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Wireless Personal Area Networks

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Re:	IEEE 802.15.4a Call for Proposals
Abstract	[This document contains the proposals for the IEEE 802.15.4a standard, based on the UWB Direct Chaotic communications Technology]
Purpose	[This document contains the proposals for the IEEE 802.15.4a standard.]
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Table of Contents

1. Introduction

This proposal defines the entity of physical layer for ultrawideband system that uses unlicensed ultrawideband frequency range 3.1–10.6 GHz, as it is regulated in USA by Federal Bill No. 47, section 15. Ultrawideband system provides wireless communications with the data transmission rates 1, 10, 100 and 1000 kbps. The proposed ultrawideband system uses chaotic pulses as information carriers.

2. PHY Layer Technical Characteristics summary

2.1. Overview of the proposed UWB system description

Dynamic chaos (chaotic oscillations) has a number of features that make attractive its application as information carrier for communications. These features include, in particular, potentially high rates of information transmission, resistance of wideband signals to fading by multipath propagation, and possibility of confidential communications (e.g., see [15]). However, numerous studies in the field of application of chaos for communications indicate that practical realization of potential advantages of chaos meets a number of serious problems. One of them is that the proposed communication schemes using chaos were based on traditional transceiver solutions, where chaos was used as subcarriers modulating high-frequency (UHF) carrier. In this case, such an attractive feature of chaos as its wideband (ultrawideband) nature was lost to considerable extent, though it could have provided high transmission rates and large-base signals.

In order to overcome this problem, direct chaotic communication systems were proposed instead of traditional transceiver construction.

Direct chaotic communication (DCC) systems are systems based on dynamic chaos in which useful information is put into the chaotic signal generated directly in RF or microwave band [1].

A key notion of the proposed technology is the notion of *chaotic radio pulse* [2–7]. It is a signal fragment whose duration is longer than the quasiperiod of chaotic oscillations. The frequency bandwidth of the chaotic radio pulse is determined by the bandwidth of the original chaotic signal generated by chaotic source, and is independent of the pulse duration in a wide range of duration variation. This makes the chaotic radio pulse essentially different of the classical radio pulse, represented by a fragment of periodic carrier, whose frequency bandwidth Δf is determined by its duration τ

$$\Delta f \sim \frac{1}{\tau}. \qquad (2.1.1)$$

Three main ideas constitute the basis of direct chaotic communications:

- chaotic source generates chaotic oscillations directly in the prescribed microwave band;
- information is put into the chaotic signal by means of forming the corresponding sequence of chaotic radio pulses;
- information is retrieved from the microwave signal without intermediate carrier frequency transforms.

Block diagram of a direct chaotic communication system in the cases of external and internal modulation is shown in Fig. 2.1.1.

The transmitter of the system is composed of a unit of oscillator control; a chaotic source that generates the signal directly in the frequency band of information transmission, i.e., in RF or microwave band; a keying-type modulator; an amplifier; an antenna; an information source; a message source encoder, and a channel encoder.

Chaotic source provides generation of the signal with the frequency bandwidth

$$\Delta F = F_u - F_l, \tag{2.1.2}$$

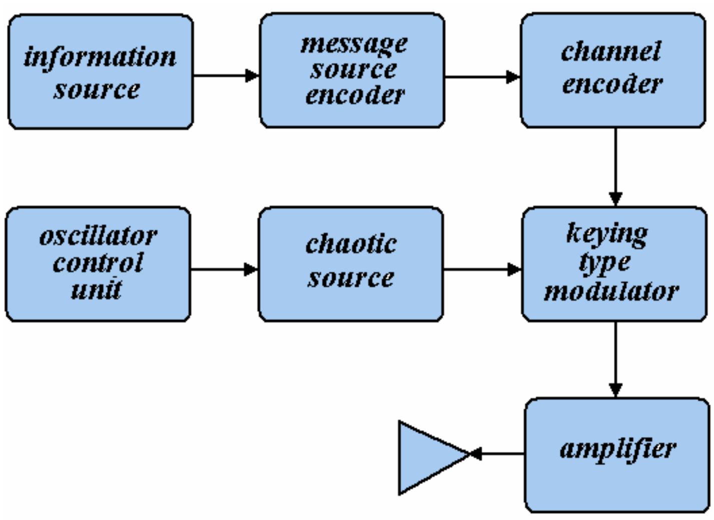
where F_l and F_u are the lower and upper boundaries of the chaotic oscillation band. The chaotic signal frequency bandwidth is the frequency range, at which boundaries the power spectral density is –20 dB of the maximum within the range.

The central frequency

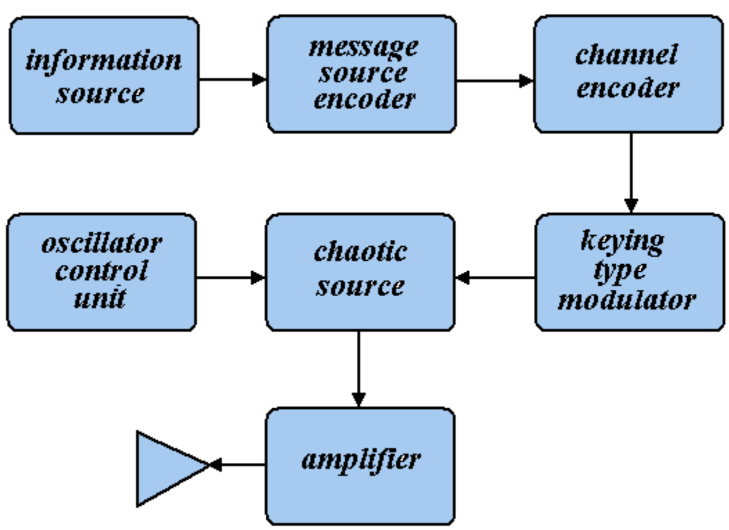
$$F_0 = (F_u + F_l)/2 \tag{2.1.3}$$

and the bandwidth ΔF of the generated signal may be adjusted by control unit. Modulator forms chaotic radio pulses and intervals between them.

Information that comes from an information source is transformed by the message source encoder into a signal that is fed to the channel encoder input, which in turn transforms it into a modulating signal that controls the modulator. Modulator forms chaotic radio pulses either by means of multiplying chaotic signal and modulating pulses (the case of external modulation, Fig. 2.1.1a), or by means of modulating the oscillator parameters (the case of internal modulation, Fig. 2.1.1b). The duration of the formed chaotic pulses may be varied in the range $\tau \sim 1/\Delta F$ to $\tau \to \infty$.



a)



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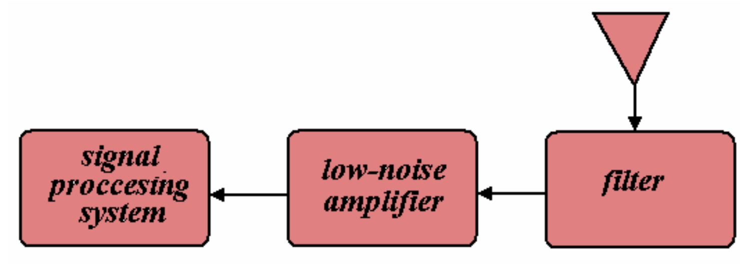


c)

Fig. 2.1.1. Block-diagram of direct chaotic communication system: (a) transmitter with external modulation; (b) transmitter with internal modulation; (c) receiver.

The formed signal is put through amplifier and is emitted to free space with wideband antenna. Information stream can be formed by means of changing the intervals between the pulses, the pulse duration, the mean square amplitude of the pulses, or by means of combining these parameters. For example, the stream can be formed so as to have constant rate of pulse positions and fixed duration of the pulses. In this case, the presence of a pulse at a certain prescribed position in the stream corresponds to transmission of symbol "1", and the absence to symbol "0".

The receiver (Fig. 2.1.1c) is composed of a broadband antenna, a filter that passes the signal within the frequency band of the transmitter, a low-noise amplifier, and a signal processing system. The sequence of chaotic radio pulses comes to the antenna and is passed through filter and amplifier. Then the signal-processing system finds the pulses and determines their parameters and location in the time domain. Then, the signal-processing system retrieves useful information from the signal either by means of integrating the pulse power over the pulse interval (noncoherent receiver), or by means of convolving the chaotic radio pulses with corresponding reference pulses generated in the receiver (coherent receiver).

2.2. Frequency plan. Coexistence with other standards

Two versions of the frequency plan are offered for consideration. The first is presented in Fig. 2.2.1a. According to this plan, three frequency subbands are allotted, each 2-GHz wide, namely, 3.1–5.1 GHz, 6.0–8.0 GHz and 8.1–10.1 GHz. The frequency band 5.1–6.0 GHz remains unused, in order to avoid collisions with systems operating at unlicensed frequencies within that band.

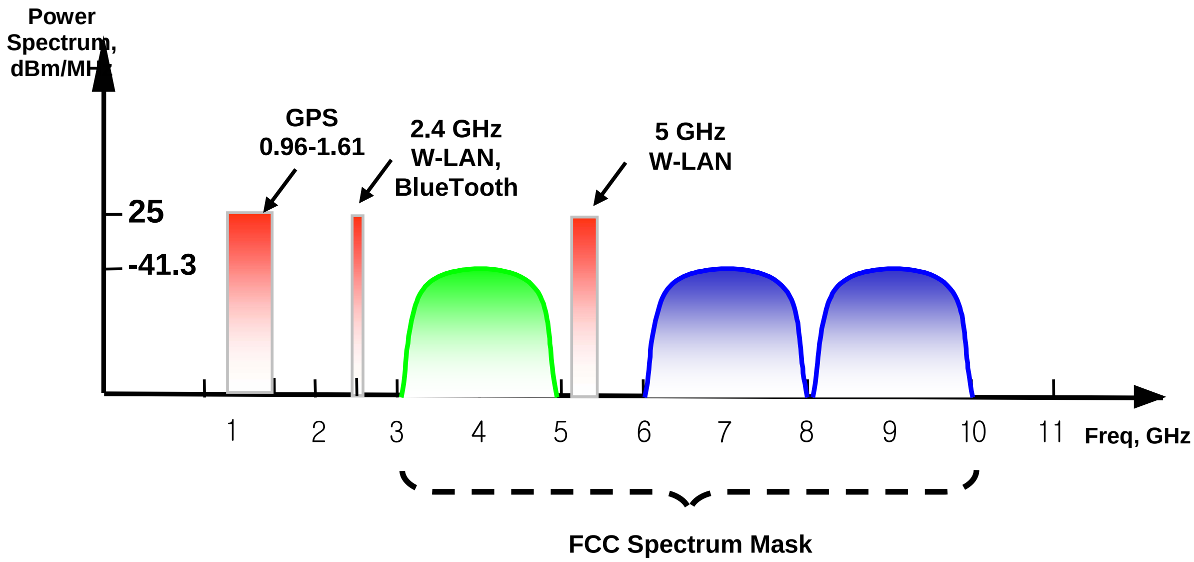
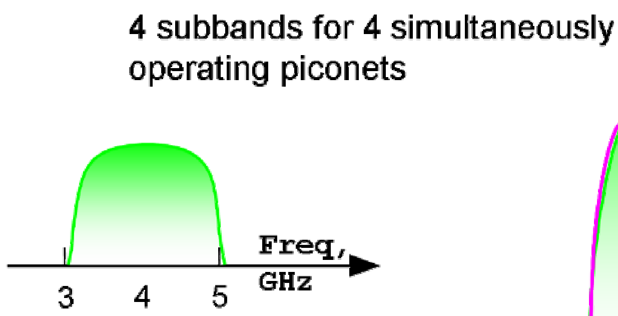
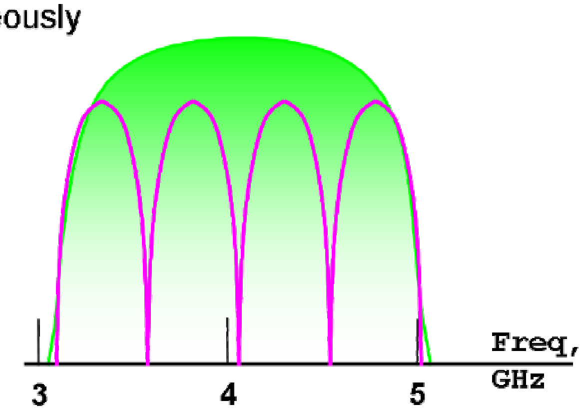


Fig. 2.2.1. Frequency plan.



Subband	fc, GHz	fL, GHz	fR, GHz
1	3,35	3,1	3,6
2	3,85	3,6	4,1
3	4,35	4,1	4,6
4	4,85	4,6	5,1



- 500 MHz bandwidth at –10 dB
- Spaced 500 MHz away

Fig. 2.2.2. 4 subbands for simultaneously operating piconets.

2.3. Chaotic radio pulse and its features

Chaotic radio pulse is a fragment of chaotic process of certain duration ***T*** (fig. 2.3.1).

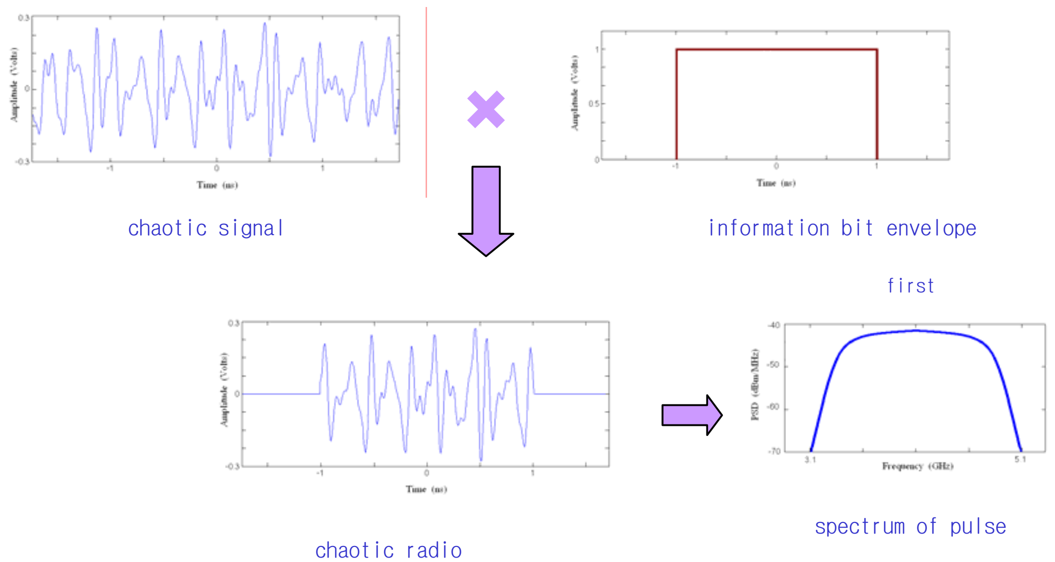


Fig. 2.3.1. Chaotic radio pulse and its features

The main features of chaotic radio pulses are presented in the figure. Chaotic radio pulse is a fragment of chaotic signal whose duration exceeds the characteristic “quasi-period” of chaotic oscillations.

