2010 International Symposium on Nonlinear Theory and its Applications
NOLTA2010, Krakow, Poland, September 5-8, 2010

# Radio Coverage Extension of the FCC-Compliant Low-Rate UWB Networking Devices

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**Abstract**— In UWB systems three factors have to be considered to design a radio link: (i) peak- and (ii) average power limits defined by FCC Regulations and (iii) low supply voltage available in handheld cheap devices. An exact mathematical model for the interpretation of FCC Regulations is derived. The radio coverage of UWB networking devices is determined and a chaos-based approach for the coverage extension is proposed.

## 1. Introduction

Ultra-WideBand (UWB) technology allows the reuse of frequency bands occupied by narrowband wireless systems by keeping the peak- and average power levels at such low values regulated by the Federal Communications Commission (FCC, USA) [1] that does not cause any harmful interference. This contribution interprets the FCC Regulations to clarify the main aspect that is usually overlooked, namely that the power limits have to be checked not over the transmitted UWB signal but at the output of a bandpass filter specified in the FCC Regulations.

In 2007 IEEE 802.15.4a Task Group approved a standard [2] for the Low-Rate (LR) UWB applications. The standard focuses mainly on the Impulse Radio (IR) approach but the application of chirp signal or chaotic signal as carriers are also permitted in UWB applications.

LR UWB Impulse Radio transceivers have been designed and built at MIT, USA [7], and in the framework of two large European projects called PULSERS [3] and EUWB [4]. The results of field tests have shown that the sensitivity of the built receivers is too low, the coverage of implemented UWB IR systems is only a few meters. Therefore an increase in bit energy that increases the coverage is essential.

Starting from the FCC Regulations, the paper introduces a novel approach for the link budget calculation to reveal the reason of low coverage. Since the ultra short duration of UWB carrier pulses is responsible for the low coverage of UWB impulse radio the UWB carrier-based approach is proposed here where the duration of UWB carrier is increased considerably and the ultra-wide bandwidth is assured by a chaotic signal. The chaotic carrier-based approach allows to increase the bit energy even by 20 dB that extends the radio coverage considerably.

## 2. Preventing Interference in Conventional Systems

To maximize sensitivity, conventional radio systems use narrowband receivers that can be modeled by a cascade connection of a bandpass channel filter and a demodulator.

### 2.1. Classes of UWB Carriers

Two classes of UWB carriers can be distinguished considering the two kinds of interferences caused: (i) UWB impulse radio with very low duty cycle and (ii) UWB carrier-based radio. In the former case the average level of corruption is negligible but the huge peaks interrupt the operation of synchronized subsystems at the victim receiver. In the latter case no huge peaks occur, the UWB signal is a wideband signal with almost uniform psd that increases noise level at the demodulator input of victim receiver.

### 2.2. FCC Power Limits

The FCC Regulations consider both kinds of interference but say nothing about the type of UWB carrier. They limit both the peak- and average powers of UWB carrier:

1. "There is a limit on the *peak* level of the emissions contained within a 50-MHz bandwidth centered on the frequency at which the highest radiated emission occurs ⋯ That limit is 0 dBm EIRP."
2. The *average* "radiated emissions ⋯ shall not exceed" -41.3 dBm EIRP "when measured using a resolution bandwidth of 1 MHz" over the frequency band of 3.1 GHz to 10.6 GHz. "The RMS average measurement is based on the use of a spectrum analyzer with a resolution bandwidth of 1 MHz, an RMS detector, and a 1 ms or less averaging time."

Note, FCC Regulations gives not only the limits but also instructions how the power limits have to be measured. FCC Regulations have been derived from the model of a narrowband receiver. Observe, neither the FCC *peak* nor *average* power limits are directly applied to the modulated UWB signals, instead, they give limits on the outputs of the two specified FCC bandpass filters.

## 3. Carrier used by UWB IR Devices

Both narrowband and wideband UWB IR devices have been defined in the IEEE Standard 802.15.4a–2007 [2], the bandwidth of the former and latter devices are about 499.2 MHz and 1.3312 GHz, respectively. The UWB IR carrier is a bandpass signal that can be decomposed into a lowpass envelope and a sinusoidal carrier. The standard does not specify the exact shape of envelope.

