IEEE 802.15.4a Impulse Radio Spectrum Shaping by Changes in Pulse Sequence

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Abstract — **This paper presents one of possible techniques of IEEE 802.15.4a ultra-wideband signal spectrum control, based on changes in sequences of transmitted pulses with very short duration time. This technique can reduce probability of mutual interferences between new ultra-wideband and existing narrowband devices, which may be helpful in further studies on allowing UWB transmission in wider range of spectrum in the European Union.**

Key words: ultra-wideband, impulse radio, spectrum shaping, electromagnetic compatibility.

I. Introduction

The IEEE 802.15.4 standard, released in 2003 and revised in 2006, describes physical and media access control layer for low data rate personal area networks. The latest extension to this standard, included in amendment 802.15.4a which was released in 2007 [1], defines new frequency ranges and higher data rates up to 27Mb/s and provides possibility to compute distance between nodes based on propagation time measurement. The highest data rates and ranging capability are available only using optional ultrawideband impulse radio physical layer. Sixteen UWB channels with bandwidth from 499,2MHz to 1354,97MHz were defined in three subbands below 10,2GHz. This frequency range is currently occupied by many narrowband radio communication devices so it should be expected that UWB transmission may be disturbed by narrowband interferences. It is obvious that UWB devices should avoid using frequency channels already occupied by existing transmissions, but in case when ultrawideband transmission has to be done in frequency range occupied by narrowband signals, some spectrum shaping techniques can be used to reduce possibility of UWB interference to narrowband systems [2,3].

II. IEEE 802.15.4a Impulse Radio

Ultrawideband (UWB) transmission in the IEEE 802.15.4a standard is based on impulse radio technique. The standard does not define exact pulse shape, but describes one mandatory pulse as any pulse that satisfies constraints of its cross-correlation function with special reference pulse, and three optional pulses, called: Chirp on UWB, Continuous Spectrum and Chaotic Pulses. From these four possibilities only optional chaotic pulses have non-deterministic time form so they cannot be used together with spectrum shaping methods proposed in this paper.

UWB transmitter activity period is divided into intervals called "chips", where chip duration time T_c is the inverse of maximum pulse repetition frequency, which is 499,2MHz. Each chip can contain at most one band-limited pulse. Chips without any pulse will later be called "empty chips".

A. Preamble

UWB frame is composed of preamble, header and data unit. The preamble chip synchronization field is made of 16 to 4096 repetitions of preamble symbol. Construction of preamble symbol is based on ternary code specified to each UWB channel. Elements from ternary code (length 31 or 127) define polarity of successive pulses, while each pulse is separated from another by $\delta_L - 1$ empty chips. Figure 1 shows construction of preamble symbol from ternary code.

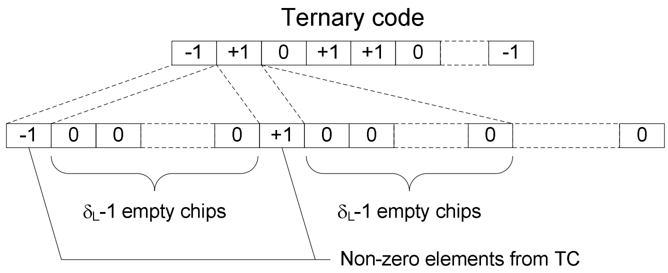

Fig. 1. Construction of preamble symbol from ternary code.

Chip synchronization field is followed by frame delimiter sequence, made of additional 8 or 64 preamble symbols multiplied by another ternary sequence.

B. Header and data unit

Structure of header and data symbol differs from preamble sequence. Every header/data symbol carries two bits of information from systematic convolutional encoder – one (systematic) bit is used to determine the position of a burst of pulses inside symbol (BPM – burst position modulation) while the other one is used to change the polarity of pulses inside burst (BPSK – binary phase shift keying). Each symbol of duration T_{dsym} (which consists integer number of chips N_{cps})

is divided into two BPM intervals of duration T_{BPM}. Location of the burst in either first or second half of the symbol indicates one bit of information. In order to limit the possibility of inter-symbol interference caused by multipath, only first half of both BPM intervals can contain burst of pulses. The burst is made of N_{cpb} pulses in the consecutive chips and has duration $T_{burst} = N_{cpb} \cdot T_c$. The polarity of each pulse is determined by second bit of information multiplied by pseudo-random sequence based on ternary code related to channel frequency. As the burst duration is shorter than half of T_{BPM} time, some multi-user access interference rejection can be achieved by defining N_{hop} possible burst position inside each half of symbol duration time. Position of pulse burst due to begin of first or second half of preamble/data symbol is determined by the same pseudo-random sequence which changes polarity of each pulse in burst. The structure and timing of header/data symbol is illustrated in figure 2.