The frequency bandwidth of chaotic radio pulse is determined by the frequency bandwidth of the original chaotic signal and is independent of the pulse duration in a wide range of duration variation. Only when the pulse duration becomes very short (of the order of quasi-period of oscillations), the pulse duration has effect on its spectrum. In our proposal this property will be used to increase chaotic source efficiency by means of using chaotic pulses with 100 ns duration. Which allows to simplify requirements to precision of synchronization of transmitter and receiver.

Potentially, chaotic communication systems have the following benefits:

1. Simple construction of chaotic sources
2. Self-synchronization of transmitter and receiver
3. Possibility of using coherent as well as incoherent receivers
4. Possibility of forming various chaotic modes in a single device
5. Flexible variation of information transmission rate
6. Naturally wideband signal
7. Variety of methods of putting information in chaotic signal
8. Additional capabilities for multiple access
9. Confidential transmission of information
10. Environmental safety

2.4. Signal structure and methods of modulation

Information is transmitted by means of a stream of chaotic radio pulses. The duration of each pulse is τ, and the duration of the time window, on which the pulse is positioned is T. Parameter

$$S = \frac{T}{\tau} \tag{2.4.1}$$

is called *duty cycle*.

Let the power of the original chaotic signal be P, and by transmitting information «1» be encoded by the fact of the presence of the chaotic radio pulse on prescribed position and «0» by its absence. Then the average power of the chaotic signal in communication channel is

$$P_{cp} = \frac{P}{2S}. \tag{2.4.2}$$

Let us denote the spectral density of chaotic signal by $s(f)$. It is not constant, as a rule, in frequency range ΔF. Therefore, a useful characteristic is mean value of spectral density in the chaotic signal frequency range

$$< s >= \frac{1}{F_в - F_н} \int_{F_н}^{F_в} s(f) df = \frac{1}{\Delta F} \int_{F_н}^{F_в} s(f) df. \tag{2.4.3}$$

The *signal base* is the value [10–11]

$$B = 2\Delta F \tau. \tag{2.4.4}$$

Depending on the value of base B, *elementary* signals with base

$$B = 2\Delta F \tau \sim 1 \tag{2.4.5}$$

and *complex* signals, satisfying the relation

$$B = 2\Delta F \tau >> 1 \tag{2.4.6}$$

are distinguished.

If the duration of chaotic radio pulse is $\tau >> 1/(2\Delta F)$, then the power spectrum of a train of chaotic radio pulses is practically the same as the spectrum of the original chaotic signal. Since the value $2\tau\Delta F$ is the signal base, then an increase the duration of chaotic radio pulse leads to increasing the signal base.

In order to understand main features of chaotic radio pulse as information carrier, let us compare it with two other carrier types: harmonic signal and ultrashort ultrawideband video pulses.

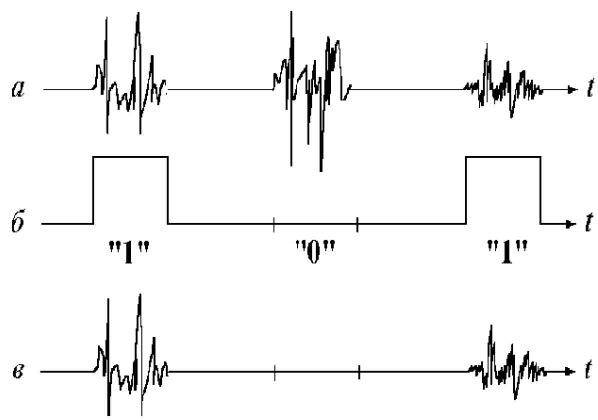
Radio pulses, obtained by multiplication of harmonic signal with frequency f_0 and video pulses with duration τ, are elementary signals, because their frequency bandwidth is $\Delta F \sim 1/\tau$ [13–14]. Despite the ultrawide bandwidth of occupied frequencies, simple-form ultrashort video pulses are also elementary [15], because the product of their duration by the frequency bandwidth is also close to unity $B = 2\tau\Delta F \sim 1$. In modern communication systems, especially in those operating in hard conditions of signal propagation (cellular systems, local wireless communications, etc.), large-base signals are preferred, as a rule. When working with signals based on harmonic carrier, spectrum-spreading techniques are used (direct spread sequences and frequency hopping) [12–14], where the signal base is increased in proportion to the spectrum spreading factor. In order to obtain large-base signals using ultrawideband ultrashort pulses, either energy of several pulses is accumulated, or the pulse form is complicated, thus increasing their duration while retaining their ultrawideband nature [16].

Unlike the above signals, the signal base in DCC is determined only by the duration of the chaotic radio pulse and information bit rate. To change B no additional elements are required in the system. Moreover, input circuits of receiver for different bitrates and base values remain the same.

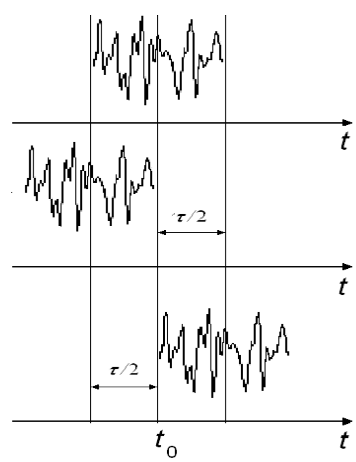
Note also that direct chaotic signals can be realized in any necessary frequency range (which is impossible in, e.g., ultrawideband systems with ultrashort pulses).

Use of chaotic radio pulses as information carrier gives various signal systems for noncoherent and coherent reception.

By noncoherent reception a pair of orthogonal signals can be made of the above-mentioned signals: the presence of chaotic radio pulse on a given position or its absence (Fig. 2.4.1a–c). Another variant of a pair of orthogonal signals is a pair of chaotic radio pulses shifted with respect to a certain known position. Here, «0» is related to a pulse shifted to the left from the fixed position, and «1» to the right of it (Fig. 2.4.1d).



a)-c)



d)

Fig. 2.4.1. Chaotic radio pulses.

Both these pairs can also be used by coherent reception. But here, there are additional capabilities.

Indeed, two arbitrary equal-length fragments of chaotic signal are practically uncorrelated, i.e., orthogonal. This circumstance can be used for making pairs of « orthogonal» signals as follows.

Transmitter and receiver incorporate chaotic sources that form equal chaotic signals. For example, sequences of chaotic radio pulses are formed. This sequence is divided in pairs, each containing two practically orthogonal signals.

This method of making «orthogonal» signal systems can be naturally generalized to groups of m signals, which allows to transmit $\log_2 m$ information bits during one active time interval.

By coherent reception, antipodal signals can also be used for communications. As in the case of orthogonal signals, equal sequences of chaotic radio pulses are formed in transmitter and receiver. When transmitting «0» the radio pulse is inverted by sign before emission, and when transmitting «1» it is emitted as is.

Note also, that uncorrelated character (orthogonality) of chaotic radio pulses is approximate. The same is true to the energy of chaotic radio pulses. It varies, in general, from pulse to pulse, and this must be taken into account by simulation of the performance of communication system.

2.5. Characteristics of DCC with AWGN channel

Expected characteristics of probability error for considered modulation methods and receivers approximately correspond to standard characteristics of signal systems, namely (for probability error $P = 10^{-3}$, spectral density of Gaussian noise N_0 and average energy of chaotic radio pulse per bit of transmitted information E_b):

– noncoherent receiver, orthogonal signals (Fig. 2.5a) – $(E_b/N_0)_{\mathrm{dB}}$ = 13–15 dB;
– coherent receiver, orthogonal signals (Fig. 2.5a) – (($E_b/N_0)_{\mathrm{dB}}$ =10–12 dB;
– coherent receiver, orthogonal signals (Fig. 2.5b) – $(E_b/N_0)_{\mathrm{dB}}$ =10–12 dB;
– coherent receiver, antipodal signals (Fig. 2.5c) – $(E_b/N_0)_{\mathrm{dB}}$ =7–8 dB.

Information in the transmitter is encoded as follows: symbol «1» is transmitted by chaotic radio pulse on a certain time position, and symbol «0» by zero radio pulse on prescribed position (i.e., by the absence of pulse). This pair of signals is orthogonal.

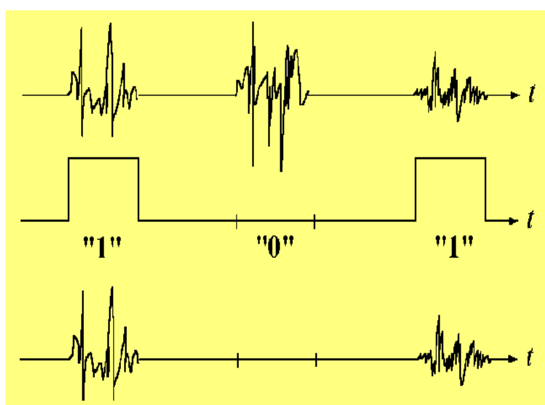


Fig. 2.5.1. Modulation

Transmitter signal $s(t)$ is transmitted through AWGN channel, where noise $w(t)$ is added, so that at the receiver input the signal becomes $x(t) = s(t) + w(t)$.

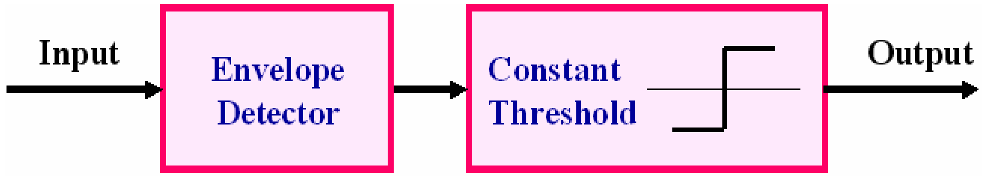


Fig. 2.5.2. Receiver Layout

Quasi-optimal noncoherent receiver for this signal pair is built as follows. On a prescribed position, the signal energy is measured and it is compared with previously chosen threshold. If the energy is above the threshold, the received symbol is decided to be «1», otherwise it is symbol «0». In order to estimate the threshold, two energy distributions are calculated, one for «zero» pulse and the other for «unit». Distribution for zero pulse is simply distribution of noise energy at the receiver input on interval of duration T_s: $\sum x_n^2 = \sum w_n^2$. Its mean is equal to noise variance. For unit pulse, distribution of the «signal + noise» energy $\sum x_n^2 = \sum(s_n + w_n)^2 \approx \sum s_n^2 + \sum w_n^2$ is calculated. Its mean is equal to the sum of the mean pulse energy and mean noise energy on T_s interval. Since the signal is chaotic, the pulse energy also varies and it has its own distribution, however with increasing pulse duration the distribution becomes narrower.

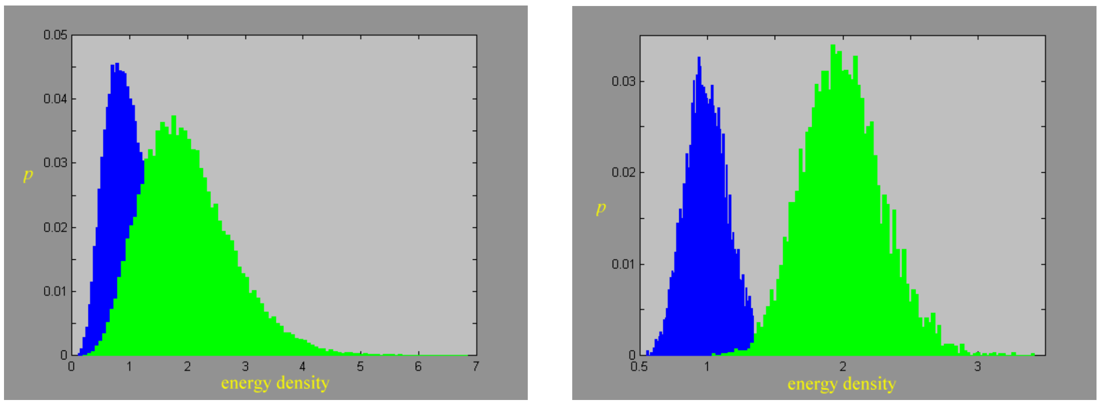


Fig. 2.5.3.

This effect is illustrated in Fig. 1, where in the left graph energy distributions for zero (blue color) and unit (green) bits are presented for minimum-length pulses τ, and in the right graph for pulses with processing gain 8, i.e., $T_s = 8\tau$. As can be seen in these plots, the distribution means remain the same, but the distributions themselves become much narrower (note that the scales of the horizontal axes are different).

As threshold, an energy value between the two distributions is taken. Four different probabilities are distinguished in this case: two 1st-order probabilities, P_0 and P_1 – probabilities of correct recognition of zero and unit bits, respectively; and two error probabilities of 2nd-order, P_{01} and P_{10} false alarm probabilities for zero and unit bits, respectively. In ideal case, $P_0 = P_1 = 1$, and $P_{01} = P_{10} = 0$.

The energy threshold is chosen so as to provide equal probabilities of error and false alarm, i.e., $P_{01} = P_{10}$. In Fig. 1b, the threshold is $E_b/N_0 \sim\ \sim 1.3$.

In time-varying channel, these distributions change, but the threshold needs no adjustment: the threshold value can be set constant at a value that ensures satisfies condition $P_{01} = P_{10}$ at minimum SNR. In this case, $P_0 \leq 1$. This corresponds to the case of maximum distance between the receiver and transmitter. Then the threshold in the receiver is kept constant. At a higher SNR the device would operate even more reliably, while at a lower (which corresponds to a distance beyond the operation limit) it will simply be inoperable (more precisely, the error probability would be above the required value).