Because of its easy implementability with CMOS [7] and easy mathematical handling, the frequency-shifted gaussian pulse is considered here as a UWB IR carrier

$$g(t) = p(t)\cos(2\pi f_C t) = V_{peak}\exp\left(-\frac{t^2}{2u_B^2}\right)\cos(2\pi f_C t) \qquad (1)$$

where $p(t)$ is the lowpass gaussian envelope, $f_C$ is the center frequency of UWB carrier and $V_{peak}$ is the pulse peak amplitude

$$V_{peak} = \sqrt{\frac{2Z_0 E_b}{\sqrt{\pi}\, u_B}} \tag{2}$$

In (2), $Z_0$ denotes the characteristic impedance over which the energy per bit $E_b$ is measured and $u_B$ is determined by the 10-dB RF bandwidth $2f_B$ of UWB IR carrier

$$u_B = \frac{1}{2\pi f_B \sqrt{\log_{10}(e)}} \tag{3}$$

Due to the gaussian envelope, the UWB carrier decreases rapidly as a function of time. Effective pulse width, introduced in spectrum analysis [5], is used to define UWB pulse duration

$$\tau_{eff} = \int_{-\infty}^{+\infty} \frac{p(t)}{V_{peak}} dt = \sqrt{2\pi}\, u_B = \frac{1}{f_B \sqrt{2\pi \log_{10}(e)}} \tag{4}$$

Since only the narrowband UWB IR devices are feasible today, only that one is considered here where $\tau_{eff} = 2.43$ ns.

## 4. Attainable Coverage of UWB IR Devices

The coverage of a radio device depends on the energy per bit. The higher the $E_b$, the larger the coverage.

### 4.1. Limits on Energy per Bit

$E_b$ is limited by three issues: (i) FCC peak and (ii) FCC average power limits, and the (iii) low supply voltage of handheld devices.

#### *4.1.1. FCC Peak Power Limit*

The peak emission defined at the output of a bandpass filter having a bandwidth of $\mathrm{RBW}_{50}^{\mathrm{FCC}} = 50$ MHz shall not exceed 1 mW. Let this bandpass filter be referred to as the FCC filter.

To express the relationship between the envelope $p(t)$ of the UWB IR carrier and the FCC peak power limit, a lowpass equivalent model for the interpretation of FCC peak power limit has been developed. In the equivalent model, depicted in Fig. 1, the lowpass equivalent of the FCC filter is driven by the envelope of UWB IR carrier. The cutoff frequency of lowpass equivalent filter is equal to the half of the FCC filter bandwidth, that is, $\mathrm{RBW}_{50}^{\mathrm{FCC}}/2 = 25$ MHz.

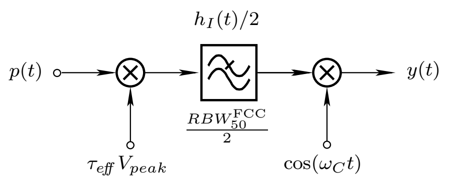


Figure 1: Lowpass equivalent model of the FCC peak power limit calculation.

The excitation $p(t)$, applied to the input of lowpass equivalent model, is a gaussian nascent function that implements a delta function provided that $\sqrt{2}u_B \to 0$. From an engineering point of view this condition is always satisfied since $f_B \gg \mathrm{RBW}_{50}^{\mathrm{FCC}}/2$. Then, considering a 50-Ω termination, the relationship between the FCC 1-mW peak power limit and the UWB IR energy per bit is obtained as

$$P_{peak}^{\mathrm{FCC}} = 0 \text{ dBm} \equiv \frac{y(0)^2}{Z_0} = \frac{2E_b}{\sqrt{\pi} u_B} (\mathrm{RBW}_{50}^{\mathrm{FCC}}\, \tau_{eff})^2 \tag{5}$$

#### *4.1.2. FCC Average Power Limit*

The average power level of UWB emission has to be measured by a spectrum analyzer with a resolution bandwidth of 1 MHz, an RMS detector, and a video filter that has 1 ms or less averaging time. The lowpass equivalent model of the FCC average power limit measurement is depicted in Fig. 2 where $\mathrm{RBW}_{1}^{\mathrm{FCC}}/2 =$ 500 kHz.

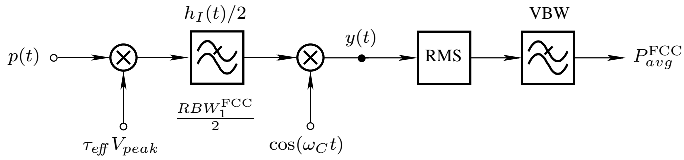


Figure 2: Lowpass equivalent model of FCC average power limit calculation.

According to the FCC Regulations the average power $P_{avg}^{\mathrm{FCC}}$ may not exceed -41.3 dBm EIRP

$$P_{avg}^{FCC} = -41.3 \text{ dBm} \equiv \frac{E_b}{\sqrt{\pi} u_B}\, 1.06\, \mathrm{RBW}_1^{\mathrm{FCC}} \frac{\tau_{eff}^2}{T_{bin}} \tag{6}$$

where $T_{bin}$ is the bit duration and constant of 1.06 appears since not ideal but gaussian filters are used in spectrum analyzers [5].

