OFDM Signal Navigation

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***Abstract* — The satellite navigation, like satellite communication, has many limits which restrict its applicability for modern location based service. One solution of such problem is to return the navigation radio beacons from satellites to the Earth nearer to the user. The aim of this study is to analyze the applicability of communication signals with OFDM orthogonal frequency division multiplex modulation scheme for mobile user positioning based on ToA (time of arrival) navigation method.**

The OFDM modulation is widely used in modern communication and broadcasting systems like digital television and digital radio broadcasting, internet access etc. Its relatively simple signal processing in the receiver, low sensitivity to the radio channel quality and applicability in single frequency networks are its advantage.

***Key Words*— LBS, OFDM, Signal ranging, Time of Arrival Navigation Method.**

I. INTRODUCTION

The satellite communication and navigation systems were developed at the second half of the last century. In the time of their beginning, the satellite systems seem to be very versatile and to be able to cover most communication and navigation applications. The great advantage of satellite systems is their large coverage, even in desert areas. However, their imperfections like long latency, inconvenient energy budget, problems with antennas, problematic mobile reception, and low capacity appeared together with the advantages. The development of mobile communication and location based services (LBS) principally implies higher requirements on such systems especially in heavily seated areas.

The problem in communication is often solved by a construction of the terrestrial communication systems in populated areas, which significantly improves availability, capacity, and energy budget. The satellite systems use then prevails in deserted areas.

The location based services have shown large development in the past decades. The outstanding role in today's location based services is occupied by satellite navigation, especially GPS; whereas the similar problems like poor indoor availability, small precision etc. arose gradually.

The solution of such problem is dislocation of the navigation beacons back from the space to the Earth and their integration with the terrestrial communication system or use of terrestrial communication stations as a navigation beacons.

The presented paper is aimed on the analysis of the utilization of modern communication signals with OFDM modulation scheme for navigation based on time of arrival positioning method.

II. OFDM

The Orthogonal Frequency Division Multiplex (OFDM) modulation is modern modulation which was especially developed for communication via fading channel. The OFDM modulation utilizes large number of modulated carriers for data transmission. Transmitted data are divided into sub streams; each sub stream is modulated onto individual carrier. This approach enables essentially extended symbol duration.

The great advantage of the OFDM modulation is its relatively simple processing in the receiver; it means simple channel equalization end data detection. This feature was achieved by utilization of the orthogonal carriers and guard interval, which protects intersymbol and intercarrier interference. The OFDM transmitted signal is given by

$$s_{OFDM}\left(t\right)=\sum_{n} v_n\left(t-nT_s\right), \quad (1)$$

where v_n is n^th^ OFDM symbol

$$v_n\left(t\right)=\begin{cases}\sum_{k=K_{\min}}^{K_{\max}} {}^{n}V_k e^{\frac{j2\pi k(t-\Delta)}{T_U}} & 0<t<T_S \\ 0 & elsewere\end{cases}, \quad (2)$$

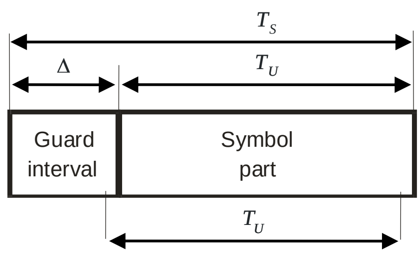

Fig. 1. OFDM symbol structure and replica signal selection.

T_s is symbol duration, T_U is duration of the orthogonal part of the OFDM symbol, $\Delta = T_s - T_U$ is guard interval duration (Fig. 1), $K_{\min}$ is index of the first and carrier $K_{\max}$ is index of the last carrier. ${}^{n}V$ is n^th^ mapped data symbol. The computationally cost effective implementation of the OFDM modulator [7] utilizes FFT.

The OFDM modulation schema has high spectral efficiency; the shape of the power spectrum is almost rectangular. This very important feature especially for terrestrial systems is reached at the expense of the modulated signal envelope, which highly varies.

