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Evaluation of Using Standard Mobile OFDM Signals for Short-Range Radar Sensors

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Abstract

One of the aims of IoT systems is to understand the environment beyond the object, and the radar sensor is one of the main physical sensors for this challenge. Potential fields of use for radar-equipped IoT platforms are intelligent transportation systems, remote healthcare, wireless robots etc. New generation cellular systems allow developing solutions for IoT which we can use for sensing and communicating at the same time.

The article discusses the possibility of providing short-range radar based on the standard OFDM signal used in mobile communication networks. Mathematical modeling is performed on a mobile radar sensor with a non-directional antenna as part of wireless communication equipment. The limits of range and speed resolution are determined when using a standard signal. The accuracy of determining the range is estimated and a signal configuration is proposed that allows improving these characteristics.

Keywords: IoT sensor, ground radar sensor, mobile communication, OFDM, radiolocation, target detection range, target resolution.

I. INTRODUCTION

Choosing the communication method is an essential part of IoT platform creation. Ideally the IoT platform should support all types of sensors and all types of communication standards, but this is not always possible to ensure in reality. The article proposes to combine sensing and communicating to solve the location problem for the IoT platform. New generation cellular systems standard promises much more than fast network with high capacity, the fifth generation of communication provides the ability to provide more diverse services compared to previous communication standards.

Relative freedom in the choice of signal configuration contributes to the development of functions that are not typical for civil communication systems. This article evaluates the possibility of using OFDM signals with the characteristics specified in the 3GPP Release 15 specification for radar purposes.

One of the most difficult applications of radar is to determine the location of a non-radiating ground targets. At the same time, the current trend in the field of radio engineering is to combine the functions of radar sensor and radio communication in one device [1], [2]. It is obvious that the requirements for a mobile radio station impose significant restrictions on its radar application. This holds in particular in the most cost-effective case where single radar station is used, which uses an antenna with a fairly narrow radiation pattern to measure the distance to the target and the azimuth or direction to the target.

However, usually the antenna of a mobile communication station is non-directional, and without the use of additional conditions or devices, it is possible to determine only the distance to the target. Preliminary estimates indicate that the accuracy of determining the range one to ten meters, but the proposed approach is useful in a number of scenarios that include the need to monitor, track and identify targets and determine the location of the sensor relative to the targets or other sensors located in the area. Calculations were performed for targets with a radar cross-section (RCS) of 0.1 m^2 (small obstacle), 1 m^2 (person), and 10 m^2 (car).

II. OFDM SIGNAL STRUCTURE IN ACCORDANCE WITH 3GPP REQUIREMENTS FOR 5G DEVICES

OFDM multiplexing technology with is widely used in modern wireless mobile communication systems and is the basis of the 5G-NR radio access system. At this stage standardization of 5G/standard IMT-2020 (in 3GPP release 15) adopted CP-OFDM (cyclic prefix-orthogonal frequency division multiplexing) in the downlink channel (DL) and CP-OFDM with FFT in the uplink channel (UL). The latter includes the "pre-encoding transformation" block, which implements the discrete Fourier transform (DFT) operation and reduces the crest factor. However, in release 16, support for DFT-s-OFDM is under discussion [3 – 5].

According to TS 38.104 [6], 5G-NR is used with OFDM subcarriers with different spectrum widths (15kHz, 30kHz, 60kHz, 120kHz and 240kHz) which makes it possible to flexibly configure the network when providing various services and levels of usage. Possible modulation schemes in 5G-NR-π include 2-BPSK, QPSK, 16QAM, 64QAM and 256QAM. The supported OFDM numerologies are shown in Table 1 [7].

Table 1: Supported transmission numerologies

μ	0	1	2	3	4
$\Delta f = 2^{\mu} \cdot 15$[kHz]	15	30	60	120	240
Cyclic prefix	Normal	Normal	Normal, Extended	Normal	Normal

In 5G-NR, the number of OFDM characters per slot does not depend on numerology and is determined only by the type of cyclic prefix: 14 characters for the Normal prefix and 12 for the Extended prefix. The unit of time-frequency resource in 5G-NR networks is the Resource Block (RB). Each subscriber terminal is allocated a certain number of resource blocks for a certain period of time. Each resource block in the frequency domain contains 12 adjacent subcarriers. The bandwidth of a single resource block depends on the numerology used. In 5G-NR, the maximum allowed bandwidth of a single radio channel is up to 100 MHz for the FR1 radio frequency block and up to 400 MHz for FR2. In 5G-NR, data transmission in the UL and DL has a frame duration of 10 ms. Each frame is divided into 10 subframes with a duration of 1 ms each. Each subframe is divided into slots, where the number of slots is 1, 2, 4, 8 or 16 slots depending on the numerology (Table 2) [7], [8].