#### *4.1.3. Supply Voltage Limit on Pulse Peak Amplitude*

The supply voltage of low-power, handheld UWB transceivers is less than 1.5 V. In the low-cost applications, considered here, an LC-transformer cannot be used to increase the signal amplitude. Consequently, the low supply voltage limits the maximum attainable peak-to-peak voltage swing at the transmitter output in 1 V. The supply voltage limit on $E_b$ is obtained from (2) as

$$E_b = \frac{\sqrt{\pi}\, u_B}{2Z_0} V_{peak}^2 = \frac{\sqrt{\pi}\, u_B}{8Z_0} \tag{7}$$

### 4.2. Link Budget Calculation

In conventional telecommunications systems, where the carrier waveform fills up the entire bit duration, the link budget calculation relies on the *signal-to-noise* ratio. This approach cannot be used in the UWB IR systems where the duty cycle is extremely low and the peak-to-average power ratio is extremely high. Instead, the link budget calculation must rely entirely on $E_b$.

#### *4.2.1. Attainable Excess Link Margin*

Let $(E_b/N_0)^{[Tx]}$ and $(E_b/N_0)^{[DEM]}$ denote the UWB signal energy per bit-to-noise power spectral density ratio available at the transmitter and required by the demodulator, respectively. The attainable excess link margin is

$$\mathrm{ELM}_{attain} = (E_b/N_0)^{[Tx]} - (E_b/N_0)^{[DEM]} \tag{8}$$

Since $N_0 = -174$ dBm |1 Hz, the first term in (8) is determined by the maximum attainable $E_b$. As shown in Sec. 4.1, $E_b$ is limited by the FCC Regulations and the supply voltage.

The effects of the three limits on $E_b$ have been calculated from (5), (6) and (7) and are plotted in Fig. 3 where $(E_b/N_0)^{[Tx]}$ is plotted against the data rate. The solid and dashed curves give the limits imposed by the FCC Regulations and the supply voltage, respectively. Two important conclusions may be drawn: (i) the low-rate UWB IR devices are *peak power limited* while the high-rate systems are *average power limited* and (ii) the low supply voltage of handheld UWB IR devices prevents even the exploitation of FCC peak power limit, a further loss in maximum attainable $E_b$ occurs.

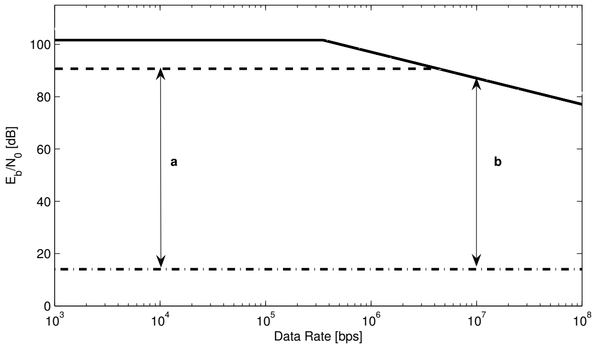


Figure 3: Determination of excess link margin. Solid and dashed curves show $(E_b/N_0)^{[Tx]}$ limited by the FCC Regulations and 1.5-V supply voltage, respectively. Dashed-dotted curve shows the typical value of $E_b/N_0$ required by a noncoherent UWB demodulator at $BER = 10^{-3}$.

The noncoherent UWB IR demodulators, the only feasible implementation for the low-cost CMOS receivers requires $(E_b/N_0)^{[DEM]} \approx 14$ dB to assure a BER of $10^{-3}$ [6]. This value is plotted by dash-dotted curve in Fig. 3.

Figure 3 gives the excess link margin graphically for a specified data rate as the distance measured between the curves of $(E_b/N_0)^{[Tx]}$ and $(E_b/N_0)^{[DEM]}$. As examples, consider two narrowband UWB IR systems with the data rates of 10 kbps and 10 Mbps. As shown by arrow "a" $\text{ELM}_{attain} = 76.3$ dB in the former case and the coverage is limited by the supply voltage. Arrow "b" gives $\text{ELM}_{attain} = 73.2$ dB for the high-rate system where the coverage is limited by the FCC average power limit.