Some radio systems like DVB-T, DAB, DRM etc. dedicate small portion of carriers for simplification of synchronization and channel equalization. These so-called continual pilot carriers or scattered pilot carriers are modulated by the known symbols and create deterministic part of the signal which can be used also for range measurement.

The next advantage of the OFDM modulation scheme is a support of the single frequency network transmitter architecture, which enables to secure good service availability in problematic areas, to cover large areas by multiple transmitters sharing the same frequency etc. The low sensitivity on channel quality especially on fading dedicates OFDM modulation scheme for mobile reception and mobile terrestrial communication and broadcasting systems.

III. Ranging Theory

The time of arrival of the signal is traditionally determined by the correlation reception method developed for radar signal processing. This method is optimal processing for AWGN channel. It was adopted for satellite navigation (GPS, GLONASS and Galileo) too. GNSS signals are transmitted continuously, so time of arrival of such signals can be determined (tracked) by feedback structure called DLL (Delay Lock Loop) Fig. 2.

The proposed navigation systems based on OFDM terrestrial transmitters can utilize determination methods, classical (snapshot) correlation reception and/or DLL signal tracking. The performance of both methods for AWGN channel is analyzed in the below.

The great advantage of the OFDM signal is the fact that the time of arrival of the signal can be determined from the part of the signal (some carriers). The signal transmitted on the other carrier will not affect such measurement. This feature enables us to use only known part of the signal for ranging without impact of the unknown transmitted data. In optimal case the replica for correlation reception can cover all signal components. The data carrier component of the signal can be synthesized from the demodulated and decoded data; i.e. from data at the output of the channel coder implemented in the system.

Time of arrival of the communication signals can be also derived from the symbol timing in some systems. The OFDM symbol duration is extremely long (hundreds or thousands of microseconds) in contrast of traditional digitally modulated signals which operate with much shorter symbols. The ordinary precision of the symbol synchronization of the OFDM is in the order of microseconds. Thus this precision is not sufficient for modern navigation systems.

A. Snapshot ranging

The minimum accessible standard deviation $\left(\sigma_r^2\right)_{MIN}$ of the measured range in additive white Gaussian noise (AWGN) channel is given by (3) and depends on the signal effective bandwidth 2β, signal energy *E*, and single side spectral power density of the noise N_0.

$$\left(\sigma_r^2\right)_{MIN} = \frac{c}{2}.\frac{N_0}{2E\beta^2} \tag{3}$$

where *c* is speed of light,

$$\beta^2 = \frac{4\pi^2}{2E}\int_{-\infty}^{\infty} f^2\left|\tilde{S}\left(f\right)\right|^2 df \tag{4}$$

and $\left|\tilde{S}\left(f\right)\right|^2$ is spectral density of energy of the processed signal complex envelope.

B. DLL tracking

The typical implementation of DLL system is in Fig. 2. The parameter τ, which should be tracked with DLL, represents inherent properties of input signal $s(t,\tau)$. The system generates signal replica $r(t,\hat{\tau})$ with parameter $\hat{\tau}$, which tries to be close to the real value of τ. The estimated parameter $\hat{\tau}$ differs from the true value τ. The difference is the tracking error $\varepsilon = \tau - \hat{\tau}$. The detector output $e(t,\varepsilon)$ is proportional to the tracking error ε, and through loop filter with transfer function $F(p)$ drives the loop NCO (VCO) with signal replica generator. The filtered tracking error sense has the polarity that forces the NCO to generate replica with parameter $\hat{\tau}$ close to real tracking value τ. In described DLL implementation we have to consider two random processes: first random process is tracking parameter τ representing random signal delay, second random process is additive noise $n(t)$ on loop input.