Table 2: Frame structure of 5G-NR

Numerology	0	1	2	3	4
The width of the subcarrier (kHz)	15	30	60	120	240
Number of slots in the subframe	1	2	4	8	16
Number of slots in the frame Slot	10	20	40	80	160
Slot duration (ms)	1.0	0.5	0.25	0.125	0.0625
Symbol duration (µs)	66.7	33.3	16.6	8.33	4.17
Cyclic prefix duration (µs)	4.7	2.41	1.205	0.6	0.3

III. ESTIMATION OF RADAR SENSOR PARAMETERS OF THE 5G-OFDM SIGNAL

According to the basic radar equation [9] the detection range of objects with a given radar cross-section (RCS) in conditions of limited energy resources is determined by the formula:

$$\mathrm{d} = \sqrt[4]{\frac{\mathrm{P_{tx}G_{tx}G_{rx}A\lambda^2}}{(4\pi)^3\mathrm{P_{rx}}}}, \qquad (1)$$

where

P_{tx} – signal output power of the transmitter,

P_{rx} – signal power at the receiver input,

G_{tx} – the gain of the transmitting antenna,

G_{rx} – the gain of the receiving antenna,

A – effective RCS of the target,

λ – wavelength,

d – distance between the receiving antenna and the target.

For calculations with formulas (1) and (2) the wavelength λ of the central subcarrier is used.

Based on the signal parameters, it is possible to calculate the detection limits of range and speed and the resolution of the radar sensor [10].

Calculation of the maximum target detection range d_{max} can be calculated by the formula (2):

$$\mathrm{d_{max}} = \frac{\mathrm{c}}{2\Delta\mathrm{f}}, \qquad (2)$$

where c – speed of light.

As can be seen from (2), the maximum target detection range does not depend on the radiation power of the transmitter, but depends only on the parameters of the standard 5G-NR signal [11].

The calculation of the range resolution Δd is determined by the formula:

$$\Delta d = \frac{c}{2\Delta f N}. \qquad (3)$$

where N – number of subcarriers.

The detection limit for speed in such a system is determined by the difference between subcarriers, i.e. it is the speed at which the Doppler shift frequency is equal to the distance between subcarriers:

$$v_{max} = \frac{c}{2T_0 f_c}, \qquad (4)$$

where

$T_0 = (\frac{1}{\Delta f} + T_G)$ – the symbol duration,

f_c – the carrier frequency.

Since the value of v depends on the Doppler frequency offset, which can be either positive or negative, the speed limit is determined in the range $|v| = v_{max}/2$.

The calculation of the speed resolution is determined by the formula:

$$\Delta v = \mathrm{c}\,/2T_F f_c, \qquad (5)$$

where T_F – the frame duration.

Tables 3 and 4 show the results of calculations using formulas (1) – (5) for the following parameter values (corresponding to the parameters of Wide Area Base Stations in accordance with 3GPP TS 38.104): the carrier frequency is 4.8 GHz (FR1 band), the distance between subcarriers is 15 kHz, the bandwidth is 30 MHz with 2048 subcarriers. The RCS of the targets were selected as 0.1 m^2 (small obstacle), 1 m^2 (person), and 10 m^2 (car).

Table 3: Target detection range for different RCS

Size of the RCS	Target detection range d (meters)
0.1 m^2	15.36
1 m^2	27.31
10 m^2	48.57

As can be seen from table 4, the target detection range is inversely correlated with the target speed limit, which is due to Doppler uncertainty. Building a three-dimensional graph of the dependence of the maximum range on the maximum determined speed allows you to determine the time actually available for processing radar sensor information and making a decision, as shown in Fig. 1.

The further away the object is, the lower the speed that the radar sensor can unambiguously resolve, and the more time is available to make a decision. For detection of a target located at a distance of 10 km, the available time is 21 s (corresponds to μ=0), as for a range of 625 m – 0.08 s (corresponding to μ=4) is available.

