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Design of radio communication systems for unmanned transport applications

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ABSTRACT
In the paper the principle of OFDMA-based radio communication systems design for unmanned transport applications is presented. The concept of system radio interface is analysed and its basic parameters proposals are considered. In the last part of the paper some air interface characteristics useful for optimization of throughput and system capacity are considered.

KEYWORDS: unmanned communications, air interface design, unmanned transport

1. Introduction

Unmanned transport communication is one of the most popular technical challenges in modern telematics. It's well known that the role of unmanned transport systematically grows. When we talk about the future we must take into account the transport of cargo but equally interesting is the transport of the people. So, the role of radio communication between Unmanned Aerial Vehicles (UAV) and some radio-stations is very high, especially, when we take into account high transmission rate of data in modern systems.

In this paper we take into account the role of unmanned transport systems in the case when transport is realized in coastal zone and at sea. In this case we can talk about the connections established between coastal radio-stations (base stations) and UAVs which can fly under sea and under coast. So, it can be e.g. coast guard UAVs, medical UAVs and Maritime Search and Rescue Services, and many others. A common set for these applications of radio communication system is that in real perspective of communication development high speed communication is necessary, dedicated for multimedia communications and general data transmission. Taking into account this consideration we must first make the requirements of proposed system depending on conditions of its work. In this paper we analyse the situation when the communication is realized in seaside zone when base station is stationary, and mobile station is localized in UAV. The UAVs are typically under the sea or under the coast. It plays the main role in the problem of radio-wave propagation in analysed system.

If we want to analyse radio communication system requirements then we must take into account two points of view. First, important is the application of UAVs what determines the sense of communication. Second is the problem of kinds of communication, i.e. control information transmission, voice transmission, data transmission and its type, etc. In first case we can talk about civil cargo transport, civil people transport, medical transport, coast guards and military applications etc. From the point of view of future applications we can see that data transmission is very important, especially of two types. First multimedia communication, and second is the M2M communication. From the point of view of system design, in each type of communication, important is transmission rate and quality, as well as the signal coverage in a system.

2. Conditions of signals propagation and system proposal

2.1. Channel model

From the point of view of radio-wave propagation we can see that the transmission of coast-to-air under sea is dominant in our case. In typical situations the 2-ray propagation model is used for modelling of radio-wave propagation and signal loss. In this model we must take into account 2 main components of multipath signal propagation. The 1-st is the LOS (line-of-sight) component and the 2-nd is the component reflected from the surface of the sea [3-6] what is presented in fig. 1.

The impulse response of this channel is given by

$$h(t,\tau)=\alpha_0(t)\delta(\tau-\tau_0)+\alpha_s(t)e^{-j2\pi\frac{\Delta R_k}{\lambda}}\Gamma(t)\delta(\tau-\tau_0) \qquad \textbf{(1)}$$

when:

$\alpha_0(t)$ – the complex amplitude of the LOS component,

$\alpha_s(t)$ – the complex amplitude of reflected component,

$\Gamma(t)=\frac{\sin\theta-X}{\sin\theta+X}$ – is the reflection coefficient from the sea surface,

$e^{-j2\pi\frac{\Delta R_k}{\lambda}}$ – the variable for representation of phase shift between the LOS and the reflected component, depending on the shift $DR_k = X + X' - l_{LOS}$ relative to the wavelength λ.

In the case of coastal transmission it is possible to receive some additional components reflected from the coast obstacles. So, for better interpretation of this situation a wideband channel model can be employed. The model of wideband channel can be presented as the FIR filter, consisting of the delay line and not more than 4 branches, what we can see in fig. 1b. The received signal *y(t)* is the vector sum of signals received in different propagation paths with various delays and phase. The first component is the LOS signal of temporary complex amplitude $a_0(t)$ and phase shift ϕ_0. The probability of amplitude of this component is given by the Rician distribution. The 2-nd component is reflected from the surface of the sea, of the $a_s(t)$ amplitude and ϕ_s phase shift. The probability of amplitude of this component is given by the Rayleigh distribution.

a)

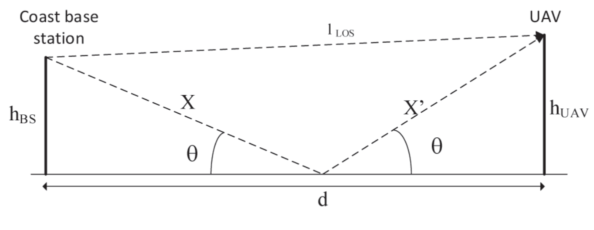

Fig. 1a. Channel model: the 2-ray propagation model for flat earth [own study]

b)

