be the identity permutation (12345), and consider the number of constellation points which differ from in f positions. We denote this number by $A_f(M)$, which is equal to the number of choosing f from M frequencies and deranging them. This means

$$A_f(M) = \binom{M}{f} d(f) \quad , \tag{6}$$

where $d(f)$ is the number of derangements of length f. Furthermore, the number of derangements can be computed using the recursion, $d(n)=nd(n-1)+(-1)^n$, with the initial condition, $d(1)=0$. Using this weight enumerator, we have the word error rate bound

$$P_w(M) \le \sum_f A_f(M) Q\left(\sqrt{\frac{fE_s}{N_o}}\right) \approx \frac{M(M-1))}{2} Q\left(\sqrt{\frac{2E_s}{N_o}}\right) \quad , \tag{7}$$

and the symbol error rate bound

$$P_s(M) \le \sum_f \frac{f}{M} A_f(M) Q\left(\sqrt{\frac{fE_s}{N_o}}\right) \approx (M-1) Q\left(\sqrt{\frac{2E_s}{N_o}}\right) \quad . \tag{8}$$

It is noted that the SED shown by SK is similar to that of antipodal modulations e.g. BPSK, and hence will have equivalent error performance. Fig. 7 shows the BER from the above equations versus a simulation of SK in an AWGN case.

The analysis for the case when phase bits are added will follow similar lines where the SED is calculated between the amplitude of the received frequencies.

III. PERFORMANCE RESULTS OF SK

Results with AWGN and MP Channels

Decoding an SK symbol with phase bits requires a two stage process. In the first stage, the SK sequence is decoded, and in the second stage, the polarity of each pulse is decoded. Fig. 8 shows the bit error rate (BER) of a turbo coded SK system over AWGN channel. The overall BER when decoding a bipolar SK sequence is depicted by a dash line, the BER when decoding just the SK sequence is depicted by a line with circle, and the BER when decoding just the polarity is depicted by a dotted line. There is not much difference between these three curves. However, SK outperformed the theoretical BPSK by 2 dB with only three iterations.

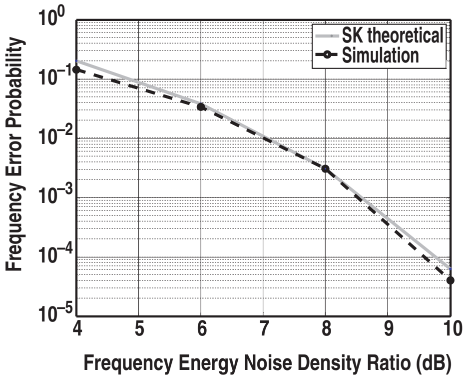

Fig. 7. Comparison between theoretical and analytical results of SK.

Data rate and range are two metrics often used when designing a real life communications system. Given a target data rate of 110 Mbps and 200 Mbps, Table I shows an example link budget for a high data rate 5-band system with 0 dB antenna gains. Table II shows the minimum and mean ranges of SK with 90% outage rate for four different channel models as selected by the IEEE 802.15.TG3a [8]. These channels modeled four indoor environments without the shadowing; Channel Model 1 (CM1) represents 0-4 m Line-of-Sight (LoS), CM2 represents 0-4 m non-LoS, CM3 represents 4-10 m non-LoS and CM4 represents a very bad multipath channel. The respective root-mean-square (RMS) delay spreads are 5.28, 8.03, 14.28, and 25 ns. The results showed the minimum and average distance supported by the 110 Mbps system at a packet error rate of 8%. These distances are averaged over the best 90 out of 100 channel simulations for each channel model. In general, we see the range decreases as expected with worse multipath channel. CM1 is an exception because the inter-pulse interference was the dominant impairment when the channel has a very short RMS delay spread.

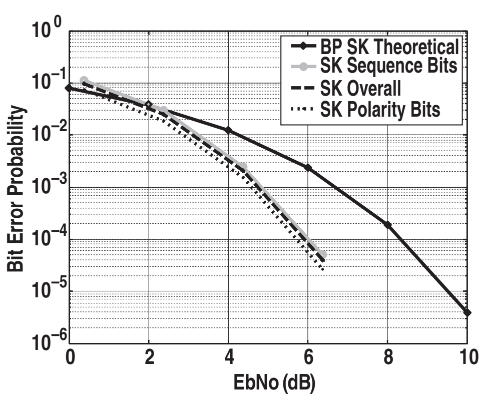

Fig. 8. Simulation results comparing systems using 5-SK and BPSK.