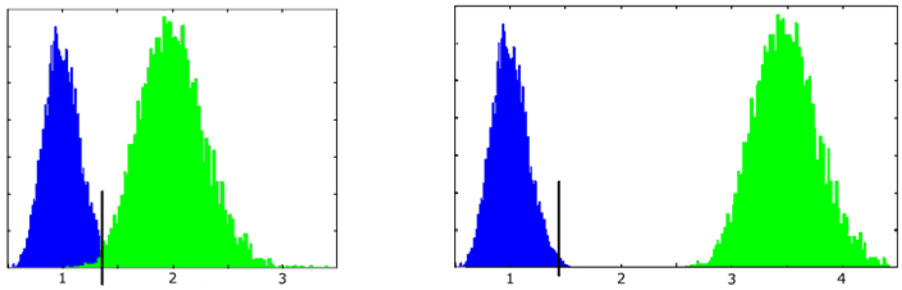


Fig 2.5.4. Distributions of energy per bit for same-duration pulses at different distances: (a) maximum distance; (b) less distance. Constant threshold is shown.

The receiver operation with constant threshold is schematically shown in Fig.. 2. At minimum admissible signal-to-noise ratio (e.g., $E_b/N_0 = 16$ dB) the threshold is chosen once and for all, so as to ensure equal probabilities of error and false alarm (e.g., at a level $P_{01} = P_{10} = 10^{-3}$) (Fig. 2a). This corresponds to maximum distance of communication system operation. At a less distance, the energy distribution of unit bit moves to the right, because energy and signal-to-noise ratio both increase (Fig. 2b). As can be seen in Fig. 2, with this constant threshold the system can operate in all distance range. In this case, the probability of correct recognition of zero bit P_0 will remain the same $P_0 = 1 - P_{01} = 0.999$, while the probability of unit bit recognition will be $P_1 = 1$. Thus, in all operation range the system with flawlessly receive unit bits and with probability $P_{01} = 10^{-3}$ make mistakes with receiving zero bits. This gives PER = 10^{-2}.

The noise level at the receiver input w_n is determined by the temperature noise of the medium and the receiver temperature (amplifier noise calculated back to the input). In time-varying channel, e.g., due to multipath propagation, the channel response can change, which can cause a change in SNR, however, the noise temperature remains the same, since said temperatures remain the same. This means that the constant-threshold system will remain operable.

The situation with appearing/disappearing noise sources in the channel is special. Development of communication system that can operate in such conditions is a separate problem that needs separate investigation.

2.6. PHY frame structure

The frame structure is the same as in 802.15.4 standart.

PHY Packet Fields

- Preamble (32 bits) – synchronization
- SFD (Start of Frame Delimiter) (8 bits) – specifies frame type
- PHR (PHY Header) (8 bits) – Sync Burst flag, PSDU length
- PSDU (PHY Service Data Unit) (0 to 127 bytes) – Data field

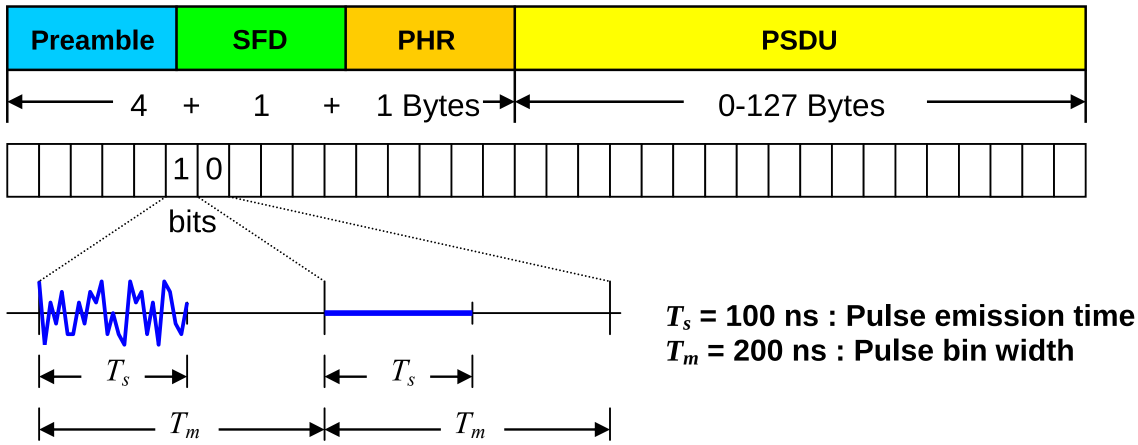


Fig. 2.6.1. Frame structure

2.7. Transceiver Architecture

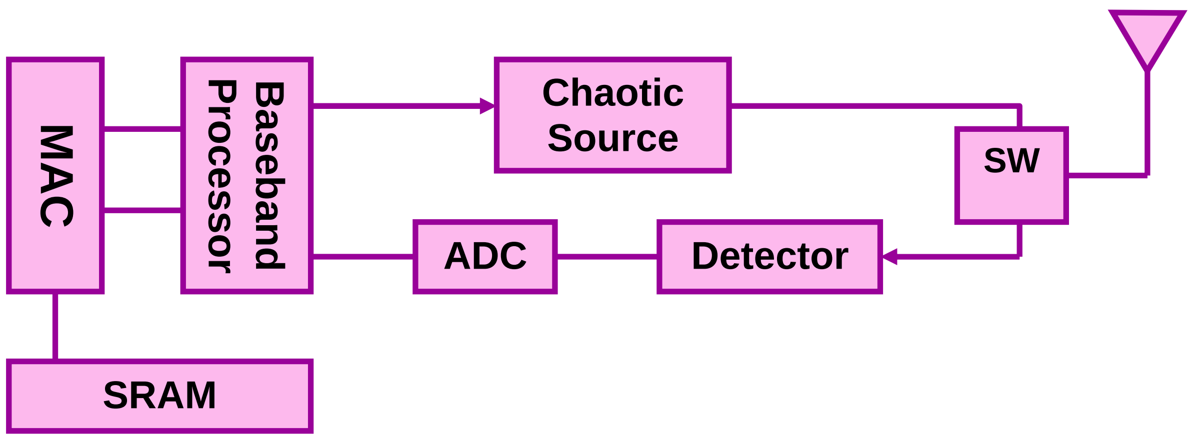


Fig. 2.7.1. Transceiver architecture

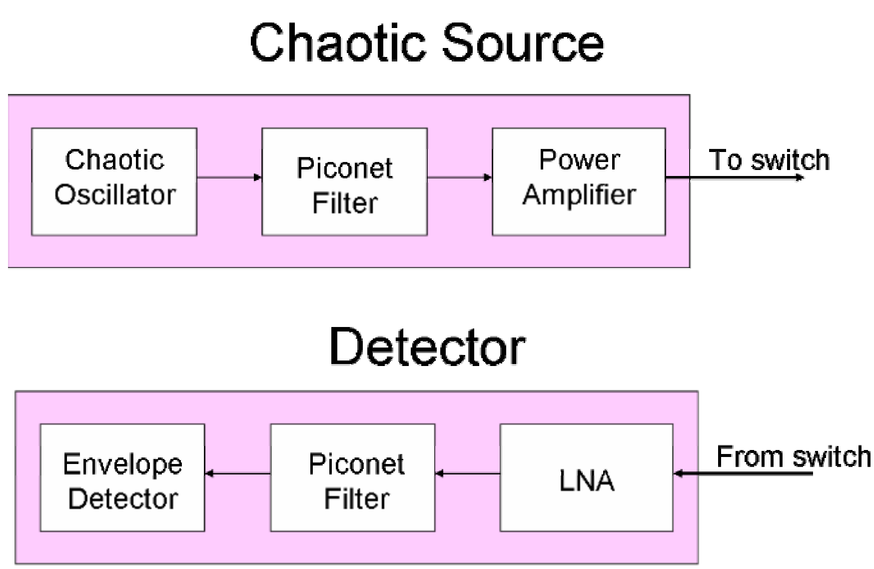


Fig. 2.7.2. Structure of chaotic source and detector.

- Very simple modulation scheme: on-off power supply is used for modulation
- Additional power consumption

Transmitter:

- source of ultrawideband chaotic signals, generating chaotic carrier in required frequency subbands 3.1-3.6 GHz, 3.6-4.1 GHz, 4.1-4.6 GHz, 4.6-5.1 GHz of band (3–5 GHz);
- modulator, controlling the chaotic carrier
- amplifier of signal in required frequency band
- omni-directional transceiver antenna, emitting (receiving) signal in required frequency band.

Receiver:

- demodulator, retrieving information component from the received chaotic signal

Digital module, matching transmitted and received two-level information signals with network adaptor of personal computer (standard Ethernet 10/100).

Radio Transmitter: Example 1

- UWB bandwidth 500 MHz
- UWB Transmit power
  - PSD = --57.0 dBm/MHz
  - Average power = -30 dBm => 1 μW
- Energy/bit (@ 1 kbps) = 1 nJ/bit

Radio Transmitter: Example 2

- UWB bandwidth 500 MHz
- UWB Transmit power
  - PSD = -47.0 dBm/MHz
  - Average power = -20 dBm => 10 μW
- Energy/bit (@ 10 kbps) = 1 nJ/bit

Radio Receiver: Example 1

- Low power UWB radio: not a software radio!
  - Analog section:
    - No LNA: increase transmit power, allow higher noise figure
    - No oscillator at the receiver: envelope detector
- Digital section:
  Circuits running at symbol rate (kHz or MHz), not at RF rates (GHz)

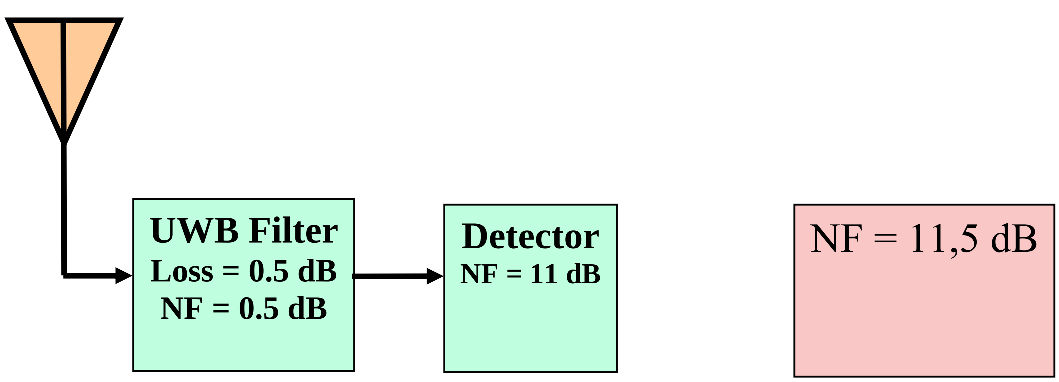


Fig. 2.7.1. Radio receiver. Example 1.

Radio Receiver: Example 2

- Low power UWB radio: not a software radio!
  - Analog section:
    - LNA 7 dB: less noise figure
    - No oscillator at the receiver: envelope detector
- Digital section:
  Circuits running at symbol rate (kHz or MHz), not at RF rates (GHz)

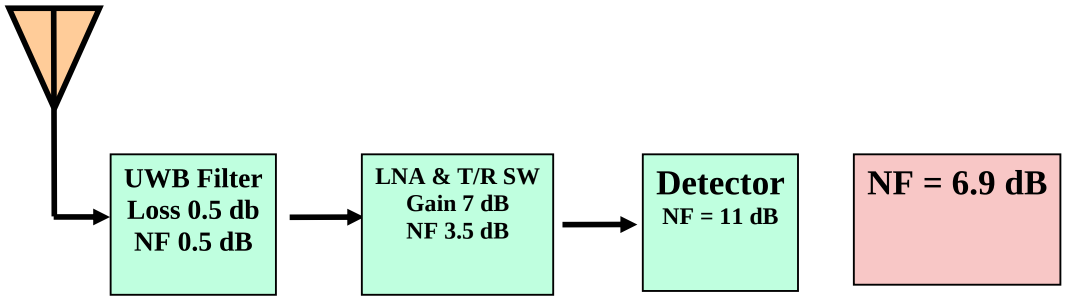


Fig. 2.7.2. Radio receiver. Example 2.

2.8. Summary of Characteristics

The main characteristics of the proposed solution are presented in the Table.

As an information carrier the chaotic radio pulse stream is used.

It is possible to use three bands of 2 GHz bandwidth: 3.1-5.1, 6.1-8.1, and 8.2-10.2 GHz (12 channels of 500 MHz bandwidth).

We use the chaotic pulses with 100 ns duration.

In agreement with 802.15.4a requirements transmission with 3 bit rates (1 kbps, 10 kbps, 1Mbps) for individual link is provided. The highest possible aggregated bit rate in this case is 5 Mbps.

The period of battery life is determined by the generator efficiency, bit rate and duty cycle.

Information carrier	Chaotic radio pulses	
Band division	3 bands within FCC Mask (3.1-5.1, 6.1-8.1 and 8.2-10.2 GHz)	
Channel bandwidth	4 channels with 500 MHz in each 2.0 GHz band	
Pulse duration	100 ns	
Individual bit rate	1 Kbps	10 Kbps
Transmit power	-30 dBm	-20 dBm
Battery life	2.5 year 100% duty cycle	2.5 year 10% duty cycle
Aggregated bit rate	Up to 10 Mbps	

2.9. Scalability

Frequency and transmission bandwidth scalability

The technology allows us to organize transmission in different frequency bands.

For example, 3.1 – 5.1 GHz, 6.0 – 8.0 GHz and 8.1 – 10.1 GHz with frequency bandwidth 2 GHz. Frequency band 5.1 – 6.0 GHz is not used to avoid collisions with the other systems operating at unlicensed frequencies in this frequency band.

Alternative version is the use of frequency bands 3.1 – 4.6 GHz, 4.6 – 6.1 GHz, 6.1 – 7.6. GHz, 7.6 – 9.1 GHz and 9.1 –10.6 GHz with the bandwidth 1.5 GHz.

Bit rate scalability.

The technology allows to cover the whole range of bit rates from bits per second to 1 Gbps.

In the proposed system allows different bit rates are realized by means of varying duty circle at the constant pulse duration or by means of varying the pulse duration.

In the Table the possibility of varying bit rate from several bps till 5 Mbps is shown by means of varying duty circle at the pulse duration 100 ns.