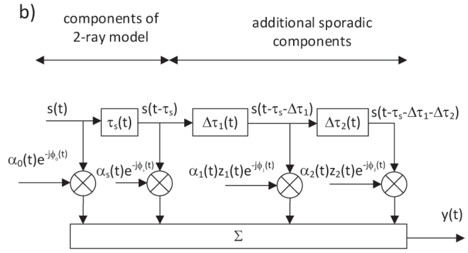

Fig. 1b. Channel model: wideband channel model [own study]

Whereas the remaining components additionally depend on stochastic process, respectively *z1(t)* and *z2(t)* which determines their existence. The probability distribution of occurrence of these components is largely undefined. But it is understood, however, that the probability of amplitude of second component and other components results from the Rayleigh distribution.

There are not many publications on the problem of channel modelling for analysed propagation conditions. Some information we can find in [9-10], and, especially most suitable for UAVs, in models investigated by NASA [3-8]. In this case signals transmission between coast radio-station with UAVs is researched and some measurements of channel characteristics are presented. The research was made on the basis of 2-ray model taking into account the radio wave reflections from waving surface of the sea (salty water). The reflection of a radio wave from irregular sea surface may result in large radio wave phase-shift. But most important conclusions are that additional components plays very low role in signals transmission and reception in this propagation environment [3-8] due to their small power. So, they are not important from the point of view of OFDM system design.

2.2. Channel parameters

The main problem in the design of OFDM systems involves selecting time-frequency parameters of radio interface. The way of selection these parameters depends on propagation environments characteristics. Especially important are correlation time, delay spread and coherence bandwidth as well as Doppler shift and Doppler spread. On the basis of research presented in [7-10], we can see that the correlation time and delay spread for investigated propagation environments are very short. The delay spread was measured for short distance between vehicle and coast station and for larger distance. In general delay spread was very short for larger distance and slightly longer for short distance. But in both cases delay spread was not larger than 50 ns, and in the most critical situation increased to 250 ns. This is very important information from the point of view of the OFDM system design. We know that small delay spread allows the use of short time guard T_g between OFDM symbols. In typical situation the time guard should be a few times larger than maximum delay spread which is possible in a given propagation environment.

Taking into account the situation when delay spread grows due to the reflections from some obstacles in sea shore, terrain shaping and building development we set the minimum time guard to 1 ms. Note that this is approximately 5 times less than the so-called short time guard used in LTE (Long Term Evolution). It means that the OFDM technique is better for the use in sea propagation environment in comparison to urban, suburban or rural environments, as in typical case of LTE.

It's well known that the coherence bandwidth B_c of multipath channel in which the correlation time equals several dozen ns, can be approximately over a dozen MHz, and for a few hundred ns – approximately a few MHz. It means that within the band of signal received (B = 10 MHz) should be no more than one strongly suppressed component-subcarrier. And in the general case may not even be any component strongly suppressed. However, the longer correlation time reaching a few μs can cause strong frequency selectivity. It means that in relatively long periods of time the channel can't be frequency selective despite the large channel bandwidth.

Doppler spread as well as Doppler shift depends on speed of motion of UAVs relative to coast base stations. So, in our project important is the assumption of maximum speed of UAV. We know that in typical situation the speed is relatively small but today it can be observed UAVs with record speed approximately 250 km/h.

2.3. Basic assumptions of the system proposed

The basic assumptions of proposed system are connected with the problem of data communication with high transmission rate using wideband channel of 10 MHz. In this system we can use the OFDMA transmission in TDD duplex mode. System works at 1.4 MHz frequency. For transmission of signals in a radio interface we use the OFDM technique, in which the transmission in overall frequency band is made using a number of orthogonal subcarriers transmitted simultaneously. This method of transmission allows increasing the immunity of signals transmitted on frequency selective signal fadings, which are the most problematic in wideband radio communication systems. The basic set of parameters is presented in tab. 1.

Table 1. Basic parameters for proposed radio interface

Parameter	Value
Multiple access/ duplex method	OFDMA/TDD
Centre frequency	1.4 GHz
Signal band	10 MHz
Modulation	QPSK and 16 QAM
Channel coding	Convolutional coding (3,1,9)
FFT size	1024
Number of OFDM symbols in a single slot (per 0.5 ms)	6, 7 or 8
Physical resource size	12 subcarriers x 8 (7 or 6) OFDM symbols

The basic unit of OFDMA resources is the resource block which size is defined in time-frequency domain. In time domain resources are divided depending on the number of OFDM symbols used in a single time slot. In frequency domain resources are divided into a number of subcarriers. The size of this block is 12 subcarriers and 6, 7 or 8 OFDM symbols in a single slot what we can see in fig. 2.