Table I
Link Budget from IEEE 802.15.3a Proposal

Parameter	>110 Mbps	>200 Mbps	Unit
Throughput (Rb)	119.6	257.4	Mbps
Center frequency Fc	4.8	4.8	GHz
Path loss at 1 meter [L1=20Log(4PI*Fc/c)]	46.0	46.0	dB
Path loss at d meters [L2=20log(d)]	20.0	12.0	dB
Rx power (Pr =Pt-L1-L2)	-73.8	-65.9	dBm
Average noise power per bit [N=-174 +10*log(Rb)]	-93.2	-89.9	dBm
Rx Noise Figure Referred to the Antenna Terminal (Nf)	7.0	7.0	dB
Average noise power per bit (Pn=N+Nf)	-86.2	-82.9	dBm
Minimum Eb/No (S)	5.4	4.5	dB
Implementation Loss(I)	3.0	3.0	dB
Symbol Rate	13.0	19.5	MHz
Bits per symbol	11.5	16.5	
Raw Bit rate	149.5	321.8	Mbps
Code rate	0.8	0.8	
Pulse Tx power (Pt)	0.5	-1.3	dBm
Link Margin (M=Pr-Pn-S-I)	4.0	9.5	dB
Min. Rx Sensitivity Level (Pr-M)	-77.8	-75.4	dBm
Range	15.8	12.0	m

Table II
Supported Distances Based on SK Simulation
Using IEEE 802.15.3a Channel Model (No Shadowing)

	Average Range (m)	Min. Range (m)
CM1	10.7	8.3
CM2	10.8	9.3
CM3	9.5	7.4
CM4	8.0	6.6

Experimental Results

During the period from 2001-2003, several generations of experimental transceivers based on SK waveforms were fabricated and tested. The operational parameters of the third system are summarized in Table III. In this system, a simple receiver architecture with no Rakes was selected.

Table III
Operational Parameters of the
SK Experimental System

Operating Frequency	3.1–5.7 GHz
Number of Sub-Bands	5
Bandwidth of Each Sub-Band	500 MHz
Over the Air Data Rate	40, 80, or 120 Mbps
Pulse Repetition Frequency	6, 12, or 18 MHz
Receiver Noise Figure	4.5 dB
Interfaces	Parallel or USB full speed
Latency for USB Traffic	<300 ns

A photograph of the system is shown in Fig. 9. A key design goal was the use of a flexible, reconfigurable architecture, with the baseband processing accomplished using FPGA technology.

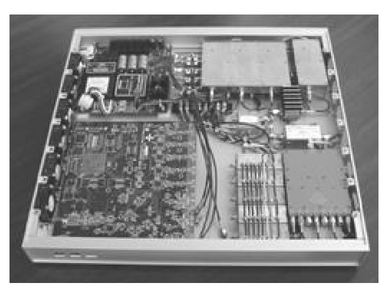

Fig. 9. Photograph of the third generation UWB transceiver based on SK modulation.

A unique feature of this system was the incorporation of an adaptation layer to permit transparent USB cable replacement. The system could also be used with any antenna having sufficient rf bandwidth, including several designs developed at General Atomics as well as the newly available compact UWB antenna module from Taiyo Yuden [11].

The performance of the system was characterized in indoor LoS and non-LoS environments. Since non-LoS performance is highly dependent on the precise multipath characteristics of the environment, the results are difficult to interpret and are not reported here.

Fig. 10 shows BER vs. range for the indoor LoS tests using the 40 Mbps mode and 3.25 dBi gain reference antennas. These antennas are axisymmetic bi-conical horns with a 360 degree azimuthal radiation pattern. The experimental results follow fairly closely to the expected performance using link budget analysis. Some data points performed better than the analytical curve; we attribute this to constructive interference of the UWB system due to multipath environment.

IV. CONCLUSION

With 7.5 GHz of available bandwidths opened by the FCC UWB systems, we can now build wireless systems that enjoy low power, cost and complexity. Traditional UWB systems are single band impulse radios. New innovations divide the spectrum and signal over multiple frequency bands. The advantages of using multiple bands are flexibility in selecting a frequency plan that is free of interference or regulatory constraints, and the ability to design a scalable system that optimizes between cost and performance.

We presented SK, a modulation that is well suited for multiband UWB system. By encoding information in the order of the frequency sent, SK provides exceptional data rates while keeping complexity in balance. We achieve additional benefits when combining SK with a low duty cycle PRF, where we have lower power consumption while avoid inter-pulse interference.

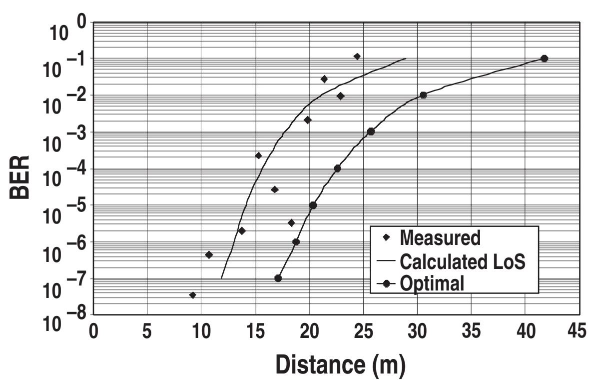

Fig. 10. LoS performance of the uncoded experimental system indoors. Also shown are LoS projections from link budget analysis for the experimental system and for a system with an optimal receiver.

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