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Ultra Wideband Transceivers Based on Chaotic Pulses and their Application to Wireless Body Area Networks

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Abstract– Application of chaotic oscillations to communications began in 1990s, and in the beginning of 2000s practical schemes of communications using chaotic signals were proposed, e.g., a scheme of direct chaotic communications. This scheme appeared to be practical, and ultrawideband chaotic signals were adopted in IEEE standards 802.15.4a (2007) for wireless sensor networks and 802.15.6 (2012) for wireless body area networks (WBAN). Here, we discuss design of transceivers using ultrawideband chaotic pulses and analyze requirements of WBANs on wireless communication devices, and then consider the prospects of ultrawideband chaotic transceivers in WBANs.

1. Introduction

The history of applying chaotic oscillations of nonlinear dynamic systems to communications began in 1990s [1–6]. Many early hopes were associated with chaotic synchronization [7], but this phenomenon appeared to be extremely sensitive to perturbations in channel and to parameter precision (e.g., [8]), so, the next works on chaotic communications were mainly focused on the circuits without chaotic synchronization.

Since 2000, practical schemes of communications using chaotic oscillations appeared, e.g., a scheme of direct chaotic communications [9–12]. In this scheme, information bits are transmitted with chaotic radio pulses, i.e., fragments of chaotic oscillations. The spectrum of chaotic radio pulses is close to the spectrum of the original chaotic oscillations, if the pulse is not too short. This allows us to vary the chaotic pulse length to a large extent, consequently changing the transmission bitrate, without necessity to modify the input and output circuits of the receiver and transmitter, respectively.

The approach of direct chaotic communications is based on three main ideas:

1. Chaotic oscillator produces oscillations directly in the frequency band intended for communications (matching the central frequency and bandwidth), e.g., in microwaves.
2. In the transmitter, binary information in put into the chaotic signal by means of forming corresponding sequence of chaotic radio pulses.
3. In the receiver, information is retrieved from the retrieved chaotic signal in this same frequency band, without frequency down-conversion.

Due to the common feature of chaotic oscillations, the spectrum of chaotic oscillations is naturally wideband or even ultrawideband (UWB). And since the decision of FCC to permit unlicensed use of 3.1–10.6 GHz frequency band for UWB signals [13], chaotic radio pulses proved to be quite suitable for UWB communications. Chaotic pulses were adopted as optional solution in IEEE 802.15.4a standard (2007) [14]. That was the first time the chaotic pulses were acknowledged by international scientific community as an effective information carrier for UWB wireless communication systems. IEEE 802.15.6 Standard for WBAN is the second standard where wireless direct chaotic communication technology is used, now as one of the mandatory solutions [15].

Standard 802.15.6 is a modern paradigm of public health care, based on constant or periodic monitoring of physical state, vital parameters, and physical activity of people, either ill or healthy. Rapid development of electronics, personal communications, computer science, passive detectors of physiological parameters, and active means of self-treatment adds to this approach and shifts the focus of health care from hospitals to the man himself. In this context, wireless networks of sensors placed in, on and around the human body to observe its state, have great potential for future treatment technologies.

The use of UWB in WBANs, in particular, is caused by necessity to get away from the occupied frequency range of 2.4 GHz. Many medical applications require highly reliable communication channel; no interference with other radio systems is allowed, especially with Wi-Fi and Bluetooth.

The standard assumes that WBAN data rate can vary from 100 Kbps to 10 Mbps. Pulses with linear frequency modulation (chirps), chaotic pulses, as well as other types of pulses [15] are adopted as potential data carriers.

However, chirps give rates up to 1 Mbps, therefore they cannot be used in all WBAN applications. Solution based on chaotic pulses does not have this limitation. Furthermore, compared to UWB communications using ultra short pulses [16], chaotic communication systems have such advantages as: easy implementation, lower power consumption and lower requirements to synchronization accuracy.

In this report we discuss design of transceivers using ultrawideband chaotic pulses and analyze requirements of body area networks on wireless communications, and then compare these requirements with capabilities of the designed transceiver.

2. Transceivers using chaotic pulses

In IEEE 802.15.6 Standard three types of pulse signals are proposed as information carrier: chirp pulses, chaotic pulses and short pulses.

UWB direct chaotic transceiver (DCT) that we discuss here is intended for data transmission in "peer-to-peer" mode and for use in UWB wireless sensor networks. It can be used as a terminal node, a relay and a base station (connected to PC). The device has special slot for sensor board and it can get data from this sensor board both as analog signal or through digital interfaces.

Physical level PHY of this device corresponds to IEEE 802.15.4a standard.

The block diagram of this device is presented in Fig. 1. Its RF part consists of a transmitter, a receiver and a switch. Transceiver works in semi-duplex mode. When the signal is transmitted, the switch commutes transmitter output with antenna input, and microwave signal does not get into the receiver channel. When the signal is received, situation is opposite. So, the switch isolates transmitter from receiver.