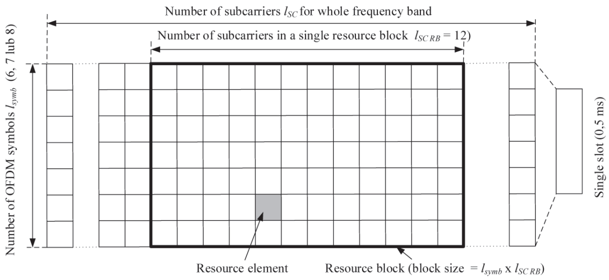

Fig. 2. Resource block format in the designed system [own study]

The number of resource blocks is dependent on set subcarrier spacing. A single resource block consists of data sent on 12 subcarriers in a single slot of 0.5 ms duration. The block size depends on the number of OFDM symbols per slot. A single resource element carries 2 or 4 bits depending on modulation type: QPSK or 16 QAM, respectively. So, the resource element it is the smallest unit of information sent on a single subcarrier in OFDM symbol duration.

3. System design process

The goal of this consideration is to present how propagation conditions affect the throughput in designed system. So, we analyse the principles of OFDMA interface design and achievable throughput in our system.

3.1. The principles of OFDMA interface design

Design process of OFDM systems begins from selection of FFT size which depends on planned number of subcarriers in OFDM signal, and on channel bandwidth (10 MHz). The FFT size is the power of 2 in typical situation due to low complexity of FFT implementation in this case. We can see that in the case of 10 MHz channel band we can use the 1024 FFT size. As one can see a few hundred of subcarriers are needed in designed system. If assigned number of subcarriers is less than 1024 then we use these subcarriers only (so-called active subcarriers) and other subcarriers are set to zero.

Subcarrier spacing should be much larger than the Doppler spread which depends on speed of motion of vehicles. If speed of motion of terminals is high then we must take into account higher *Df*. In most systems designed *Df* is over dozen kHz, and it is proper even for very large (more than 500 km/h) vehicle speed. So, the subcarrier spacing must meet the condition

$$\Delta f >> \Delta f_{Doppler} \qquad (2)$$

Sampling frequency in the radio interface depends on *Df* and on the number of subcarriers (FFT_{size}). So, it is given by

$$f_s = \mathrm{FFT}_{size} \cdot \Delta f \quad (3)$$

The OFDM symbol duration depends on *Df* and it can be estimated as

$$T_{OFDM} = \frac{1}{\Delta f} \quad (4)$$

But total transmission period T_{TR} is the sum of the OFDM symbol period and time guard. T_{TR} depends on the number of designed OFDM symbols per time unit and duration of a single time slot. In our system the time slot duration is T_{slot} = 0.5 ms what we can see in fig. 2. In a single time slot we can transmit (N_{symb}) 6, 7 or 8 OFDM symbols.

Total transmission period can be calculated as

$$T_{TR} = \frac{T_{slot}}{N_{symb}} = T_{OFDM} + T_g \quad (5)$$

Using the T_{TR} and T_{OFDM} we can estimate necessary time guard T_g between consecutively transmitted OFDM symbols. The most critical assumption is that T_g should be greater than maximum delay spread in dedicated propagation environment what means that

$$T_g > \Delta T_{delay} \quad (6)$$

However it would be better if $T_g >> \Delta T_{delay}$. In our project we assume that minimum T_g is not less than 1 ms.

3.2. Throughput estimation

The total throughput available in 10 MHz frequency channel, which can be understood as the capacity, depends on channel bandwidth, the number of subcarriers, and the number of resource elements, and resource blocks as well as on the number of OFDM symbols allocated in a single slot. Additionally, the capacity depends on modulation type and coding rate, i.e. on the number of bits per modulation symbol when M-ary phase modulation is used. Thus, a major capacity estimation problem is the determination of the number of available physical resource blocks for a given user. Moreover, the plan of the structure of the data transmitted in a single time slot as well as the number of OFDM symbols available for this user with the exception of control data overhead are important.