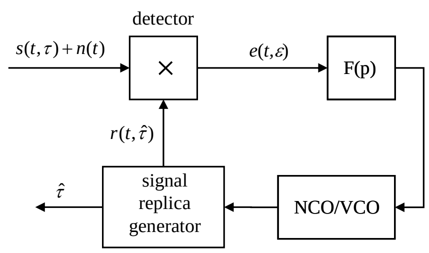

Fig. 2. Real implementation of DLL system.

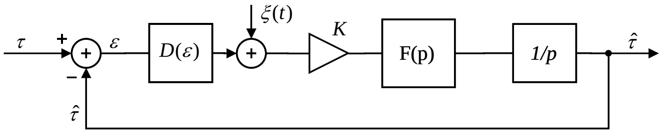

Fig. 3. Equivalent model of tracking system (DLL).

Contemporary theory of tracking systems uses the Equivalent Model (EM) concept for representation and analysis of real tracking system. The EM has unified structure and therefore offers a unified analysis of DLL too. Particular EMs, derived from various real DLL implementations, differ in the EM parameters.

The equivalent model (EM) is shown in Fig. 3. In contrast to real implementation of DLL, EM has tracking parameter τ in explicit form. Therefore the loop detector is represented as a subtracter. The loop nonlinearity is represented with equivalent loop detector characteristic $D(.)$. Advantage for analysis is to normalize $D(.)$ to the unitary slope and possible disagreement to involve into loop gain K. The random loop excitation (τ and $n(t)$) can be used with an appropriate transformation represented as equivalent loop noise $\xi(t)$. It is sufficient to derive $\xi(t)$ only from additive noise $n(t)$ in common analysis and then τ remains as random excitation of EM. The loop filters in DLL and EM are identical; the NCO is represented as integrator.

A significant simplification of analysis, but sufficient for many purposes, can be achieved with linearization of EM. Since the only non-linear block in EM is equivalent detector characteristics $D(\varepsilon)$, the linearization of EM consists in removing of the detector characteristic block and incorporation its slope K_D into equivalent loop gain K, see Fig. 4.

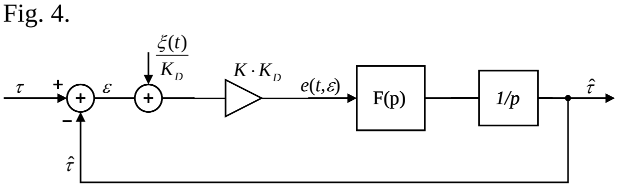

Fig. 4. Linearized equivalent model of tracking system (DLL).

We denote open loop filter transfer function as

$$X(p) = \frac{KF(p)}{p} \tag{5}$$

then for tracking error $\varepsilon(p) = \tau(p) - \hat{\tau}(p)$ and estimated tracking value $\hat{\tau}(p)$ we can write

$$(\varepsilon + \xi)X = \hat{\tau} \tag{6}$$

$$\varepsilon = \tau\frac{1}{X+1} - \xi\frac{X}{X+1} = \tau(1-H) - \xi H \tag{7}$$

The $H(p)$ is the closed loop transfer function

$$H(p) = \frac{X(p)}{X(p)+1} = \frac{KF(p)}{KF(p)+1} \tag{8}$$

The important parameter of the loop is its noise bandwidth defined as

$$B_n = \frac{1}{2\pi}\int_0^{\infty} |H(j\omega)|^2 d\omega \tag{9}$$

We have two variables in equivalent model which can be considered as random: it is tracking value τ, which represents random signal delay, and equivalent loop noise ξ, which mostly represents additive noise in loop input.