Table 4: 5G-NR OFDM radar sensor parameters

Numerology	0	1	2	3	4
Target detection range limit d_{max}, (meters)	10000	5000	2500	1250	625
The range resolution of Δd (meters)	4.880				
Limits of the target speed v_{max}, m/s	469	936	1883	3752	7494
Speed resolution Δv, m/s	3.125				

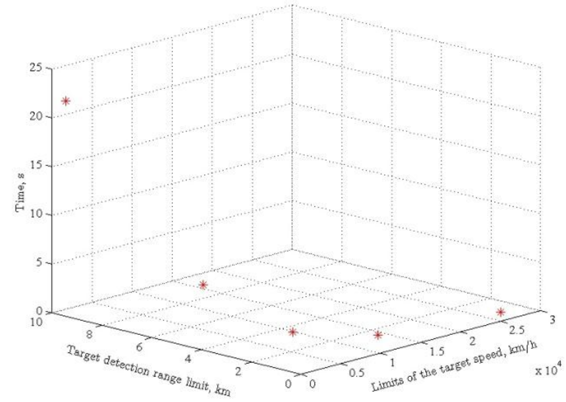

Fig. 1. Dependence of the maximum detection range on speed for different numerology values

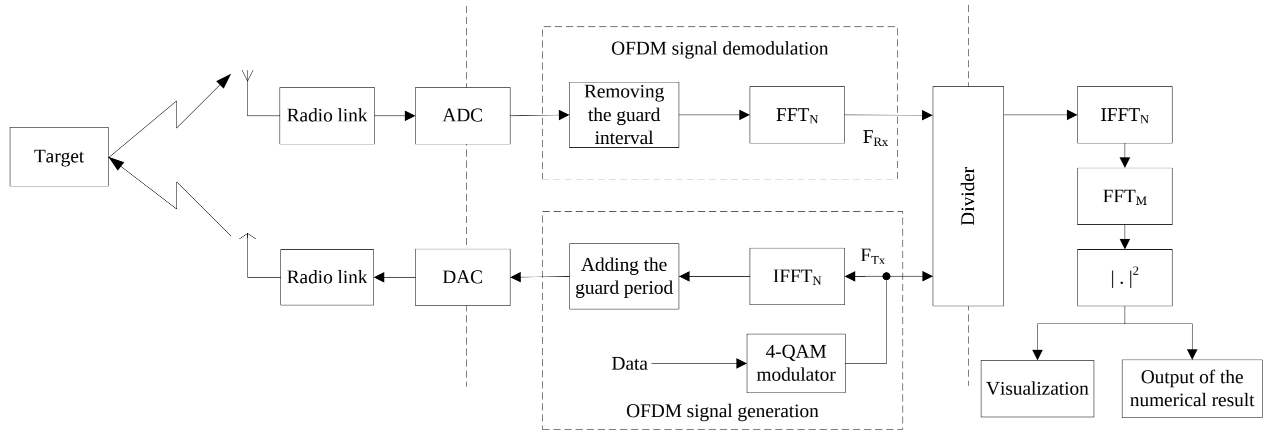

Fig. 2. The block diagram

IV. MODELING OF PROCESSING RADAR INFORMATION BY OFDM RADAR SENSOR

The principles of radar information processing by OFDM radar sensor were previously reviewed by some of the authors [11]. This article focuses on investigating the challenges of using standard 5G signals for radar sensor.

Fig. 2 shows a block diagram of the radar sensor module, the processing unit corresponds to the "maximum likelihood method", and the structure of the receiving and transmitting parts are standard for the technology.

The scheme is represented by a set of standard blocks that perform the standard functions of a classical OFDM signal transceiver. The "target" block contains information about the target: its distance and speed. For range-frequency processing, different consecutive periods are taken into account. The transmitted signal as well as the received signal form an array, where each row represents a signal from one period, and each column represents a signal from each period that has the same carrier frequency. Element-by-element division of the received signal by the transmitted signal in the "Divider" block is performed to eliminate the modulation effect, that is, the signal at the output of this block will contain all information about the target, regardless of the actual transmitted or received data, and leaves radar data, which is processed further by the "maximum likelihood method".

The input part "Processing of radar data" is the radar cube, representing as an array which contains information about the frequency transmitted in its rows, and the information about the propagation time of the signal in its columns. The channel transfer function is obtained by division, since it will contain all information about the target, regardless of the actual data transmitted or received.