Bit rate	Pulse duration	Duty circle
<1 kbps	100 ns	>10000
1 kbps	100 ns	10000
10 kbps	100 ns	1000
1 Mbps	100 ns	10
5 Mbps	100 ns	2

Use of radio pulses with duration less than 20 ns allows to increase bit rate keeping the power consumption constant. Using longer pulses at constant bit rate will cause an increase of power consumption, but will also increase the system stability to the environmental attack (it will decrease the number of errors of signal receiving, and will increase transmission range).

Shorter pulses provide data transmission with higher bit rates (up to 1 Gbps).

Pulse duration and duty circle are controlled by modulator.

Power consumption.

Power is saved due to switching on the receiver and transmitter so that they function only during their direct operation intervals. For example, if information is transmitted with duty cycle less than one, then for the time between information positions the transmitter and receiver are switched off. This mode is possible due to large pulse duration (~ 100 ns). This duration is enough to cope with transient processes in power supplies and to ensure establishment of operation mode of transceiver elements.

In the Table, power consumption at various bit rates is shown.

Transmission Rate *V*, kbps	Average Emitted Power *Pe*, mW	Average Power Consumption *Pav* (η = 5%)	Continuous operation time AAA battery, years
1	2·10-4	15.5 μW	8.3 100% duty cycle
10	2·10-3	87.5 μW	15 10% duty cycle
1000	2·10-1	8 mW	16.4 0.1% duty cycle

It is possible to decrease power consumption at a constant bit rate by means of using shorter chaotic radio pulses. This approach can be applied in applications with rather good environment conditions (weak multipath) or at short distances.

Distance scalability.

Technology permits to realize communications over short, middle, large and very large distances. This capability is given by good scalability of transmission rates, possibility of using omnidirectional and directional antennas, and conventional amplifier technology.

In the Table, transmission range as a function of increasing bit rate is shown. Pulse duration is constant. (For Link margin = 0 dB).

Parameter	Value	Value
Bitrate, Kbps	1	10
Pulse duration, ns	100	100
Max. connection distance, free space, m	120	120
Max. connection distance, channel 8, m	100	100

2.10. Link Margin

Example link margin for the maximum average Tx power according to FCC mask is shown in Table 1.

Table 1.

Parameter	**Value**	**Value**
Throughput (Rb), Kbps	**1**	**10**
Duty cyrcle, dB	**-40**	**-30**
Average Tx Power (PT), dBm	**-14.3**	**-14.3**
Geometric central frequency Fc, GHz	**3.35**	**3.35**
Path loss at 1 m (L1), dB	**44.5**	**44.5**
Path loss at 30 m (L2), dB	**30**	**30**
Tx antenna gain (GT), dB	**0**	**0**
Rx antenna gain (GR), dB	**-3**	**-3**
Rx Power at 30 m (PR=PT+GT+GR-L1-L2), dBm	**-91.8**	**-91.8**
Average noise power per bit (N=-174+10*log10(Rb)), dBm	**-144.0**	**-134.0**
Rx noise figure referred to the antenna terminal (NF), dB	**7.0**	**7.0**
Total average noise power per bit (PN=N+NF), dBm	**-137**	**-127**
Minimum Eb/No (S), dB	**14**	**14**
Raw bit rate, kbps	**2**	**20**
Code rate	**0.5**	**0.5**
Implementation loss (I), dB	**3**	**3**
Link Margin at 30 m (M=PR-PN-S-I), dB	**28.2**	**18.2**
Rx sensitivity level, dB	**-120(-80)**	**-110(-80)**

Example Link Margin with optimal average Tx power is shown in Table 2.

Table 2.

Parameter	**Value**	**Value**
Throughput (Rb), Kbps	**1**	**10**
Duty cyrcle, dB	**-40**	**-30**
Average Tx Power (PT), dBm	**-30**	**-20**
Geometric central frequency Fc, GHz	**3.35**	**3.35**
Path loss at 1 m (L1), dB	**44.5**	**44.5**
Path loss at 30 m (L2), dB	**30**	**30**

Tx antenna gain (GT), dB	**0**	**0**
Rx antenna gain (GR), dB	**-3**	**-3**
Rx Power at 30 m (PR=PT+GT+GR-L1-L2), dBm	**-107.5**	**-97.5**
Average noise power per bit (N=-174+10*log10(Rb)), dBm	**-144.0**	**-134.0**
Rx noise figure referred to the antenna terminal (NF), dB	**7.0**	**7.0**
Total average noise power per bit (PN=N+NF), dBm	**-137**	**-127**
Minimum Eb/No (S), dB	**14**	**14**
Raw bit rate, kbps	**2**	**20**
Code rate	**0.5**	**0.5**
Implementation loss (I), dB	**3**	**3**
Link Margin at 30 m (M=PR-PN-S-I), dB	**12.5**	**12.5**
Rx sensitivity level, dB	**-120(-80)**	**-110(-80)**

3. Topology

3.1. Device Types

In our proposal we use devices of two classes: full function devices (data collectors) and reduced-function devices (sensors).

Full function devices (data collectors) must have the following properties:

- It can form networks of any topology (e.g., star, peer-to-peer, cluster tree).
- It can be used as a retransmitter (device that only re-emit received signal), cluster head (main device in the cell that coordinates operation of any other devices in the cell) (in the case of cluster tree topology) or PAN coordinator (device that coordinates the work of all personal network).
- This device can talk with any other device.
- This device can implement such functions as media control, routing, message relaying, synchronization, localization, local address assignment.

Reduced Function Device (sensor) has the following properties:

- It can form star topology only.
- It cannot be used as retransmitter , cluster head or network coordinator.
- This device can talk only with full-function devices (retransmitter , cluster head or network coordinator) and cannot talk with other reduced-function devices (sensors).
- This device has very simple implementation and low power consumption.

	Full Function Device (data collector)	**Reduced-Function Device (sensor)**
Topology	Any topology (star, peer-to-peer, cluster star)	Star topology only
Network function	Network coordinator, cluster head, retransmitter (repeater) capable	Cannot become a network coordinator or retransmitter
Interaction with other devices	Talks to any other device	Talks only to a network coordinator or retransmitter

Functions	Media control, routing, message relaying, synchronization, localization, local address assignment	Media control, localization, local address assignment
Implementation complexity		Very simple implementation
Power consumption		Low power consumption

3.2. Star Topology

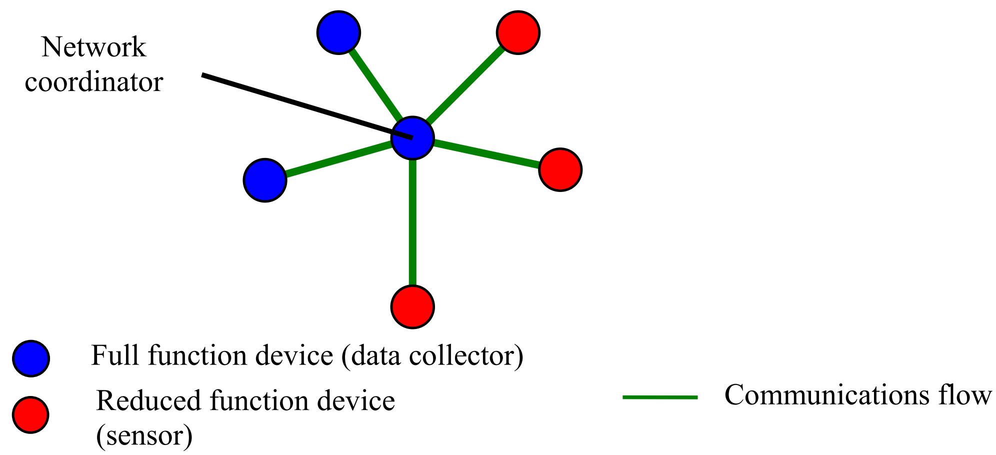


Fig. 3.2.1. Star topology

In star topology, data may be exchanged only between the coordinator (FFD) and a device (FFD or RFD).

An FFD may establish its own network and become the PAN coordinator. All star networks operate independently. Both FFDs and RFDs may join the network.

3.3. Peer-Peer Topology

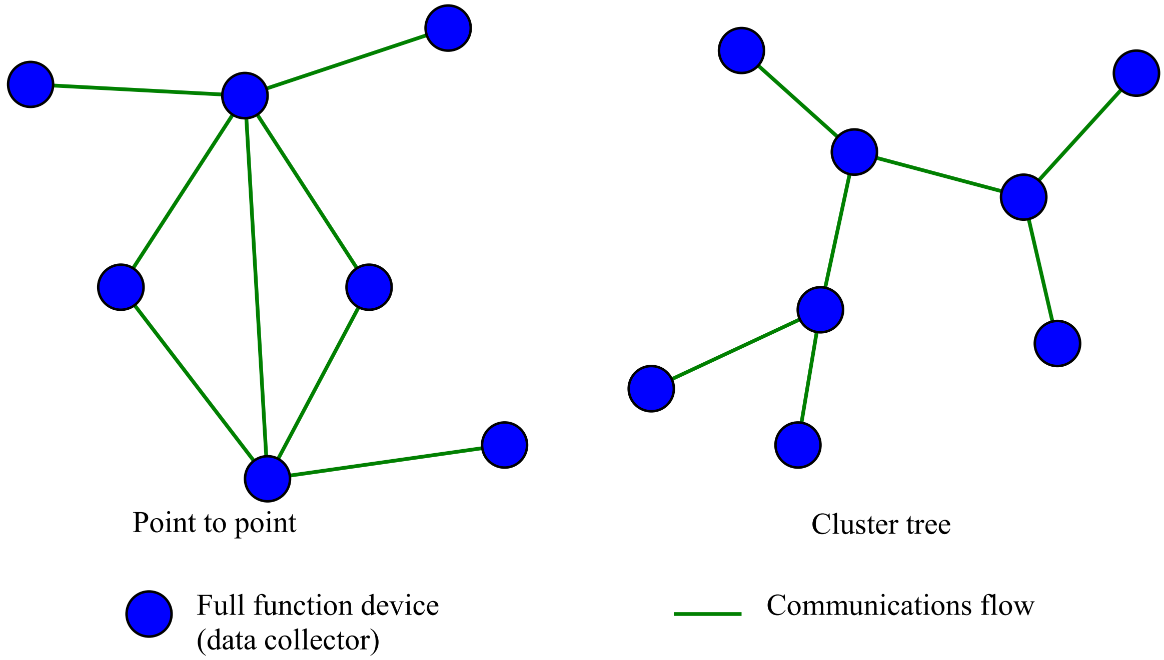


Рис. 3.3.1. Peer-to-peer topology

In a peer-to-peer topology, data may be exchanged between any two devices (FFDs). Each device is capable of communicating with any other device. One FFD device will be nominated as the PAN coordinator.

3.4. Combined Topology (Cluster Star)

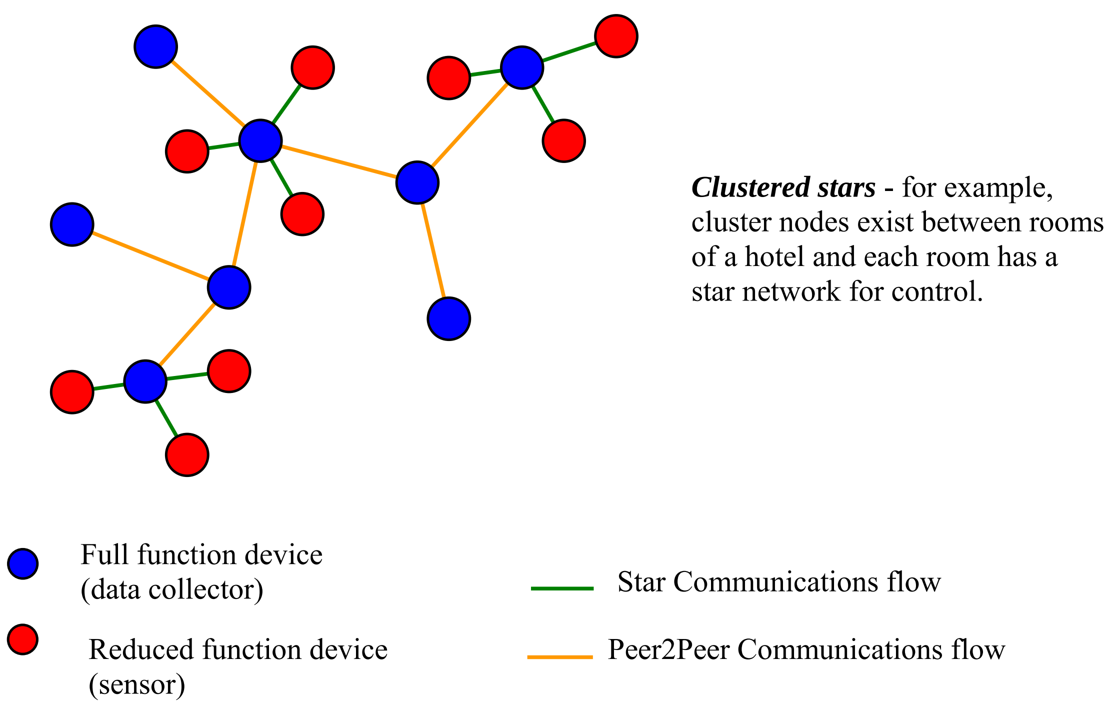


Рис. 3.4.1. Cluster star topology

It is multilevel topology. A combination of star and peer-to-peer topologies. The network is divided in clusters. Within each cluster the sensors are connected by star topology with re-transmitters, re-transmitters are connected with each other and with the cluster head by star topology or peer-to-peer. Each cluster head is connected with the others by star or peer-to-peer topology. Information is transferred through the chain to the network coordinator.

4. Bit Rate

According to requirements to the standard, in our proposal operation with three individual link bit rates is implied: 1 kbps, 10 kbps, 1 Mbps. To operate with these rates, the following scheme of information stream is used. Each information bit is represented by a chaotic radio pulse of 100 ns duration with 1/2 duty cycle. At 1 kbps bitrate in the beginning of each second a source sends a packet of 1000 bits. Thus, each source takes 200 μs to transmit information. The rest time is used for transmission by other devices. At 1 Mbps bitrate the time of transmission of each of the sources increases to 200 ms, and simultaneous transmission of information is possible only to 5 devices, which gives aggregated bit rate 5 Mbps.

Note that for such a scheme of data transmission location and synchronization of devices is necessary, in order to organize the queue of information packets in the stream.