For investigation of tracking error characteristics we will suppose the independency of both random variables τ and ξ. The power spectral density (PSD) of tracking error can be therefore expressed as follows

$$C_\varepsilon(j\omega) = C_\tau(j\omega)\left|1-H(j\omega)\right|^2 + C_\xi(j\omega)\left|H(j\omega)\right|^2. \tag{10}$$

Variance of tracking error is then

$$\begin{aligned}\mathrm{var}[\varepsilon] &= \frac{1}{2\pi}\int_{-\infty}^{\infty} C_\varepsilon(j\omega)d\omega = \\ &= \frac{1}{2\pi}\int_{-\infty}^{\infty} C_\tau(j\omega)\left|1-H(j\omega)\right|^2 d\omega + \\ &+ \frac{1}{2\pi}\int_{-\infty}^{\infty} C_\xi(j\omega)\left|H(j\omega)\right|^2 d\omega.\end{aligned} \tag{11}$$

Since the B_n is generally very narrow we can the formula above overwrite as

$$\mathrm{var}[\varepsilon] = \frac{1}{2\pi}\int_{-\infty}^{\infty} C_\tau(j\omega)\left|1-H(j\omega)\right|^2 d\omega + 2C_\xi(0)B_n \tag{12}$$

The tracking system has two main sources of disturbances: additive noise, which is in eq. (12) represented as $C_\xi(0)$, and random fluctuation of tracking parameter τ which is characterized with $C_\tau(j\omega)$. To minimize the impact of the additive noise, the B_n should be as small as possible. However the small value of B_n causes the large value of the first term in eq. (12). Thus, the loop cannot adequately react to quick change of the tracking parameter τ. Therefore the choice of B_n (or $H(j\omega)$) is always some trade-off.

IV. System candidates

The aim of this chapter is to describe and analyze some main representatives of communication and broadcasting systems based on OFDM modulation.

A. *DVB-T*

The digital video broadcasting terrestrial DVB-T [3] is the European digital television system based on OFDM modulation operating at traditional television very high frequency VHF and ultra high frequency UHF bands with traditional channel spacing 8, 7 MHz or possibly 6 and 5 MHz. The system therefore can be implemented in various regions without changes of frequency planning. The system can be fit to the local conditions by application of the 8K or 2K mode (indicates approximate number of OFDM carriers), utilization of various guard interval durations, code rates of the forward error correction coding, and number (4, 16 or 64) of modulation states of individual carriers modulation. This enables to setup bit rate of the broadcasted data to affect minimum value of the signal to noise ratio required for system operation, and consequently to influence the coverage.

The digital video broadcasting terrestrial handheld (DVB-H) system arises from the DVB-T systems by minor supplements. The system has upgraded channel coding to be able to switch on the receiver front end for only portion of time and thereby save energy of the device. The OFDM modulation schemas are very similar, the small difference is in number of carriers which is approximately 4000 (4K mode).

TABLE I
REQUIRED C/N [DB] FOR TRANSMISSION TO ACHIEVE BER 2.10^{-4} AFTER VITERBI DECODER FOR AWGN CHANNEL

Carrier modulation	Code rate				
	1/2	2/3	3/4	5/6	7/8
QPSK	3.1	4.9	5.9	6.9	7.7
16 QAM	8.8	11.1	12.5	13.5	13.9
64 QAM	14.4	16.5	18.0	19.3	20.1

The required signal to noise ratio to ensure proper function of the system is in Table I. The DVB-T system requires for proper performance to achieve bit error rate BER 2×10^{-4} on the output of the outer coder.

The Table II describes allocation of the OFDM carriers for data transfer (data carriers), symbol synchronization (scattered pilot carriers and continual pilot carriers), and transmission parameter signaling channel TPS (TPS carriers). The percentage of transmitted power dedicated for each transmission is also mentioned there.

TABLE II
CARRIER AND POWER ALLOCATION FOR CHANNEL SPACEING 8 MHZ

	Mode			
	2K		8K	
	No	Power	No	Power
scattered pilot carriers	143	13.7% boosted (16/9)	569	13.7% boosted (16/9)
continual pilot carriers	45	4.3% boosted (16/9)	177	4.3% boosted (16/9)
TPS carriers	17	0.9% normal (1)	68	0.9% normal (1)
data carriers	1500	81.1% normal (1)	6003	81.1% normal (1)
Total	1705	100 %	6817	100%

The most complex DVB-T ranging algorithms must utilize all signal power. The replica for correlation reception is therefore created from demodulated data after their correction by channel codes. This introduces significant latency to the system because of robust channel coding based on concatenated forward error correction code.