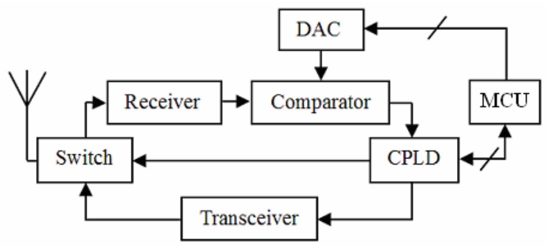

Figure 1. Transceiver structure.
DAC – digital-to-analog converter, MCU – microcontroller, CPLD – Complex Programmable Logic Device

As a source of chaotic signal in transmitter, a deterministic analog nonlinear dynamical system is used that generates chaotic oscillations directly in microwave frequency range with preassigned power spectrum envelope (Fig. 2). Bipolar transistor BFP620 with cutoff frequency 70 GHz is used in the scheme as the active element. In Fig. 2, F is a high-pass chip filter with 2.7 GHz cutoff. The theory of such chaotic sources and examples can be found in [17].

The delays of switching the dynamical system to and off the oscillation mode are small, which allows transmitter modulation by means of switching the supply voltage. This gives energy saving by chaotic pulse formation, because between pulses the chaotic oscillator is turned off and doesn't consume power.

Envelope detector of the receiver comprises a low noise amplifier (20 dB) and a logarithmic detector with dynamic range of 50 dB and sensitivity of –50 dBm.

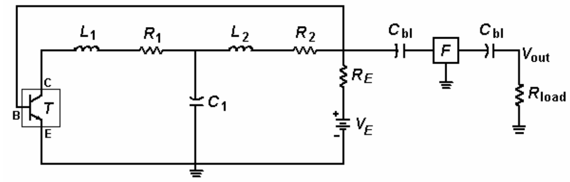

Figure 2. Chaotic oscillator
$L_1 = L_2 = 3.6$nHn, $C_1 = 0.1$pF, $R_E = 15$Ohm, $C_{bl} = 200$pF, $V_E = 2$V

Switch is controlled by Complex Programmable Logic Device (CPLD). CPLD also implements preliminary processing of pulses obtained from receiver and formation of pulses of necessary length and duty cycle for transmitter. Since CPLD works only with digital signals, a comparator is used to transform analog pulses to digital form. Comparator threshold voltage is specified by digital-to-analog converter adjusted by microcontroller (MCU).

MCU coordinates operation of the device as a whole. It controls DAC, activates transmission, reception and sleep modes in agreement with the loaded program; stores information necessary for operation of the device in the network; includes interfaces for communication with external devices.

Transceiver board is represented in Fig. 3.

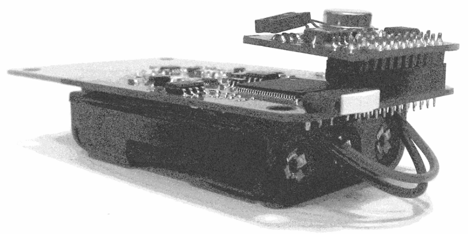

Figure 3. UWB direct chaotic transceiver with sensor board

To work in sensor network, transceivers must operate long enough time without battery replacement. So, by design of the transceiver a lot of attention was paid to power saving, and sleep modes in particular.

To save energy, the transceiver uses sleep modes. In "shallow" sleep mode, transmitter consumes approximately 100 times less power when in active mode, in deep sleep mode 20 times less than in sleep mode. Two sleep modes are used, because it takes much more time to return to active mode from deep sleep mode than from sleep mode. This is the reason to use sleep mode during small pauses of operation (within data packet) and deep sleep mode for long pauses.

Transceiver can work both in wireless sensor network with static routing and in a self-organizing network. In the case of static routing, IDs of neighbor nodes of each device and the routes of data transmission are preliminary assigned.

Self-organization algorithm includes the following stages:

- waking up transmitters from deep sleep mode;

- detection of neighbor transceivers and setting connections with them;
- calculation of route to selected node;
- sending unused transceivers to deep sleep mode.

Typical power spectrum of emitted UWB signal is given in Fig. 4.

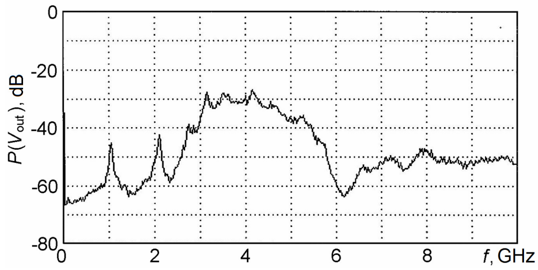

Figure 4. Power spectrum of emitted signal

Physical bit rate of the device is 6 Mbps. It allows not only to vary data bitrates in a wide range 1 Kbps to 6 Mbps, but also to achieve considerable power saving due to fast packet transmission of low-rate data stream and setting device to sleep mode between data packets.

In Table 1 main performance parameters of direct chaotic transceiver are given.