5. Range

The maximum distance between communicating nodes is generally 0 to 30 m. In some cases, mainly assets tracking, the range has to be extended to several hundreds of meters. Possibly relaying of messages could be used in such situations. In most of the cases the link data rate can be limited to a few Kbps where the range is very large, however the number of nodes is very large (up to thousands) and the data collector needs to absorb large aggregated data rate (in sustained mode, and particularly in burst mode).

6. Coexistence and Interference Resistance

6.1. Multiple access

All three standard methods of multiple access: frequency, time and code division, can be realized in DCC.

Time division considered below is of the most interest.

Time division. Let there be an ideal chanel with bandwidth W and Gaussian noise with spectral density N_0. Carrying capacity of such channel for information signal with mean power P is equal to

$$C = W \log_2(1 + \frac{P}{WN_0})\,. \tag{6.1.1}$$

In the case of direct chaotic scheme $W = \Delta F$, where ΔF is the bandwidth of chaotic signal. Compare the carrying capacity of this channel with that of the channel for K users with time-division multiple access and condition that ith user's signal has mean power $P_i = P$ for all $1 < i < K$.

In the system with time-division multiple access each user transmits information during $1/K$ of the time in all the bandwidth ΔF with the signal power KP. Hence, carrying capacity per one user is equal to

$$C_K = \frac{\Delta F}{K}\log_2(1+\frac{KP}{\Delta F N_0}). \tag{6.1.2}$$

Total carrying capacity of the multiple access channel of DCC is

$$C' = KC_K = \Delta F \log_2(1+\frac{KP}{\Delta F N_0}), \tag{6.1.3}$$

i.e., theoretically it is higher than the channel capacity for single user. This is achieved due to higher signal-to-noise ratio (coefficient K under logarithm).

Relations (6.1.1)-(6.1.3) show that multiple access in DCC can effectively be realized by means of time division of the signals.

Let the signal energy per bit be $E_b = P/C_K$. Then relation (6.1.2) can be rewritten as

$$\frac{KC_K}{\Delta F} = \log_2(1+\frac{KC_K}{\Delta F}\frac{E_б}{N_0}), \tag{6.1.4}$$

and relation (6.1.1) as

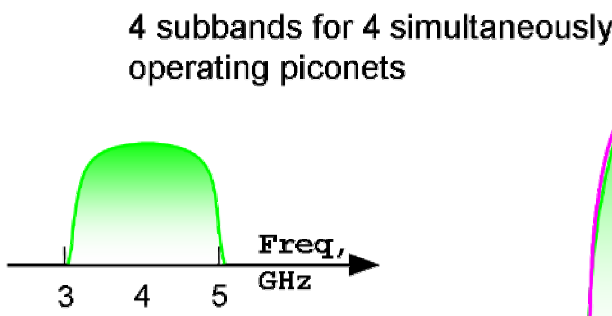
$$\frac{C}{\Delta F} = \log_2(1+\frac{C}{\Delta F}\frac{E_б}{N_0}). \tag{6.1.5}$$

All relations (6.1.1)–(6.1.5) are upper boundaries. In real systems the carrying capacity in multiple access mode is determined by the dependence of the carrying capacity of single-user system ob signal-to-noise ratio. Fir example, in multi-user DCC with time division the same carrying capacity per one user is achievable both by coherent and noncoherent reception. However, in noncoherent case it is achieved at a little higher value of E_b/N_0.

Multiple access in DCC can also be organized with the use of packet data transmission in terms of IEEE 802.11 standard.

6.2. Simultaneously operating piconets

Four independent frequency channels on 500 MHz guarantee simultaneously operating four piconets with aggregated bit rate up to 5 Mbps in each of them.



Subband	fc, GHz	fL, GHz	fR, GHz
1	3,35	3,1	3,6
2	3,85	3,6	4,1
3	4,35	4,1	4,6
4	4,85	4,6	5,1

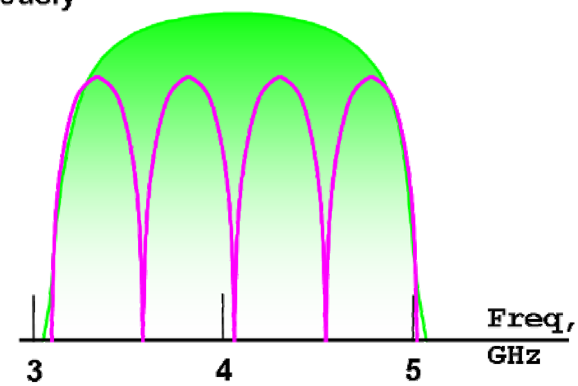


Fig. 6.2.1. Subbands for simultaneously operating piconets

6.3. Electromagnetic compatibility

In the case of low duty cycle the sequence of wideband (ultrawideband)chaotic radio pulses interferes with signals of traditional narrowband radio circuits only on very short time intervals. For example, at bitrate 10^6 bps and duration of each pulse 10^{-8} s, duty cycle is $S = 1/100$, so the time of interference is 1% of the time of system operation. In this case, the average emitted power is 200 times less than the mean power during emission of chaotic radio pulses. If, for example, the transmitter's emission power is 200 mW, then the average emitter power is only 1 mW.

Consider interaction of narrowband and wideband chaotic signals in more detail. A typical interference of narrowband communication systems is wideband noise. Method for combating it is frequency filtering. Matching the receiver band with the frequency range of the received signal allows to cut off the most part of the noise energy. The remaining noise energy $\frac{N_0}{2}\Delta F$ represents the energy of the interference signal.

In the case of wideband and ultrawideband direct chaotic systems the situation is different. Besides white Gaussian noise, here interference is represented by narrowband signals of devices operating within the same frequency band. In noncoherent receiver mean power of the interference signal at the receiver input is

$$P_n = \int_{F_н}^{F_в} \frac{N_0}{2} df + \int_{F_{н1}}^{F_в} S_{уз}(f) df, \qquad (6.3.1)$$

where $S_{nrw}(f)$ is spectral density of the narrowband signal. Assume for simplicity that there is only one narrowband signal, with the spectral density constant within certain frequency range and equal to zero out of it.

Let us denote the ratio of the bandwidths of chaotic to narrowband signals by M, and the ratio of the powers of narrowband to chaotic signals within the band of the narrowband interference signal, necessary for receiving information with admissible error probability, by L. (This ratio is equal to the ratio of spectral densities). Then the total power of interference signal is

$$P_n = (1 + \frac{L}{M}) \frac{N_0}{2} \Delta F \tag{6.3.2}$$

Example. Receiver bandwidth 100 MHz; narrowband signal bandwidth 1 MHz; L = 15 dB, then

$$P_n = (1 + \frac{30}{100}) P_n^0 = 1.3 P_n^0 , \tag{6.3.3}$$

where P_n^0 is the power of interference represented by Gaussian noise in the frequency range of chaotic signal.

If information stream of chaotic radio pulses has duty cycle S, then effective mean power of interference is decreased by a factor of S.

$$P_{эфф} = \frac{P_n}{S} \tag{6.3.4}$$

Let the same amount of information 1 Mbps be transmitted using narrowband and wideband chaotic signal, duty cycle in the case of chaotic signal be 1/100 and $L = (E_b/N_0)_{,dB} = 15$. Denote by $E_{nrw,n}$ the energy of narrowband signal obtained by wideband receiver during receiving one information bit. As follows from (6.2.3)–(6.2.4), effective add-on to the level of Gaussian noise is 30%, and the level of interference contributed by narrowband signal is $(E_{nrw,n}/E_b)_{dB} = -20$ dB. Thus, distortions brought by narrowband information signal do not exceed admissible level of L = 15 dB, consequently, they are no interference for wideband information signal.

Consider now the effect of wideband information signal on narrowband information signal under the same conditions (ratio $(E_b/N_0)_{dB}$ = 15 dB). Denote by $E_{w,n}$ the energy of wideband chaotic signal, obtained by narrowband receiver during receiving one information bit. With account of duty cycle S = 1/100 this energy is by 5 dB less than the energy of the interference contributed by Gaussian noise. Therefore, ratio $(E_{w,n}/E_b)_{dB} = -20$ dB. That is, distortion of narrowband signal due of receiving a part of wideband signal is also negligible.

Thus, information-carrying traditional narrowband and wideband (ultrawideband)direct chaotic signals have weak effect on each other and in many cases their simultaneous operation is admissible. Actually, this gives chance to again use already occupied bands of microwave frequencies.

6.4. Effects of multipath propagation

In multipath channel radio waves travel many different paths and arrive at the receiver from different directions with different delays and undergo different attenuation. At the receiver input they are summed. This gives two main negative factors of multipath channel: signal fading and inter-symbol interference. Let us consider the effect of these factors on the system of low-bitrate ultrawideband communications.

1. *Fading*. In general, adding waves leads to their interference. In the case of harmonic carrier this can give amplification as well as fading, depending on the phase difference. However, in the case of ultrawideband chaotic signal the beams at the receiver input are uncorrelated, since autocorrelation function of chaotic signal rapidly decreases. This means that adding beams always leads to an increase of received signal energy. Let there be two beams $x_1(k)$ and $x_2(k)$, k = 1, 2, … is discrete time, then each carries energy $E_1 = \sum x_1^2(k)$ and $E_2 = \sum x_2^2(k)$. As a result of

summarizing beams energy is obtained $E = \sum(x_1 + x_2)^2 = \sum x_1^2 + \sum x_2^2 + 2\sum x_1 x_2 \approx E_1 + E_2$, because $\sum x_1 x_2 \approx 0$.

Thus, summation of ultrawideband chaotic signal beams in receiver increases the level of input signal of the receiver.

2. The second negative factor of multipath channel is *inter-symbol interference*. If the tail of multipath responses is very long, then the energy transferred by the beams of one symbol can come to the position of another symbol, thus causing errors. A frequent method to combat this effect is introduction of guard interval. The expenses here is loss of a part of the energy that arrives on this interval (energy is not accumulated on the guard interval).

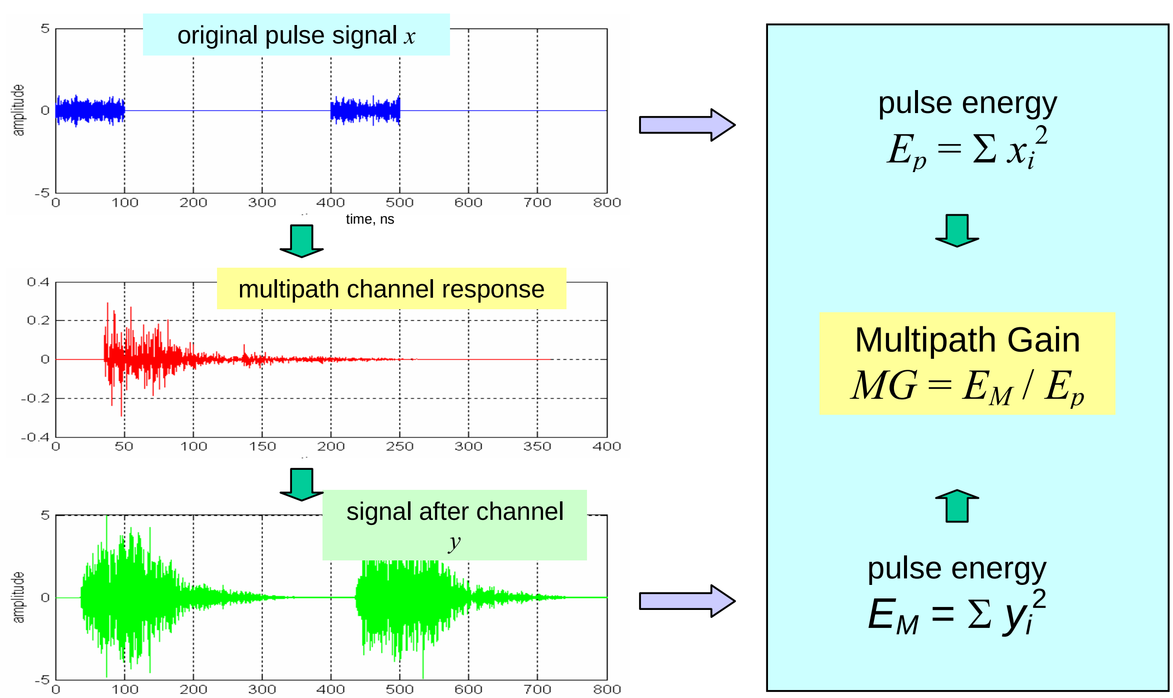
However, if the duration of radio pulse is large enough, is comparable with the duration of multipath response, the most part of energy comes to the symbol position, which not only decreases error, but also increases energy efficiency of the receiver.

Fir example, if the length of the tail of multipath response H_n approx. 150 ns, and the duration of radio pulse is 10 ns, then to mitigate the effect of inter-symbol interference a guard interval as long as approximately 100 ns is necessary (main energy of multipath response is concentrated in its first third). This imposes restrictions on the bit rate. If in the receiver the energy of the radio pulse is measured on time interval 10 ns, equal to the original duration of the pulse (in order to decrease noise reception), then most pulse energy will be lost on the guard interval.

However, if the duration of radio pulse is made 100 ns with 100-ns guard interval, then the main part of the pulse energy will fit the pulse position and the receiver efficiency will be much higher.

Thus, it becomes clear that in the case of ultrawideband low-bitrate communications with long radio pulses multipath propagation gives certain advantages. A possibility appears of increasing energy efficiency due to summation of beams' power.

For quantitative estimation of this effect of multipath propagation we introduce a notion of Multipath Gain. This is the ratio of the energy of radio pulse with all beams received on a certain time interval to the energy of radio pulse brought by one strongest beam.



Channel Model	AWGN	R-LOS	O-LOS	I-NLOS

Multipath Gain	0 dB	~ 4 dB	~ 6 dB	~ 10 dB

7. Channel Model

It is anticipated that the channel environment will be dramatically different from the current ones (i.e. those established for 2.4Ghz, 5Ghz, High Bit Rate UWB), due to the high specificities of the considered applications.

Outdoor environment has to be taken into account, not necessarily restricted to LOS. Large range is a common characteristic to most of the applications, specific harsh environments need to be considered, e.g. factory environment or large containers, with strong multipath effects.