So, taking into account early observations we can estimate throughput R_p [bps] using the following expression

$$R_p = n_b\, \eta_{cod}\, l_{SC\,RB}\, \nu_{loss}\, {l_{symb}}/{T_{slot}} \quad (7)$$

where:
- n_b [b/symbol] is the number of bits which depends on modulation type (QPSK: n_b = 2, 16QAM: n_b = 4, 64QAM: n_b = 6),
- h_{cod} is a channel coding rate,
- $l_{SC\,RB}$ is the number of subcarriers (resulting from the number of resource blocks),
- l_{symb} is the number of OFDM symbols assigned in a single slot (6, 7 or 8),
- T_{slot} = 0.5 ms is time slot duration,
- n_{loss} – the loss factor resulting from the use of certain OFDM symbols by the control data [1] (n_{loss} = 0.86).

In our analysis there is not important the value of throughput for different system configurations. The goal of analysis is that we find effective configurations of radio interface parameters. That's why we calculate normalized values of throughput R_p/R_{min} what means that calculated value of throughput is divided by throughput for worst case configuration.

4. Results of analysis

Now, we can see the results of throughput achieved for different configurations of OFDM parameters. The parameters calculated for the LTE system are analysed what allows comparison of results with known system.

4.1. OFDM parameters for different configurations of radio interface

The OFDM parameters for different interface configurations are presented in tab. 2. We can see there the number of resource block NB, *Df*, T_{OFDM} and number of subcarriers in 10 MHz band (no. of SC). These parameters are then taken into account during the calculations of T_g, and $T_{OFDM} + T_g$ for different number of resource blocks (and subcarriers) and for various number of OFDM symbols in the 0.5 ms single slot.

Note that minimum acceptable T_g should be greater than 1 ms due to the assumption resulting from signal propagation conditions. So, we can see that minimum T_g in tab. 2 can be 2.49 ms, 2.84 ms and 1.26 ms, respectively, because if we use greater number of resource blocks ten resulting in small T_g for each number of OFDM symbols. Additionally, for LTE we were taken into account two situations when so-called long and short cyclic prefix is used what corresponds to the 6 or 7 OFDM symbols in a single slot. In LTE, there is not possible the use of 8 OFDM symbols.

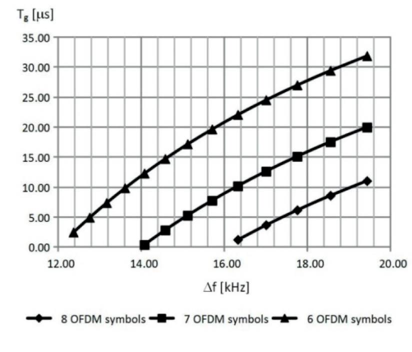

Fig. 3. Time guard as a function of subcarrier spacing for different number of OFDM symbols in single slot [own study]

Additionally, the results of T_g calculation depending on *Df*, for different number of OFDM symbols, we can see in fig. 3. There we can see the effect of subcarrier spacing on guard time acceptable in a system.

Table 2. Results of OFDM parameters estimation for different operating conditions

					6 symbols		7 symbols		8 symbols	
	RB	Df	T_{OFDM} [ms]	No. of SC	$T_{OFDM}+T_g$ [ms]	T_g [ms]	$T_{OFDM}+T_g$ [ms]	T_g [ms]	$T_{OFDM}+T_g$ [ms]	T_g [ms]
Proposed system analysis	44	18.56	53.88	528	83.33	29.45	71.43	17.55	62.50	8.62
	46	17.76	56.31	552		27.03		15.12		6.19
	48	17.01	58.79	576		24.54		12.64		3.71
	50	16.33	61.24	600		22.10		10.19		1.26
	52	15.71	63.65	624		19.68		7.77	non - realizable	
	54	15.12	66.14	648		17.20		5.29		
	56	14.58	68.59	672		14.75		2.84		
	58	14.08	71.02	694		12.31	non - realizable			
	60	13.61	73.48	720		9.86				
	62	13.17	75.93	744		7.40				
	64	12.76	78.37	768		4.96				
	66	12.37	80.84	792		2.49				
LTE	50	15.00	66.67	600	long cyclic prefix (16.67 ms)		short cyclic prefix (5.2 ms and 4.69 ms)		non - realizable	
					83.33	16.67	71.43	~ 4.76		

4.2. Throughput optimisation

For comparable estimation of throughput achieved for different system configurations we use the R_p/R_{min} throughput normalized to its minimum value in our calculations. Estimation was made using all configurations from tab. 2. Normalized throughput is then the indicator for the use of resources (in our case it was 6 OFDM symbols and 44 resource blocks). As we can see, the best proposal is for 8 OFDM symbols per slot when calculated guard time is $T_g = 1.26$ ms, assuming that T_g should be greater than 1 ms.