The long latency can cause problem with stability of the DLL therefore the optimal range determination method is limited to snapshot navigation.

The utilization of deterministic part of the signal (scattered pilots, continual pilots or TPS carriers possibly) significantly simplifies signal processing. Signal processing is not burden by long latency. The signal time of arrival therefore can be estimated by tracking (DLL) too.

The calculated range measurement errors from one OFDM symbol snapshot for various configurations are in Table III. The theoretical results were verified by the computer simulation and experimentally for continual pilot carrier snapshoot navigation (Table IV).

TABLE III
DVB-T 8K SIGNAL RANGE MEASUREMENT ERROR

SNR [dB]	Continual pilot carriers σ_r [m]	Scattered & Continual pilot carriers σ_r [m]	Complete signal σ_r [m]
5	0.487	0.425	0.180
10	0.274	0.239	0.101
15	0.144	0.126	0.053
20	0.086	0.075	0.032
25	0.048	0.042	0.018
30	0.028	0.025	0.010

TABLE IV
DVB-T 8K SIGNAL RANGE MEASUREMENT ERROR
(CONTINUAL CARRIERS ONLY)

SNR [dB]	Theory σ_r [m]	Simulation σ_r [m]	Measurement σ_r [m]
5	0.487	0.422	0.494
10	0.274	0.224	0.286
15	0.144	0.134	0.168
20	0.086	0.079	0.105
25	0.048	0.046	0.92
30	0.028	0.031	0.83

B. DAB

The Digital Audio Broadcasting DAB [4] is the digital radio system developed in Europe which operates in Band III (147-230 MHz) and L-band. The system supports terrestrial and satellite broadcasting. The system utilises OFDM modulation schemas similar to DVB-T. The channel bandwidth (1.537 MHz) is approximately 1/4 of the channel bandwidth of the DVB-T.

The DAB system should supplement FM radio broadcasting.

The application of the DAB for positioning is similar like for DVB-T. The signal processing can be based on the same algorithms. The expected range measurement precision is worse than at the DVB-T due to the narrower signal bandwidth. The range error caused by the AWGN is approximately four times higher than the range error of the DVB-T measurement for the same signal to noise ratio.

C. DRM

The Digital Radio Mondiale DRM [5] is the standard for digital radio broadcasting in traditional radio bands up to 30 MHz. This standard therefore covers LW, MW and SW bands. The system improves quality of radio broadcasting in these bands to VHF FM quality. The DRM has large coverage due to the ionosphere refraction of these frequencies. In addition, these frequencies easily penetrate to the indoor environment and undergrounds.

The DRM standard is compatible with existing radio channels and supports three different bandwidths: half bandwidth (4.5 or 5 kHz), standard bandwidth (9 or 10 kHz) and double bandwidth (18 or 20 kHz).

The operating frequencies and signal bandwidth are comparable with the Loran-C system but in contrast the DRM transmits continual signal in time which enables to increase ranging precision.

VIII. CONCLUSIONS

The paper analysed alternative positioning methods suitable for populated areas based on terrestrial communication and broadcasting signals with OFDM modulation. The suitable systems operate in various frequency bands and have different coverage. Our analyses of the performance were focused on the DVB-T systems only because this system is implemented in the Czech Republic. The signals of the DRM or DAB systems are not available in required quality.

The analyses and preliminary experiments has shown that the communication signals with the OFDM modulation can be used for range measurement.

The utilisation of various communication and navigation signals of various bandwidths and frequencies dramatically improves system diversity and thereby we can accomplish good coverage and availability in various outdoor and indoor environments, even in underground.

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