Table 1. Technical parameters of UWB chaotic transceiver

Supported applications	Home and industrial automation, medicine, etc.
Distance	5 – 7 m (indoors)
Data bitrate	1 Kbps – 6 Mbps
Power Consumption	0.09 mW in deep sleep mode (100%); 27 mW at 256 Kbps; 70 mW at 1024 Kbps
Emitted power	10 uW (–20 dBm) at 256 Kbps 40 uW (–14 dBm) at 1024Kbps
Network size	Large, up to 65K nodes
Biological safety	High

3. BAN requirements to communication systems

In general, wireless body area sensor network is a system of heterogeneous devices located in the vicinity of the user's body (or within the body) and interacting between themselves and with the central coordinator node by means of wireless communications, in order to give the user some useful effect.

Sensors and actuators can be, in general, of both medical or nonmedical purpose.

In-body network applications include monitoring and adjustment programs for pacemakers and implanted heart defibrillators, control of bladder functions and rehabilitation of limb movement. On-body medical applications include monitoring ECG, blood pressure, temperature and respiration. With WBAN, patients retain considerable physical mobility and are less attached to hospital.

Nonmedical applications include: checking lost things, joining social networks, sports, fitness, entertainment, special (monitoring pilots, firemen, emergency crewmen, etc) and military applications (diminishing fatigue and raising combat readiness of soldiers).

Number of sensor nodes is determined by the BAN purpose, and is expected to be in the range 20–50 [18, 19].

Table 2. Typical data rates for various node types

Application	Data rate, Kbps	Bandwidth, Hz	Sensor ADC bits
ECG (12 leads)	288	100-1000	12
EMG	320	0-10,000	16
EEG (12 leads)	43.2	0-150	12
Blood saturation	16	0-1	8
Glucose check	1.6	0-50	16
Temperature	0.12	0-1	8
Motion sensor	0.035	0-500	12
Cochlear implant	100	–	–
Artificial retina	50-700	–	–
Sound	1000	–	–
Voice	50-100	–	–

Data rate. Typical data rates for various node types are given in Table 2. As can be seen, they are not large, as a whole. However, if several WBAN devices work at the same time (e.g., several motion, ECG, EMG, glucose sensors, etc.), then the aggregate data rate can easily achieve several Mbps, which is above PHY data rate of most today's low-power wireless communication technologies.

Reliability of data transfer is determined by Bit-Error-Rate (BER) and Packet-Error-Rate (PER). For a medical device, reliability requirements change with the data rate. Low-rate devices can handle high BER (e.g., 10^{-4}), whereas higher-rate devices need lower BER values (e.g., $10^{-8}…10^{-10}$). Also, necessary BER values depend on significance of the data.

Power consumption. Sensor node power consumption can be divided in three parts: sensor consumption, (wireless) communications, and data processing [20]. As is assumed, the most power is consumed by wireless communications. Available power on the node is often restricted. In most cases, the size and weight of the battery determine the size and weight of the entire device. In certain applications the node must operate for moths and even years without service. For instance, cardiac pacemaker or glucose meter require battery life time of more that 5 years. Battery life time is especially critical for implanted devices. Necessity of battery replacement or recharge increases the price and lowers comfort of use of not only small-size implanted devices, but also of larger devices.

Ease of use. In most cases, BANs are used and will be used either by patients themselves or by medical staff, not by ICT engineers. Hence, the network must be capable of self-configuration and self-maintenance. Each time a node is placed on the body and is turned on, it must be able to join the network and find data routes automatically.

The network cannot be considered static. The "body" can be moving (walking, running, bending, etc.), which adds fading and shading effects. Nodes must be small and compatible with portable or implanted applications to make BAN invisible and comfortable.

Main requirements of IEEE 802.15.6 Standard on parameters of communication systems are given in Table 3.

Table 3. Requirements of IEEE 802.15.6 Standard

Supported applications	Medicine, game, entertainment, sports, etc.
Distance range	2–5 m (indoor)
Data bitrate	1 Kbps – 10 Mbps
Power consumption	0.01 mW (sleep mode) 40 mW (active), 500 Kbps
Emission power	25 uW (–16 dBm)
Network size	medium, up to 256 nodes
Safety, comfort	Yes

Experience, gained in the beginning of 2000s in design and application of wireless communication tools devoted to work with human body, has led to idea of standard BAN model for medical and consumer applications.

In 2007 IEEE 802 Committee formed a Task Group called IEEE 802.15.6 for BAN Standard [21]. The task of the group was to sort existing solutions and to define new physical layer PHY (frequency bands) and MAC layer for BANs. The first draft version of IEEE 802.15.6 Standard was published in May 2010. The final version was adopted February 29, 2012 [15].

4. Ways of application of chaotic pulses to body area networks

Comparison of DCT parameters with demands of IEEE 802.15.6 Standard shows that characteristics of the described 3–5 GHz transceiver intended for UWB wireless sensor networks using chaotic pulses as information carrier are close to those required by the Standard, aside from frequency range that can be changed by means of designing a corresponding chaotic oscillator.

5. Conclusions

Recent achievements of electronics and radio science allow us to create body area networks for various medical and nonmedical applications. To regulate development and application of such networks, a new standard for wireless personal communications IEEE 802.15.6 is adopted.

An important role in this standard is given to wireless ultrawideband communication systems using chaotic radio pulses. As is shown in this report, recently developed direct chaotic UWB transceivers are close by main characteristics to the requirements of IEEE 802.15.6 Standard.

Acknowledgments

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