AWGN channel

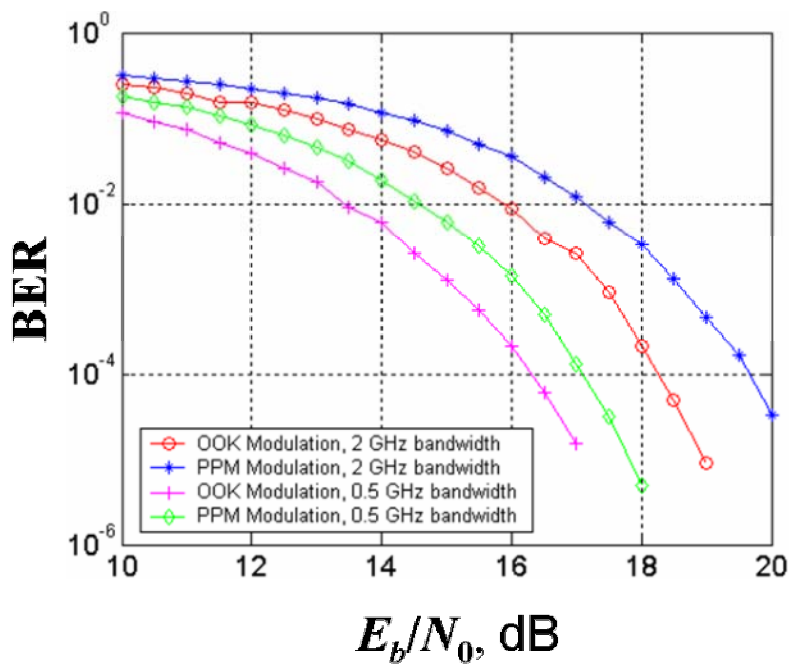


Fig. 7.1. BER (bit error ratio) as a function of the ratio of energy-per-bit to spectral density of noise in the channel.

Multipath channel

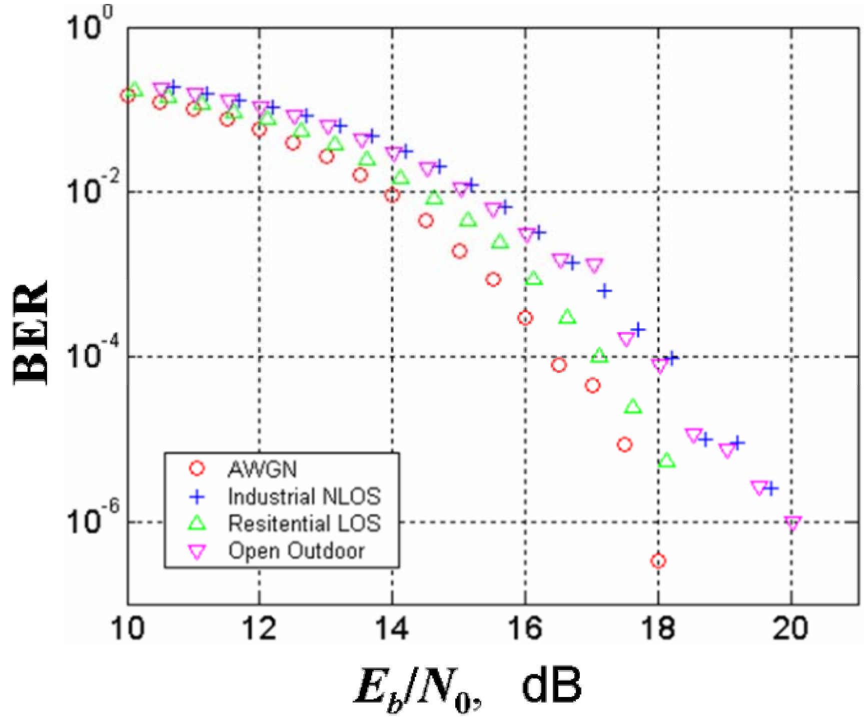


Fig. 7.2. Performance of the system in multipath channels (BER).

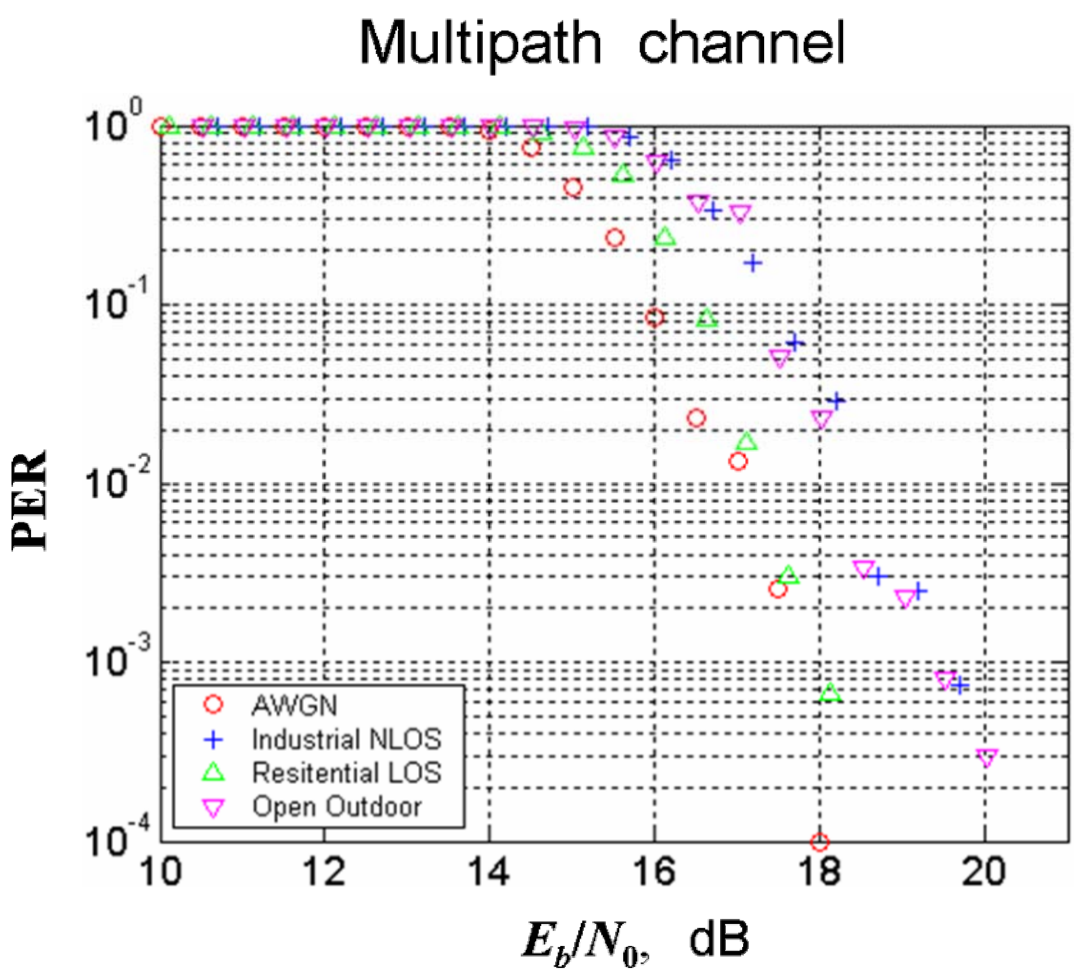


Fig. 7.2. Performance of the system in multipath channels (PER).

8. Power Consumption

Transmission Rate *V,* kbps	Average Emitted Power *Pe*, mW	Average Power Consumption *Pav* (η = 5%)	Continuous operation time AAA battery, years
1	2·10-4	15.5 μW	8.3 100% duty cycle
10	2·10-3	87.5 μW	15 10% duty cycle
100	2·10-2	8 mW	16.4 0.1% duty cycle

Bit duration = 100 ns, emission power = 4 mW

Reasoning. For such emission power and maximum bitrate of 1 Mbps we satisfy restrictions of FCC on the level of spectral density. If in concrete application the bit rate will be limited, e.g., to 10 Mbps, then the power emitted during pulse can be increased by two orders of magnitude, hence the range increased by approximately 10 times.

In order to estimate consumed power, one can use, e.g., results of Ref. [19]. Available in electronic form. A receiver/transmitter for Bluetooth system is proposed in the paper.

In our case, maximum emitted power is approximately ten times less. So, even at bitrate 1 Mbps and efficiency only 5% (which is half the efficiency of oscillator in the mentioned chipset, advantage in consumption is approx. 2.0–2.5 times.

Average Rx consumption in on / stby mode < 15 mA / 5 μA
AAA battery 1.5 V   Capacity 750 mAh

Let us calculate power consumption for 1 kbps transmission rate.

By calculating power consumption, instantaneous Tx emission power is taken P = 4 mW and the duration of one bit is τ = 100 ns (+100 ns guard interval). Then at 1 kbps rate the time of emission is 100 μs per second. However, by calculation of average emission time and, consequently, average emitted power note that zero and unit bits are equi-probable? Whereas zero bit is transmitted by zero-power pulse. Hence, the average emitted power at 1 kbps rate is 0.2 μW.

Considered are three variants of Tx efficiency: 0.5%, 1% and 5%. Then the Tx average consumption power is 40 – 4 μW. If the transceiver is supplied by a 1.5 V battery, then consumption current is 27 – 2.7 μA.

By estimating the receiver we imply that the transceiver operation is symmetrical, i.e., that its transmission and reception time is approximately equal. The Rx consumption power in 'on' mode is assumed equal to the Tx consumption power. The Rx consumption power in 'standby' mode is taken 5 μA.

As follows from the Table, two-year operation time in high-rate version (1 Mbps) is possible with duty cycle 1/1000 – 1/100. That is, the transceiver must communicate once in 15 – 1.5 minutes (transmitting 10 Mbit of information).

Long battery life suggests that very efficient power saving modes need to be put in place, in particular for devices that transmit sporadically. In addition the coordination of nodes must not induce frequent wake up of nodes.

Isochronous clock management, e.g. for localization, will require periodic synchronization of the devices with the central node. However clocks consume very little power, several μA which will slightly change the standby-mode consumption.

9. Quality of service

Requirements to QoS are formulated in IEEE 802.15.4 standard Including the following questions:

- access to communication medium
- error correction
- access to data traffic
- network security architecture
- cryptography
- etc.

The critical factor is the reliability of the transmission, meaning that strong error correction methods need to be provided. Real time communication is required, latency may exist but must be controlled (jitter elimination for localization). Two critical functionalities are foreseen:
- synchronization of nodes (mainly for localization),
- capability to provide fast reaction in emergency situations

All solutions proposed for IEEE 802.15.4 standard will also work here.

10. Form Factor

In Ref. [19] data for Bluetooth chipset is presented. According to this data, use of 0.25-μ CMOS technology gives receiver/transmitter chip with the size 2 mm×2 mm. In our estimates we make for approximately the same figures.

MEASURED PERFORMANCE OF RX/TX

Receiver	
Noise Figure	6 dB
Voltage Gain	50 dB
Image Rejection Ratio	41 dB
Input Return Loss	12 dB
Signal/Intermodulation Ratio	26 dB
Power Dissipation	
LNA and Mixers	6.25 mW
Divider	3.75 mW
Baseband Amplifiers	3.5 mW
Baseband Filters	4 mW
Total	17.5 mW
Transmitter	
Output Power	0 dBm
Sidebands	–30 dBc
Power Dissipation	12 mW
Technology	0.25–um CMOS
Supply Voltage	2.5 V
Area	1.83 mm x 2 mm

Present test beds are made with lamped elements, the size twice as large as required. According to plans, within a year a chip specification is to be produced. This chip accomplishes the proposed technology. After that the required form-factor will be achieved.

11. Antenna

The antenna form factor must be small enough to be compatible with the overall form factor (see above). The PHY characteristics (band in use) must allow for a planar or wire antenna. Omnidirectional antenna is the nominal requirement. This is due to the environment and the impossibility to predict the position of a device antenna. The antenna must be very robust.

In this proposal the requirements to antenna are practically the same as in IEEE 802.15.3a standard.

At present, there is an planar antenna manufactures on foil-clad fiberglass. Its size is as large as two SD Memory cards. It is omnidirectional in the plane perpendicular to the antenna plane. Its is ultrawideband (1–6 GHz) and its gain is rather uniform in frequency domain (not filtering).

Requirements to antenna can be formulated as follows:

Range	3–5 ГГц
Directivity pattern	omnidirectional
VSWR	< 2
Gain within the band	0 dB
Gain out of band	– 20 dB

12. Complexity and cost

Complexity should be minimal to enable mass commercial adoption for a variety of cost sensitive products. Complexity and BOM shall be minimized. The cost for a node has to be limited to 1$ or even a fraction of a $ for very large volumes of production (up to millions of chips per month). In a number of applications, the components are to be considered as throwaway after use.

12.1. Unit Manufacturing Cost/Complexity

12.1.1 The structure

The structure of the device is depicted on the fig.3.1. The digital part of the device includes Encoder and Decoder. Other parts form the analog part.

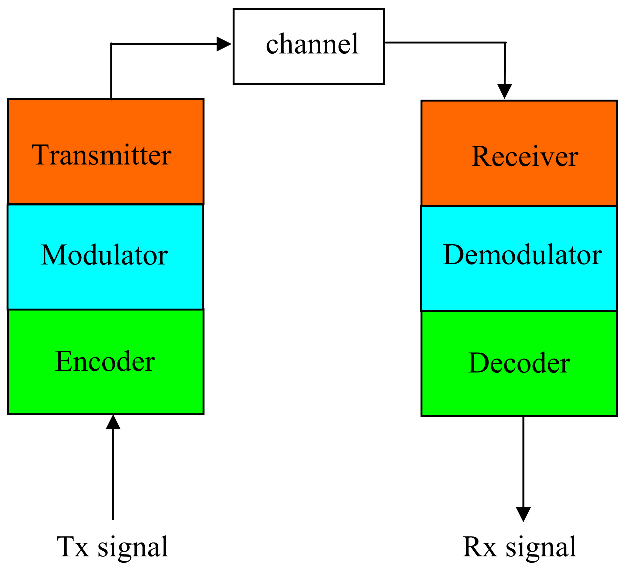


Fig. 12.1. Structure of the device

12.1.1.1 Encoder/Decoder

The encoder provides the following services: forward error coding, scrambling and packet formation, including preamble attachment. The decoder performs preamble detection, synchronization and error elimination. Also this part of the device will provide some of the MAC services.

12.1.1.2 Modulator/Demodulator

The modulator performs the on_off modulation of the chaotic signal with the baseband signal, generated by the Encoder by means of RF switch. The demodulator implements RF envelope detector and baseband amplifier.

12.1.1.3 Transmitter /Receiver

The transmitter includes antenna. The receiver includes antenna, low noise amplifier and band pass filter.