#### *4.2.2. UWB IR Device Related Parameters*

The $\text{ELM}_{attain}$ has to cover the (i) path loss, (ii) receiver noise contribution and the (iii) effects of transmit and receive antennas

$$a_{CH} + \underbrace{NF_{Rx} + I_{LOSS} - G_{Tx} - \eta_{ant}^{[Tx]}(f) - G_{Rx} - \eta_{ant}^{[Rx]}(f)}_{UWB\ IR\ device\ related\ parameters} \quad (9)$$

where $a_{CH}$ is the path loss including multipath, $NF_{Rx}$ and $I_{LOSS}$ denote the overall noise figure and implementation loss, respectively, of the UWB IR receiver. The gain and frequency dependence of transmit and receive antennas are accounted by the $G$ and $\eta_{ant}(f)$ terms. Note, each parameter has to be substituted in decibels in (9).

The parameters of built UWB impulse radio receivers have been reported recently in [7]. Only low- or zero-gain antennas can be used in the handheld applications. Let the frequency dependence of antenna be neglected in our calculation. Then the sum of *UWB IR device related parameters* is about 14 dB.

#### *4.2.3. Path Loss*

The path loss is a random variable, its mean depends on both the distance of transmit and receive antennas and the frequency. The Channel Modeling Subgroup of IEEE 802.15.4a adopted the "power-law" model and decomposed the path loss into four terms

$$a_{CH} = PL_0 + 10\,n\,\log_{10}(d/d_0) + 20(\kappa+1)\log_{10}(f/f_0) + S \quad (10)$$

where $PL_0$ is the path loss at the reference distance $d_0 = 1$ m and reference frequency $f_0 = 5$ GHz, $n$ is the path loss exponent, $\kappa$ describes the frequency dependence of path loss and $S$ is a random variable with zero mean. The distance $d$ and frequency $f$ have to be substituted in meters and GHz, respectively.

### 4.3. Coverage of UWB IR Devices

To get the radio coverage, first the UWB IR device related parameters have to be deduced from the attainable ELM plotted in Fig. 3. Then substituting $S = 0$ into (10), the mean coverage can be calculated.

Consider a typical low-rate application where the data rate is less than 75 kbps. Assuming Non-Line-Of-Sight (NLOS) propagation (10) gives 2 m and 1.4 m for the mean value of coverage in indoor *residential* and *office* applications, respectively. These attainable link distances are so short that the implementation of WLAN systems with UWB impulse radio devices is not feasible. To solve the problem, $(E_b/N_0)^{[Tx]}$ *must be increased considerably*.

There are two solutions to the problem: the energy per bit can be increased by using (i) more than one UWB carrier pulse to transmit one bit information or by applying the (ii) *UWB carrier-based* approach. The latter approach is considered here.

## 5. Improving UWB Radio Coverage using the UWB Carrier-Based Approach

The very short pulse duration and the 1.5-V supply voltage limit are responsible for the low $E_b$ in UWB impulse radio. In the UWB carrier-based approach an inherently wideband wavelet is used as UWB carrier, consequently, the duration of UWB wavelet can be increased considerably. Recall, the larger the wavelet duration, the larger the $E_b$ and the UWB radio coverage.

### 5.1. Generation of UWB Carrier

The block diagram of UWB carrier generation is shown in Fig. 4 where a Bernoulli shift map is used to provide a discrete-time chaotic signal which is converted into an analog waveform by a Zero-order Hold (ZoH) circuit. Then an FM modulator generates an ultra-wideband signal with constant envelope. Finally, a switch is used to form the UWB carrier wavelets with duration of $T_{ch}$ and repetition rate of $T_{bin}$.

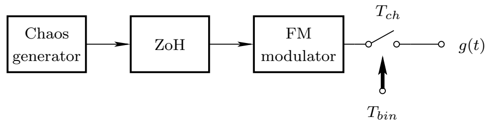


Figure 4: Generation of a constant envelope UWB carrier.

As shown in Fig. 5, a smooth spectrum satisfying the FCC Regulations is obtained with an adequate choice of circuit parameters. The duration of UWB carrier wavelets has been chosen to 300 ns in order to permit the generated chaotic signal to cover the entire state space of Bernoulli shift generator. If so then the spectrum of each UWB carrier wavelet becomes identical.

### 5.2. Exploitation of FCC Peak Power Limit

As shown in Fig. 3, the low-rate UWB IR devices are peak power limited. Unfortunately, the handheld devices even cannot exploit the FCC peak power limit because their voltage swing at the transmitter output is limited by the low supply voltage.