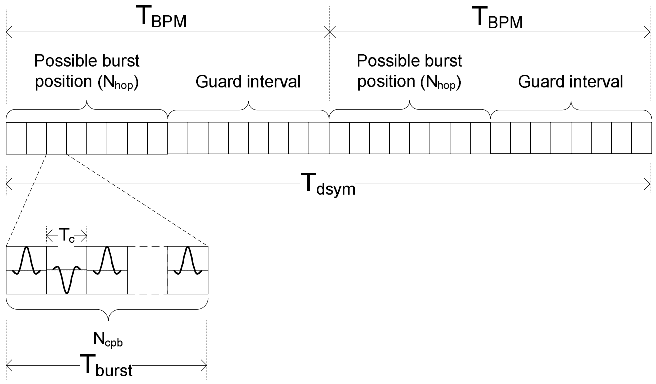

Fig. 2. Structure of UWB header and data symbol.

III. SPECTRUM SHAPING

Assume that UWB impulse radio signal with modified spectrum has to be received by receiver designed for IEEE 802.15.4a transmissions. It means that the pulse shape should not be altered in significant way. Because all beacon frames in beacon-enabled personal area network (PAN) have to be transmitted using mandatory pulse shape, authors decided not to change UWB pulse shape at all. Instead, pulse sequence time structure will be altered in order to reduce spectral power density at specified frequencies f_k.

Let's divide whole frame into fragments containing N chips. If the only UWB pulse with positive polarity and unitary amplitude is transmitted in $n-th$ chip, real and imaginary part of it's spectrum can be described by expressions [4]:

$$\mathrm{Pre}_n(f) = \int p(t)\cos(2\pi f \cdot (t + nT_c))dt \qquad (1)$$

$$\mathrm{Pim}_n(f) = \int p(t)\sin(2\pi f \cdot (t + nT_c))dt \qquad (2)$$

where T_c is the chip duration time and $p(t)$ is the time form of single pulse. Noting relative amplitudes of pulses in successive elements from c_n (for unchanged pulse sequence, elements from sequence c_n are equal -1, 0 or $+1$), we have real and imaginary part of N chips long sequence spectrum:

$$\mathrm{Pre}(f) = \sum_{n=1}^{N} c_n \cdot \mathrm{Pre}_n(f) \qquad (3)$$

$$\mathrm{Pim}(f) = \sum_{n=1}^{N} c_n \cdot \mathrm{Pim}_n(f) \qquad (4)$$

Changing values of particular elements from sequence c_n we can minimize the value of expression (5) and therefore reduce the impulse radio signal power spectral density at specified K frequencies f_k:

$$P = \sum_{k=1}^{K} \left[\mathrm{Pre}(f_k)^2 + \mathrm{Pim}(f_k)^2\right]^2 \qquad (5)$$

If pulse shape $p(t)$ cannot be changed, value of expression (5) can be altered by generating additional pulses in empty chips or alternatively by changing the amplitude of existing pulses in frame structure.

A. *Generation of additional pulses*

In the first method any existing pulses in transmitted signal are left unchanged, while some additional pulses of reduced amplitude a_d (and positive or negative polarity) are being generated in some empty chips. Additional pulses with lower energy can be compared to some kind of multipath propagation phenomenon, so most impulse radio receivers should deal with them without significant loss in transmission quality (BER).

It is obvious that any additional pulses in pseudo-random preamble sequence will affect it's autocorrelation function. But simulation results proved that when the whole preamble is divided into fragments of length N which is not a multiplicity of single pseudo-random preamble sequence, additional pulses will be placed in different chips in every N chip fragment and autocorrelation function of such modified preamble will still be acceptable (fig. 3).

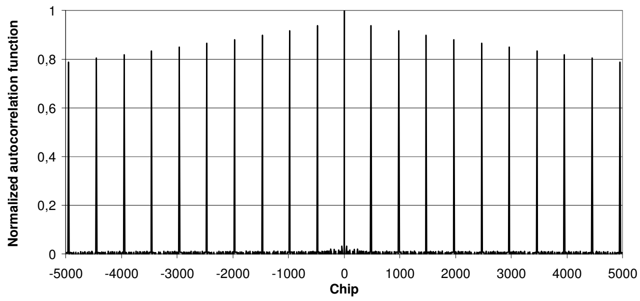

Fig. 3. Normalized autocorrelation function of preamble sequence with additional pulses of a_d=0,3

To reduce possibility of increasing bit error rate for header and data frame bits, additional pulses should be generated only in the first half of the T_{BPM} period, in first or second half of header/data symbol respectively.