In fig. 4 we can see the results of throughput estimation as a function of subcarrier spacing D*f*. If we take into account less number of OFDM symbols in a slot then we can achieve the same throughput using less *Df* value in comparison to greater number of OFDM symbols. But if larger *Df* is preferred, it is better to use greater number of OFDM symbols.

The first conclusion is that larger number of OFDM symbols not always gives greater throughput. But large number of OFDM symbols is preferred because it is achieved when *Df* is larger. And larger values of *Df* are preferable for high speed of UAVs. The second conclusion is that analysed propagation environment are very good from the point of view the use of OFDM transmission for data transmission because we can use small T_g periods at relative large *Df* values. It is possible to use large number of OFDM symbols for a single slot what guarantees high spectral efficiency.

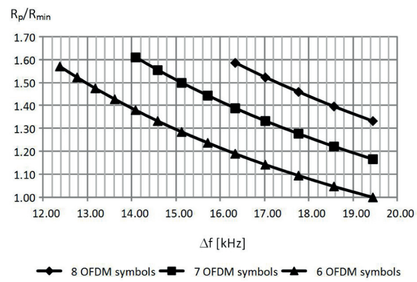

Fig. 1. Normalized throughput as a function of subcarrier spacing for different number of OFDM symbols in a single slot [own study]

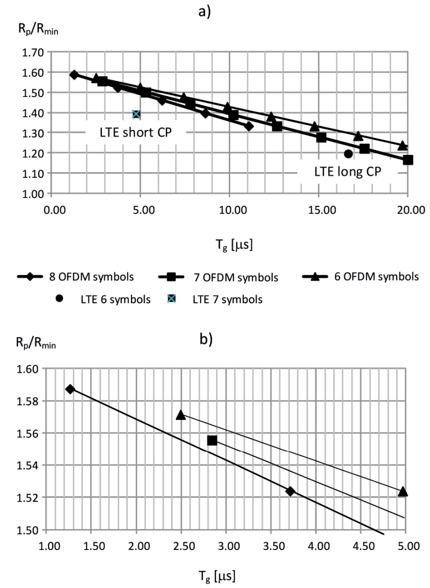

Fig. 5. Normalized throughput as a function of time guard for different number of OFDM symbols in a single slot: a) full range of available subcarrier spacing and results for LTE; b) narrowed range for better presentation of the best results [own study]

In fig. 5 the normalized throughput available in different configurations of T_g is presented. In fig. 5a the full range of guard time analysed is shown, and in fig. 5b the range of short guard time is presented for better visualisation. We can see that the greatest throughput is achieved for the largest number of OFDM symbols in a single slot. For the case of 7 symbols, the throughput higher than 1.56 is not realizable due to too short guard time in this case. That's why this throughput is less than the throughput achieved for 6 OFDM symbols. Very important is that the optimum number of OFDM symbols is dependent on designed guard time and its restriction. Note, that system is realizable only for parameters marked as points in this figure because it is dependent on predefined resource block size (the position of these points is dependent on resource block size, and only the even number of resource blocks is acceptable).

We can see that for T_g = 2.5 ms the best throughput is with 6 OFDM symbols only but in the case of T_g = 2.85 ms better results are obtained for 7 symbols. But if we take into account greater value of T_g = 3.71 ms then the best situation is when 8 symbols per slot is implemented. However when we allow the T_g value as low as possible, with assumption that T_g > 1 ms, then optimum is 8 OFDM symbols in a slot because the T_g = 1.26 ms can be implemented. Additionally, in fig. 8a the throughput available in LTE is presented for 2 possible configurations of T_g in LTE (so-called short cyclic prefix and long cyclic prefix). We see that the band of 9 MHz per 10 MHz available in LTE and taken parameters of T_g and *Df*, determine poor LTE efficiency in comparison to analysed system.

5. Conclusion

Some proposal for design of OFDMA-based system for unmanned transport applications is presented in this paper. The discussion about propagation conditions of signals transmitted in proposed system has led to the conclusion that the OFDMA interface is very suitable for the implementation of radio communication interface in this system. Due to relatively short delay spread these conditions are much better in comparison to urban environments and rural environments. It means that the OFDM technique is strongly recommended for communication with UAVs. Additionally, we can see that the configuration of OFDM parameters for LTE is much more unfavorable from the viewpoint of resource use, compared to the configurations of the proposed system. Future research directions of this consideration is connected with the problem of advanced frequency reuse in different cells of proposed system which are well described in [1-2].

Acknowledgments

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