12.1.2 Values

12.1.2.1 Encoder/Decoder

This part of the device uses approximately 800 logical gates, 1kilo bytes of SRAM and 1kilobytes of program memory(flash memory)

12.1.2.2 Modulator/Demodulator

This part of the device is composed of approximately 4 RF amplifiers/transistors, 1 RF switch,1 RF diode, 5 opamps, 1 low pass filter.

12.1.2.3 Transmitter/Receiver

This part consists of 2 low noise amplifiers and band pass filter.

12.1.2.4 Ranging Service

Ranging service will demand additional 800 logic gates in the digital part of the device and about 2 additional opamps in the analog part.

12.1.3 Die sizes

Die size of the digital part will be about 4x5 mm and the size of the analog part will be about 4x5 mm.

13. Location awareness

13.1. Background

One possible ranging procedure is presented in 15-04-0581r4 document. In this document a classical method is considered that provides measurement of Round-Trip Time-of-Flight between two asynchronous transceivers. The method uses two-way remote synchronization (Fig. 13.1.1).

Fig. 13.1.1. Timing of two-way time transfer model.

Let T_{1AT} be the moment of transmission of the first message by device ***A***; T_{1BR} the moment of reception of the first message by device ***B***; T_{1BT} the moment of transmission of the second message by device ***B***; T_{2AR} the moment of reception of the second message by device ***A***; t_0 be the time difference of the clocks of devices ***A*** and ***B***; t_p be the time of signal propagation between the two devices.

The introduced variables are coupled by the following relations:

$$T_{1BR} = T_{1AT} + t_0 + t_p, \quad (13.1.1)$$

$$T_{2AR} = T_{2BT} - t_0 + t_p. \quad (13.1.2)$$

From relations (13.1.1) and (13.1.2) and known values of T_{1AT}, T_{1BR}, T_{2AR} and T_{2BT} the values of t_p and t_0 can be determined:

$$t_p = \frac{1}{2}[(T_{2AR} - T_{1AT}) - (T_{2BT} - T_{1BR})] \quad (13.1.3)$$

$$t_0 = \frac{1}{2}[(T_{2BT} + T_{1BR}) - (T_{2AR} + T_{1AT})] \quad (13.1.4)$$

The obtained t_p gives the distance.

The use of this ranging technique can provide high accuracy in the case of high frequency of clock generator (2–4 GHz). However, this solution is expensive. For the cost to be admissible, the clock generator frequency must not exceed 100 MHz.

13.2. Proposed scheme

We propose a method for ranging based on use of two relatively low-frequency clock generators (~ 2.5 MHz). In particular, we propose to use two generators with 0.1% frequency discrepancy. The idea of the algorithm is as follows. Transceiver ***A*** is equipped with a 2.5-MHz clock generator and a synchronized clock generator with the frequency 2.5025 MHz. Each 400 ns the first transceiver emits chaotic radio pulse. In transceiver ***B*** the sequence of such pulses is received and is used for synchronization of 2.5-MHz clock generator. Besides, in an answer to each received pulse the transceiver ***B*** emits a pulse at a click of the clock generator. The emitted pulse is received by receiver ***A*** and forms a temporal mark. These marks go with clock frequency 2.5 MHz.

Then each newly-come mark is compared with clicks of the 2.5025-MHz clock generator. Due to discrepancy of frequencies for each next pulse the marks of the tow sequences will diverge against each other by

$$\delta t = \frac{\delta f}{f_1^2}, \tag{13.2.1}$$

where δf is the frequency difference of the two generators; f_1 = 2.5 MHz is the clock frequency of the first generator. At a certain time mark n_1 of some pulse and mark n_2 of the second generator the marks of the receiver and the second generator will coincide. At this moment the following condition is satisfied

$$\frac{n_1}{f_1} + t_0 + 2t_p = \frac{n_2}{f_2}. \tag{13.2.2}$$

Equation (13.2.2) has two unknown variables t_0 and t_p. The first one is constant which can be evaluated by calibration. Then t_p is unambiguously determined from Eq. (13.2.2).

Block diagram of the proposed algorithm is presented in Fig. 13.2.1.

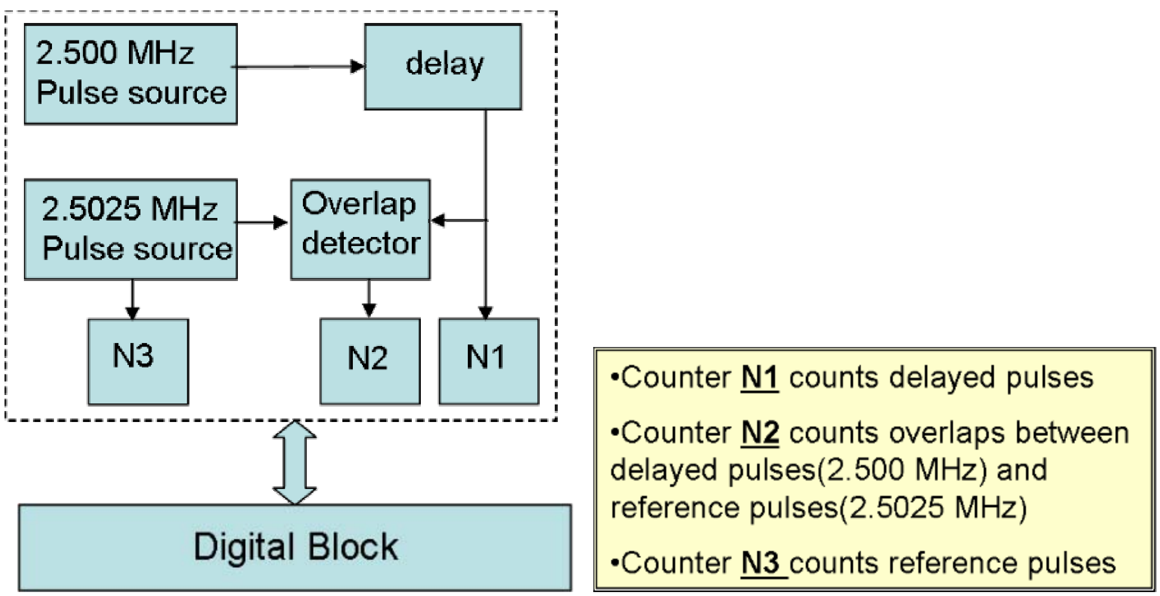


Fig. 13.2.1. Block diagram of the proposed ranging method.

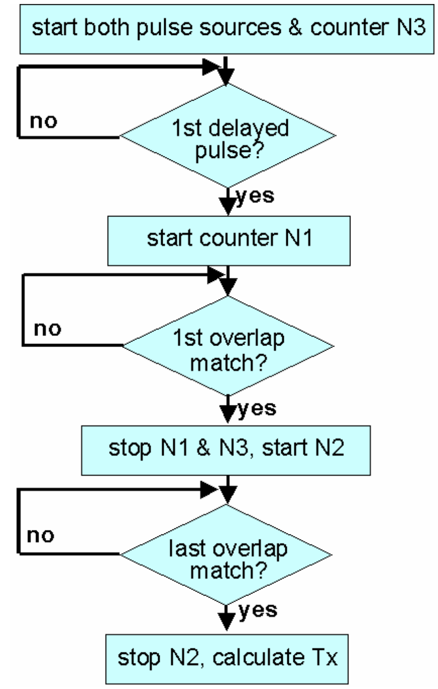


Fig. 13.2.2. Structure of the ranging algorithm.

Let us consider the algorithm in more detail.

Range is determined from the readings of three pulse counters, specially placed in the system.

Fig.13.2.3 contains time diagram depicting logistics of counters C1, C2 and C3 of the ranging circuit, based on recognition of coincidence of pulses that came reflected from the located object with rate f_0 (2.500 MHz) and pulses generated with slightly different reference rate $f_1 = f_0 + \Delta f$ (2.5025 MHz).At initial moment t_0 generators of probing pulses (repetition rate f_0) and of reference pulses (rate f_1) are started. The counter C1 of pulses of the first generator is turned off, the counter of the reference pulse generator is counting. At moment t_1 corresponding to arrival of the first probing pulse reflected from the object (is determined by leading front), the counter of pulses coming from the object is switched on. On time interval $t_1 \ldots t_2$ both counters C1 and C3 are working. At moment t_2 a circuit is started that registers the fact of coincidence (overlapping in time) of coming probing and reference pulses. At this moment counters C1 and C3 are stopped and counter C2 is started, which counts overlapping pulses. At moment t_3, when overlapping ends, counter C2 is stopped.

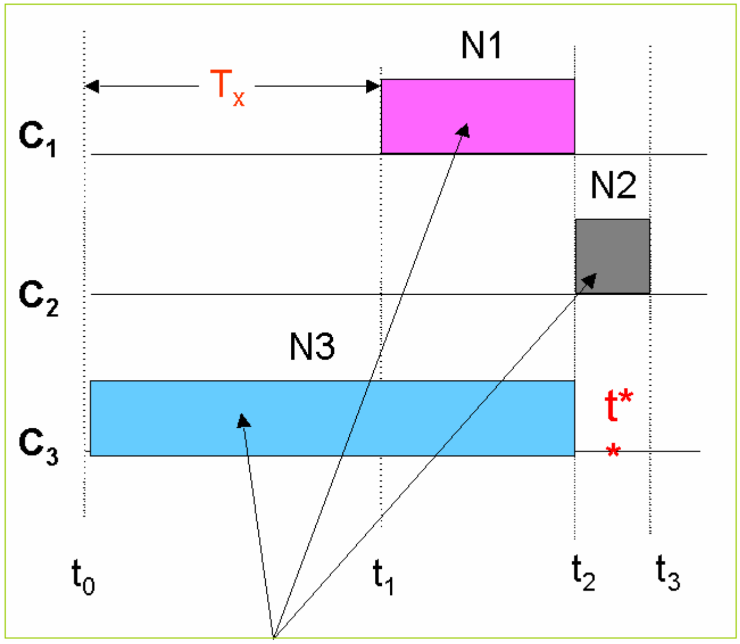
Maximum overlapping (coincidence) of pulses takes place in the middle of the interval $t_2 \ldots t_3$.

Let the counter readings be N1, N2 and N3, respectively. Then in order to determine the distance between the transmitter and the object, defined as

$$S = 0.5 * c * (T_x - t_0),$$

the value of T_x must be determined as

$$\mathbf{T_x} = (N3 + 0.5 * N2)/f_1 - (N1 + 0.5 * N2)/f_0$$



Operation time of counters C1,C2,C3 Fig. 13.2.3. Time diagrams describing the logics of operation of counters C1-C3.

13.3. Results of simulation

The scheme of simulation of ranging in ADS is shown in Fig 13.3.1. As it was pointed previously, the circuit contains two generators – one for probing pulses with pulse repetition rate 2.500 MHz and the other for reference pulses with the rate 2.5025 MHz; a delay element that imitates pulse delay on route to object and back; a multiplier to multiply delayed probing pulses with reference pulses, thus forming a sequence of overlapped pulses. The circuit also contains three counters (C1-C3) that count delayed pulses (from channel), reference and overlapped pulses, respectively. Generators of probing and reference pulses are started simultaneously. The counter of reference pulses starts with the first reference pulse. The counter of delayed pulses starts only with arrival of the first pulse from channel. The counter of overlapped pulses starts at the moment of arrival of the first pulse from the multiplier output, i.e., at the moment of first pulse overlapping. When this counter starts, the counters of delayed and reference pulses are stopped by means of disconnection of switches 1 and 2. After the counter of overlapped pulses counts all overlaps, the counter readings are processed to determine the time of delay of pulses from channel and to calculate the distance to the location object.

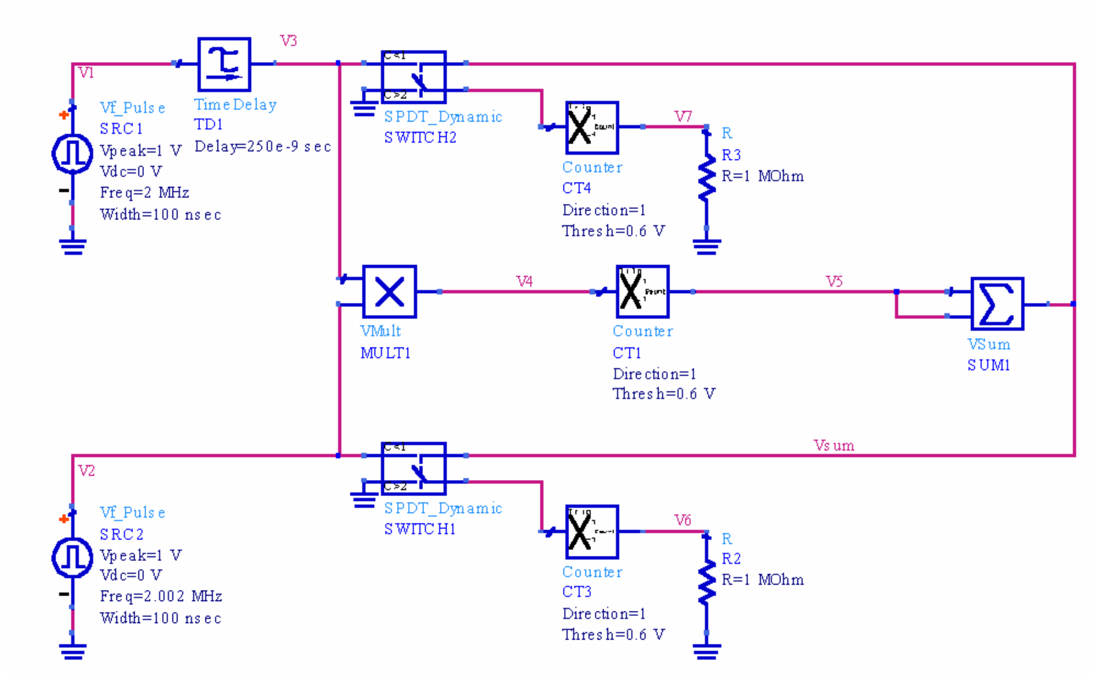


Fig. 13.3.1. Simulation circuit in ADS.

Simulation results illustrating superposition of pulses of the reference signal and of the signal reflected from the object are given in Fig. 13.3.2.