B. *Alteration of existing pulses amplitude*

In the second method amplitudes of existing pulses are being altered without any change in polarity or position of any pulse in sequence. This method can be applied for preamble and header/data pulses without any modification.

During our investigations we assumed that amplitude of each pulse can be changed only by adding or subtracting a constant fraction of it (i.e. when pulse has amplitude a, it can only be changed to $a \cdot (1+\delta_a)$ or $a \cdot (1-\delta_a)$ where coefficient δ_a should be positive and less than 1).

The outline of both methods of impulse radio signal spectrum shaping is presented on figure 4.

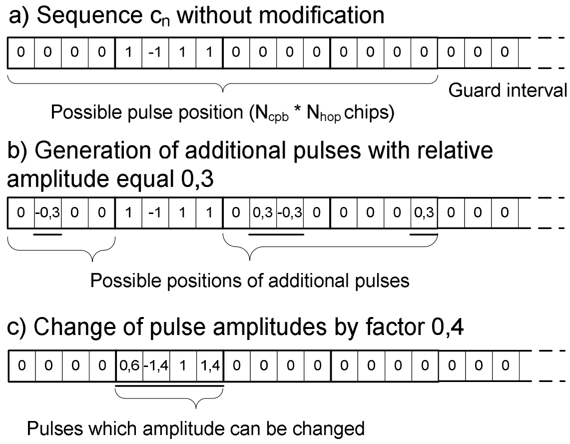

Fig. 4. The outline of impulse radio spectrum shaping.

IV. Simulation results

Because the total number of possible pulse amplitudes and polarities in every IEEE 802.15.4a header/data symbol can be very large ($3^{N_{cpb} \cdot (N_{hop}-1)}$ for the first method and $3^{N_{cpb}}$ for second one), checking every pulse sequence in search of the best solution would be highly impractical. Instead of it, a simple sub-optimal procedure was tested in simulation investigations. In this implementation, spectrum of every data symbol in UWB frame was separately modified by following algorithms:

- for every $n-th$ chip in symbol, compute values of expression (1) and (2),

- compute initial value of (5),

- first method: for every $n-th$ empty chip situated in first half of appropriate BPM period, calculate what change in value of expression (5) can be separately achieved by changing the value of zero-element in c_n to one of possible values $-a_d$ or $+a_d$. Select chip and polarity which decreases value of (5) the most and update value of applicable element in sequence c_n,

- second method: for every $n-th$ non-empty chip, calculate what change in value of (5) can be separately achieved by changing initial value a of element in c_n (initial amplitude) to one of two alternate values ($a \cdot (1-\delta_a)$ or $a \cdot (1+\delta_a)$), while polarity of each pulse is kept unchanged. Select chip and amplitude which decreases value of (5) the most, and update value of applicable element in sequence c_n,

- repeat previous step until no decrease in value of expression (5) can be made.

It is obvious that this procedure will not allow to find a global minimum of expression (5) but only one of local minima. But simulation investigations proved that even such sub-optimal procedure gives encouraging effects.

For example, figure 5 presents impulse radio signal spectrum in case of transmission in UWB channel 0 (center frequency 499,2MHz) with N_{cpb}=16 and N_{hop}=8, when power spectral density at frequency 440MHz was reduced using additional pulses generation, and figure 6 presents the same spectrum in case of changing amplitudes of selected pulses.

Because the IEEE 802.15.4a standard describes ultra-wideband pulses in baseband and additional frequency conversion is required to change signal's center frequency to desired value, any operation on pulse structure which creates notch at frequency f_0, also decreases spectral power density at frequencies $b \cdot f_c \pm (f_0 - f_c)$, where f_c is the UWB channel center frequency.

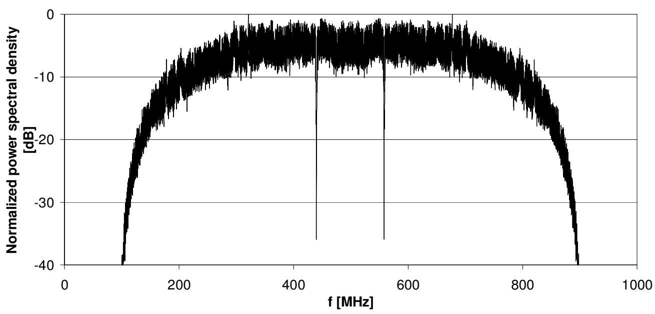

Figure 5. UWB signal spectrum in case when power density at frequency 440MHz was reduced by additional pulses.