To get range-frequency information, the inverse fast Fourier transform is performed, which is applied to each column and performed in frequency, and the fast Fourier transform is performed for each row and performed in time. These actions provide all the necessary information about the target's range and Doppler frequency, which is then converted to the target's speed.

The result of the actions previously described is a periodogram in which each reflecting object corresponds to a maximum. Periodograms are used to build a range-speed portrait of the area. The range *d* and speed *v* of targets are calculated from the local maxima of the periodogram.

Due to the relatively small power of the base station transmitter, the area of greatest interest is the so-called small distances of the order of tens of meters, which, in the absence of requirements for the delay value, corresponds to the scenario of eMBB-enhanced mobile broadband, used for resource-intensive applications and wideband Internet access.

At short distances, a margin of error of more than 10% is unacceptable for any of the possible applications of radar sensor systems in 5G.

In order to optimize the error value at short distances, while hardware and software restrictions are imposed by the standard, it is necessary to use the maximum possible signal bandwidth. For FR1, the maximum allowed bandwidth of a single radio channel is 100 MHz. When trying to increase the signal bandwidth to the maximum value, the following considerations must be taken into account.

Since the FFT/IFFT algorithms used by OFDM work efficiently with samples of dimension multiples of 2n, the number of subcarriers in OFDM is used in a similar multiplicity. Thus, the maximum achievable spectral width of the signal accounted for 61.4 MHz. Based on the simulation results, it can be concluded that changing the signal band to the maximum reduces the error in determining the range to the target by 37% for distances of 20 m or more for objects which an RCS of $1m^2$.

Increasing the signal bandwidth is possible both by increasing the number of subcarriers with minimal numerology, and by spacing between subcarriers. From the point of view of computational complexity, the latter seems preferable, since an increase in the number of subcarriers leads to an increase in the modeling time.

It should be noted that an increase in the distance between subcarriers leads to a conflict between the communication and radar applications of the system under consideration, since it entails a decrease in the speed of information transmission. Thus, this limits the possibility of using systems that combine the function of communication and location, such as 5G scenarios that do not impose high requirements for data transfer speed, for example, IoT.

Table 5: Error Estimation for distances up to 100 m

	B = 15 kHz		B = 30 kHz		B = 60 kHz	
Specified value, m	Result of the simulation, m	Error, %	Result of the simulation, m	Error, %	Result of the simulation, m	Error, %
10	19.5	95.0	14.6	46.0	12.2	22.0
20	29.3	47.0	24.4	22.0	21.9	9.5
30	39.1	30.0	34.2	14.0	31.7	5.6
40	48.8	22.0	43.9	9.8	41.5	3.8
50	58.6	17.0	53.7	7.0	51.3	2.6
60	68.4	14.0	63.5	5.8	63.5	5.8
70	78.1	11.5	73.2	4.5	73.2	4.5
80	87.9	10.0	83.0	3.8	83.0	3.8
90	97.7	8,5	92.7	3	92.8	3

V. CONCLUSION

The results obtained allow us to evaluate the possibility of radar sensor detection of objects based on the standard OFDM signal used in 5G communication networks, and the achievable values of the maximum range to the target using various methods of processing radar information, as well as different structures of the probing signal. Systems and devices based on OFDM technology belong to systems with frequency division of channels, i.e. the entire available frequency band is divided into channels that can be used for radar sensor in location mode (in order to provide greater resolution, you can allocate the entire available band), and in communication mode, a narrower channel can be allocated for each user in the area where such a device is used.

The proposed approach-adding a software-implemented radar information processing module to existing 5G devices-will reduce the cost of implementing new services. The 5G-based radar sensor module can be used, for example, in intelligent transport systems, where it is necessary to combine environmental monitoring and the transmission of information from sensors, including communication between moving objects.

Using the existing communication standard for location will reduce the cost of manufacturing devices for IoT and provide multifunctionality.

Since the radar sensor part, which is part of a IoT platform multifunctional radio and radar complex, is the most critical in choosing the operating parameters of radio equipment, such as signal transmission power, object detection range and carrier frequency, the task of creating such a complex requires evaluating the possibility of building a radar sensor with the parameters of transceivers used in existing radio equipment. In the future, it is planned to continue work in the field of research on methods for separating radar targets using non-directional antennas.

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