The use of UWB carrier based approach increases $E_b$ in two ways: it (i) increases the duration of carrier wavelet (note, $\tau_{eff} = 2.43$ ns $<< T_{ch} = 300$ ns) and, simultaneously, (ii) reduces

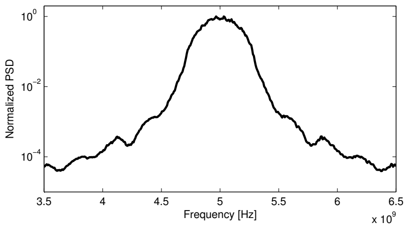


Figure 5: Spectrum of chaos-based UWB carrier, $T_{ch}$ = 300 ns.

the wavelet amplitude that belongs to the FCC peak power limit. The reduced amplitude remains below the supply voltage limit.

Recall, the FCC peak power limit says nothing about the power or amplitude of the UWB carrier, instead, it limits the peak power at the output of the FCC bandpass filter. The relationship between the parameters of UWB carrier (amplitude, duration, shape) and peak power output of FCC bandpass filter is not straightforward, an analytical expression has not yet been found.

Consider a constant envelope UWB carrier generated by the block diagram of Fig. 4, characterized by the spectrum shown in Fig. 5 and having a duration of 300 ns. Recall, the bandwidth of FCC filter is 50 MHz. The response of the FCC bandpass filter to the chaos-based UWB carrier wavelet is shown in Fig 6. Both the transient and steady-state responses can be observed in the FCC filter output that carries an AM in spite of the fact that the input is a constant envelope signal. The amplitude of UWB carrier remains below 0.22 V, consequently, the low supply voltage of the handheld UWB device does not limits $E_b$ anymore. Note, the UWB carrier-based approach allows to increase the wavelet duration considerably and also permits to fully exploit the FCC peak power limit in handheld applications.

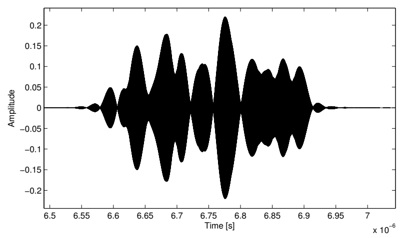


Figure 6: Response of the FCC bandpass filter to the constant envelope UWB carrier wavelet. The duration of UWB carrier wavelets is 300 ns.

### 5.3. Enhancement in Attainable Energy per Bit

To show the effectiveness of the technique proposed here the attainable energy per bits of two narrowband handheld UWB systems offering data rate of 75 kbps have been compared. In the reference solution the UWB impulse radio approach is used where 1.5-V supply voltage limits the attainable $E_b$. Due to the low $E_b$, UWB IR devices offer an unacceptable short radio coverage. The relative enhancement in $E_b$ is plotted in Fig. 7 as a function of the UWB carrier wavelet duration. A considerable enhancement can be achieved, for example, the improvements in $E_b$ are 16.2 dB and 20 dB when the durations of UWB carrier wavelet are 300 ns and 800 ns, respectively. According to (10), this large improvement significantly increases the coverage of UWB radio devices.

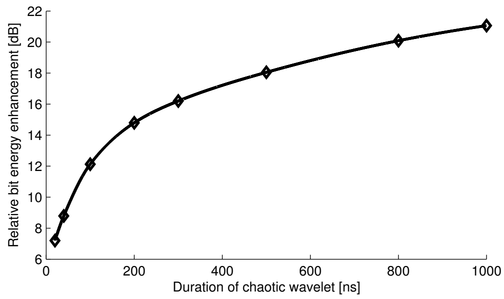


Figure 7: Improvement in attainable energy per bit when constant envelope UWB wavelets generated from a chaotic signal are used as carrier.

## 6. Conclusion

The coverage of UWB impulse radio devices is limited by the FCC Regulations because they restrict the attainable energy per bit. The low supply voltage of handheld UWB IR devices limits even further the attainable $E_b$. Deriving a novel approach for the link budget calculation this paper has shown that the maximum coverage of UWB IR devices becomes less than 2 m in indoor applications under NLOS propagation conditions. That short coverage prevents the application of the UWB impulse radio approach in WLAN applications.

Since the extremely short pulse duration is responsible for the low $E_b$ in UWB impulse radio, the use of FM modulated chaotic waveforms with relatively long duration is proposed here as a UWB carrier. A 16-dB and 20-dB improvements in $E_b$ have been achieved with the UWB carrier durations of 300 ns and 800 ns, respectively. That huge increase in energy per bit considerably improves the coverage of UWB radio devices.

## 7. Acknowledgments


This work has been financed by the Hungarian-French Intergovernmental S&T Cooperation Programme. T. Krébesz's participation was supported by the Mecenatura Fund, National Office for Research and Technology (NKTH), Hungary.


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