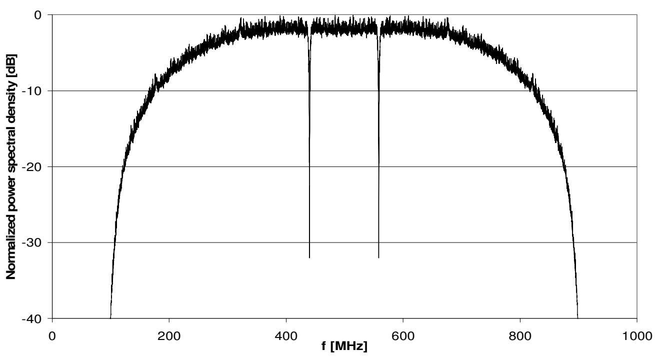

Figure 6. UWB signal spectrum in case when power density at frequency 440MHz was reduced by changing amplitudes of existing pulses.

In this examples every header and data symbol was considered separately, so the whole packet was divided into fragments of length $N = 4 \cdot N_{cpb} \cdot N_{hop}$. The length of fragments N affects the efficiency of proposed methods: the longer fragment the higher level of attenuation of unwanted frequency can be achieved but the bandwidth of suppressed frequencies become narrower.

The bandwidth of suppressed frequencies can be widened by simultaneous suppressing of several close frequencies. When difference between suppressed frequencies becomes relatively high (several MHz), separate notches in signal spectrum can be observed (fig. 7).

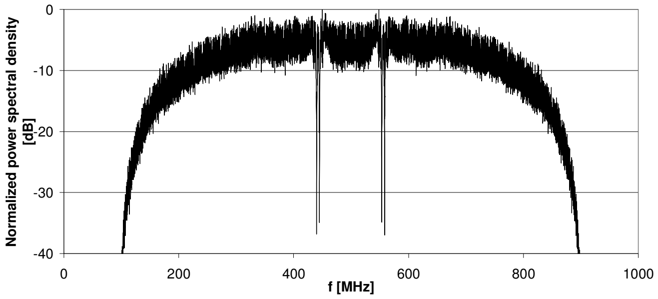

Fig. 7. Normalized power spectral density in case of simultaneous suppression of two frequencies: 440MHz and 445MHz

With assumption that frequency of narrowband signal which can possible be interfered is constant, optimal pulse sequences for preamble and every header/data symbol can be calculated once and reused for all sequent transmissions. Preamble is made of pulses with polarity described by pseudo-random sequence, so every transmitter in the same piconet uses the same preamble in every transmitted frame so the preamble sequence with modified spectrum can be calculated once and stored in memory. Position and polarity of pulses in every header/data symbols depends on values of two bits from systematic convolutional coder and well known pseudo-random sequence, so after dividing UWB packet into fragments with length equal to length of single symbol, only four different pulse sequences (which allow to reduce power spectral density at unwanted frequencies) for every header and data symbol have to be calculated and stored in memory. After that the whole transmission of every packet with any possible content can be made using pulse sequences previously prepared and stored in memory.

Simulation investigations proved that even significant change in time form of elementary pulses does not degrade efficiency of proposed methods of UWB signal shaping. For example figure 8 presents spectrum shape in case when all computations were made using mandatory pulse shape described in IEEE 802.15.4a but generated signal was made of optional pulses called "Chirp on UWB". This feature can be exploited to build UWB network with one node (for example piconet coordinator) which calculates best sequences of pulses according to current spectrum utilization, and then sends to all other nodes in its piconet some tables with calculated sequences to reuse them for transmissions in whole piconet.

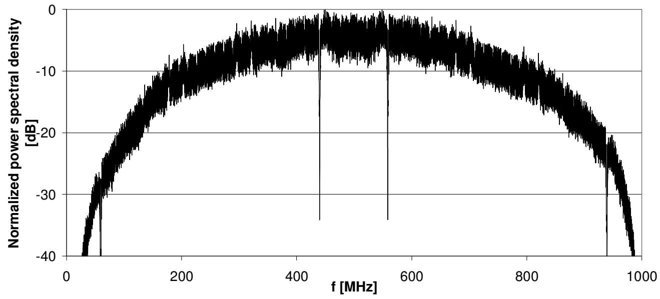

Fig. 8. Normalized power spectral density in case of suppressing frequency 440MHz, when calculations were made using mandatory pulse shape but generated sequence was made of alternate 802.15.4a „Chirp on UWB" pulses.

V. Conclusion

Computer simulations proved that proposed modifications of UWB impulse radio signal spectrum can be applied in transmitter part of radio link. Even without any changes on receiver side, generated signals can be received using coherent and non-coherent receivers. Proposed technique can be used to modify UWB signal spectrum to reduce interference to existing narrowband transmissions even for beacon frames which have to be transmitted using mandatory pulse shape. Similar modifications of pulse sequence structure, applied on receiver side of UWB link, can reduce bit error rate in case of high power narrowband interferences [5].

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