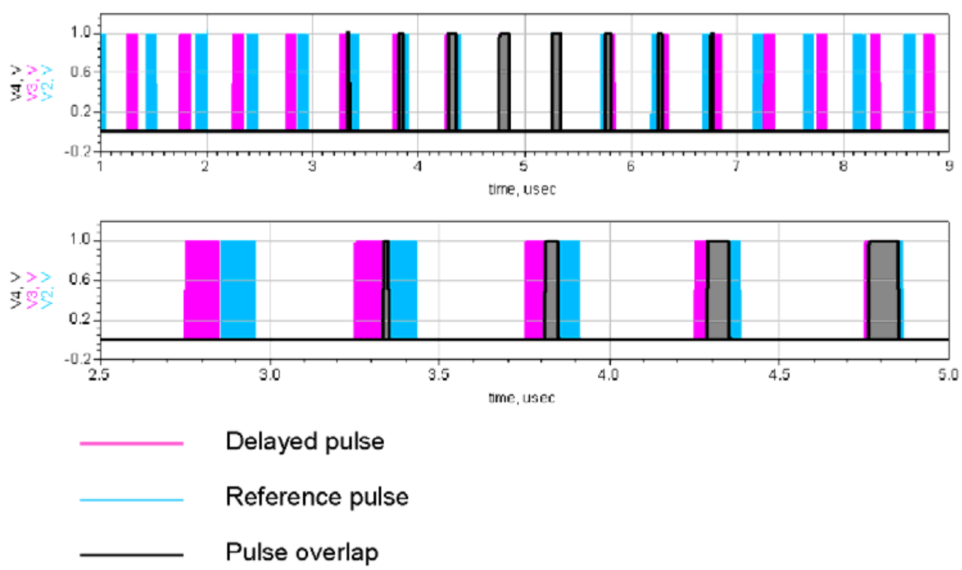


Fig. 13.3.2. Overlapping of reference and probing signal pulses.

Ranging precision depends on the frequency discrepancy of two clock generators and on the jitter by forming time marks for received pulses.

Estimates of the effect of jitter on ranging precision were made.

In simulation the pulse positions were varied, the shifts of pulse positions of both generators determined by normally distributed random values with zero mean and variance s = 1… 10 ns. This leads to errors in ranging, however the average error is zero, i.e., jitter causes no bias. STD (standard deviation, root mean square) of ranging error is given in Fig.13.3.3.Two cases are shown. The upper line is plotted for a series of 1000 ranging estimates, and the lower line is plotted for a series of 100 group estimates with 10 averaged successive measurements. As is predicted by theory, by averaging 10 measurements the root mean square error is decreased by factor of $(10)^{1/2}$ » 3, which is confirmed by simulation.

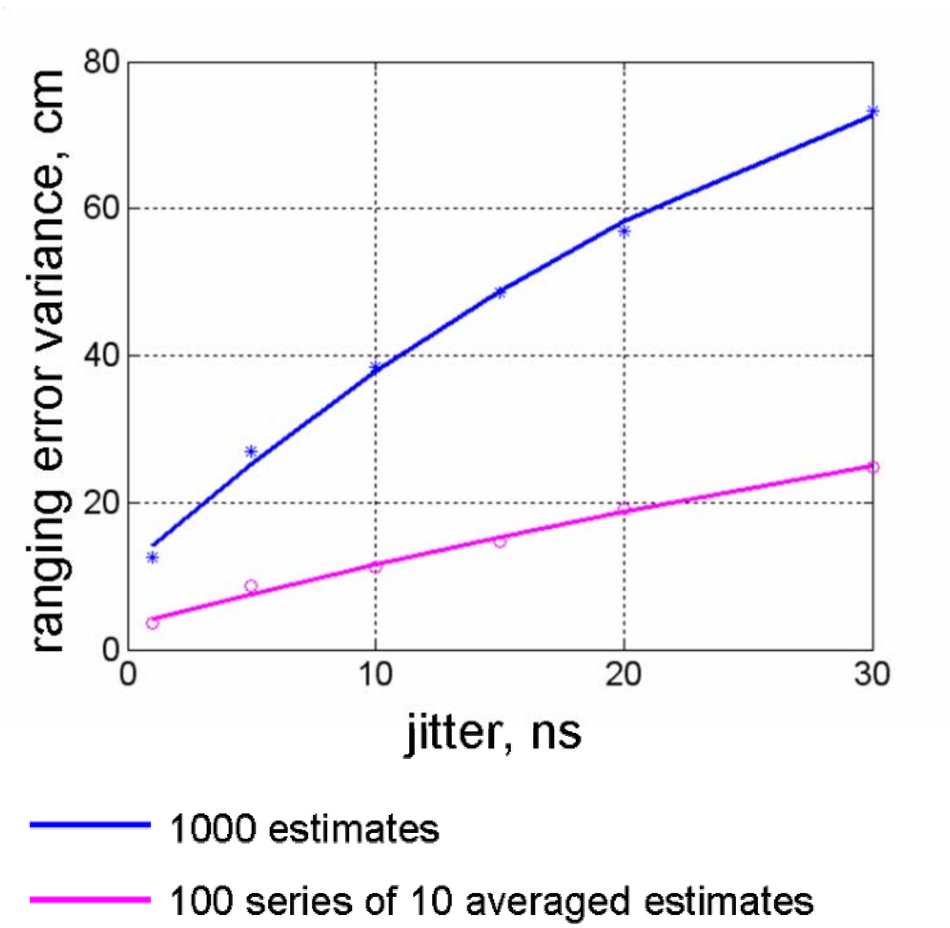


Fig. 13.3.3. Ranging error variance vs. jitter time.

Thus, to obtain higher ranging precision, one can use averaging of several measurements.

Fig. 13.3.4. shows distribution of pulse front detection time (time moments at which the signal at the output of envelope detector reaches prescribed threshold, which is 0.5 of the maximum detected signal value). Distribution is obtained for discrete chaotic signal model (independent samples). Enveloper detector was simulated by windowing summation of 400 squared samples (which corresponds to model of filter with 10 MHz pass bandwidth. One information bit position contains 800 independent samples). Distribution zero corresponds to the average front estimation time.

Estimation shoes that by above relation of frequencies the ranging accuracy will amount to 30–50 cm.

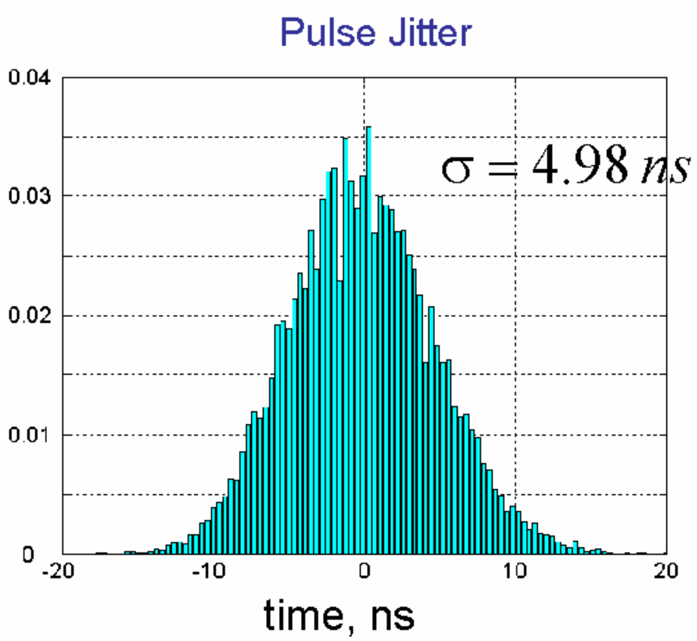


Fig. 13.3.4. The distribution of pulse front detection time

14. Mobility

Mobility means possibility to work with rapidly moving objects (up to 10 m/s). First, a function of the object tracking must be provided. By operation with rapidly moving objects the following problems can occur:

1. Doppler shift.

Since our system is wideband, Doppler shift is no problem.

2. Problem with multipath in rapidly changing channel.

Our system is extremely simple, so we do not estimate the channel in the receiver, but use guard interval for each chaotic radio pulse.

3. Low accuracy of object location.

If information is transmitted at the rate 1 kbps, then for the pulse duration 100 ns the time of transmission is 100 μs. In this case the location accuracy is 10 m. In order to improve this figure, we shall transmit 1 kbit not in one pulse, but with 100-bit packets and transmit 10 such packets a second. Each of the packets will be used to correct the object location. So, the location accuracy will improve to 1 m. If the number of bits in one packet is decreased to one bit, consequently, the number of pckets increased to 1000 a second, then the location accuracy can be increased to several centimeters.

15. Compliance and or Supplements to 802.15.4 functionality

It is envisioned that the alt-PHY project will allow supplements to 802.15.4. In addition to the PHY itself, the project may include MAC functionality necessary to support the selected PHY (see 13 above).

Function	802.15.4	802.15.4a

Low rate data transmission between nodes	Date rate – 250, 40, 20 Kbps; Range – 0-10 m or up to 100 m; Nodes – 10-1000	Date rate – 1 Mbps, 10, 1 Kbps; Range – 0-30 m or up to several hundreds meters; Nodes – 10-1000
Location awareness	Optional	Mandatory
Mobility	No	Optional

16. Regulatory matters

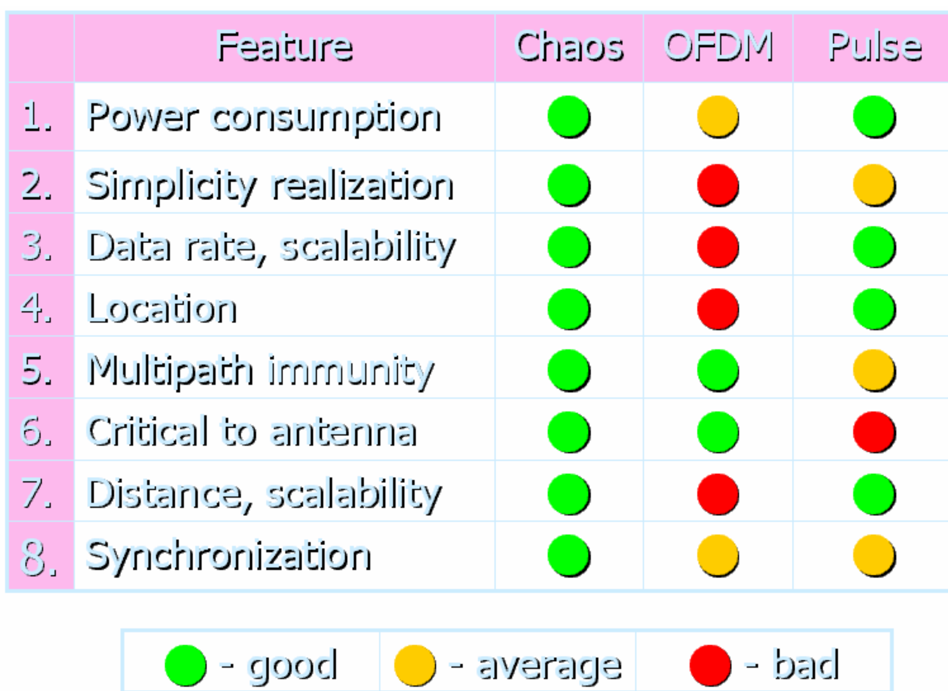
The alt-PHY standard will comply with necessary geopolitical or regional regulations.

The range 3–10 GHz (or a more narrow 3–5 GHz) was proposed by USA FCC. At present it is permitted for unlicensed use in USA, and in this question is to be solved in the nearest future in Europe

This proposal is now compatible with USA regulation (unlicensed use). In most other developed countries it is (or soon will be) permitted for unlicensed use.

17. Main features of direct chaotic systems (comparative analysis)

Below, in a common table main features of direct chaotic systems are compared to pulse and OFDM systems.



1. Power consumption. Power is saved due to switching on the receiver and transmitter so that they function only during their direct operation intervals. For example, if information is transmitted with duty cycle less than one, then for the time between information positions the transmitter and receiver are switched off. This mode is possible due to large pulse duration (~ 100 ns). This duration is enough to cope with transient processes in power supplies and to ensure establishment of operation mode of transceiver elements. With short-pulse systems this is much more difficult.

2. *Simplicity of realization*. The technology can be implemented on existing CMOS technological basis beginning with 0.35 μm. The receiver with envelope detector is used. Requirements to synchronization are very low: ~ 10 ns compared with 10 ps for pulse systems, except for the cases when very precise location is necessary. In those cases, requirements to synchronization are more tense: 0.5–1.0 ns. However, they are still much easier than for the systems with short and ultrashort pulses.

3. Bit rate scalability. The technology allows to the range of bit rates from bits per second to –3 Gbps. In ultrashort pulse systems increasing rate over 100 Mbps leads to serious complication of the system structure. OFDM is good only for high data rates.

4. Location awareness. The technology has very good performance in location of transmitting device.

5. Multipath immunity. Mitigation of fading is provided automatically due to large signal base. At low bit rates considered in the standard, mitigation of inter-symbol interference can be provided by means of introducing 100-ns guard intervals. Besides, in our case multipath propagation gives considerable advantage in energy compared to one-beam case. This effect consists in noncoherent summation of powers of many beams in the receiver. This effect is automatic and it needs no special efforts. The more beams the better. For example, for 100 approximately equivalent beams effective energy gain is approx. 20 dB.

6. Requirements to antenna. Directional pattern of antenna for chaotic signals is determined by directional patterns at separate frequencies within the signal frequency band. Here, pattern disruption, characteristic of ultrashort- and short-pulse systems, is impossible. Thus, the technology is not critical to antenna. Ordinary antennas providing necessary wide band can be used. Both omnidirectional and directional conventional antennas can be sufficiently easily realized.

7. Distance scalability. Technology permits to realize communications over short, middle, large and very large distances. These capabilities are determined by good scalability of transmission rates, possibility of using omnidirectional and directional antennas, and using conventional amplifier technology.

10. Synchronization. Requirements to synchronization in ultrawideband DCC are determined by the duration of chaotic radio pulses. The required synchronization precision is approx. 10% of the pulse duration. For instance, for 100-ns pulses the required precision is 10 ns. In applications involving location awareness, requirements to synchronization precision can be higher and achieve 0.5–1.0 ns, if location with 10 cm precision is necessary. However, is ultrashort-pulse systems required synchronization precision is 10–20 ps, and in short-pulse systems it is 0.1–0.2 ns, and these requirements must be satisfied regardless of the task, whether the system determines location or not. Thus, advantage of ultrawideband DCC in synchronization requirements is 5 to 50 times.

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