

SYNCHRONIZATION FOR OFDM-BASED COMMUNICATION SYSTEM: A BRIEF OVERVIEW

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Abstract. - The goal of current paper is to provide an overview of all synchronization tasks to be performed in orthogonal frequency – division multiplexing (OFDM) based communication system. Symbol timing and frequency synchronization solutions in systems with cyclic prefix (CP) are described. Basic channel estimation and equalization based on pilot tones is described and simulation results presented. Alternative channel estimation solutions proposed by various authors are compared. Simulation results of major synchronization tasks are presented. Simulation using Simulink software of communication systems employing different synchronization mechanisms is performed and BERs are determined. The impact of additive noise, multipath propagation and Rayleigh fading on synchronization is reviewed. Methods of improvement of OFDM synchronization mechanisms are outlined.

I. Introduction

Orthogonal frequency - division multiplexing (OFDM) has been selected as a modulation technique for the communication system chip project we are developing. Most active development period of OFDM was during the late 1990's and a wide range of solutions are described in literature since that time. We started development of OFDM system from the scratch to gain experience with existing solutions and switch to implementation of our ideas later. This work summarizes information about existing synchronization techniques as well as shares our experience in implementation and simulation of various OFDM synchronization solutions.

Similar overview can be found in [1]. This PhD thesis addresses algorithms for estimation, detection and source coding in OFDM systems. Part devoted to synchronization gives just a brief overview of synchronization algorithms and no details necessary for building practical implementations. The document contains large amount of useful links to other publications. Another, similar overview is available from [2]. Paper [3] gives a good practical basis to start building an OFDM system, but does not contain the mathematical basis of algorithms exploited. Books [4] and [5] give a good basis for synchronization and channel estimator design, but lacks the description of an advanced synchronization methods.

Although first OFDM systems were put in service more than 15 years ago, it is still a developing technology with a brilliant future. OFDM is used in such well known wireless facilities as wireless LANs (IEEE 802.11a, g, j,

n) [6], IEEE 802.16d, (WiMAX) [7], DVB (Digital Video Broadcast) terrestrial TV systems (DVB-T, DVB-H, T-DMB and ISDB-T) [8], DAB (Digital Audio Broadcast) systems: EUREKA 147, Digital Radio Mondiale, HD Radio, T-DMB and ISDB-TSB, 3GPP UMTS & 3GPP LTE (Long-Term Evolution), 4G and MC-CDMA [9]. By name of *discrete multitone modulation* (DMT) OFDM is used in wireline applications, such as ADSL and VDSL broadband access via POTS copper wiring, MoCA (Multi-media over Coax Alliance) home networking and PLC (Power Line Communication) [10].

The main idea behind OFDM is to divide incoming information flow into N independent substreams and then use these substreams to modulate a set of N mutually orthogonal subcarriers. This makes OFDM system to be more robust against signal reflection, dispersion, interference, narrowband jam and Doppler shift. Subcarriers are provided by set of orthogonal functions. In fact any orthogonal functions could be chosen as basis functions for subcarriers. Nevertheless, usually Discrete Fourier Transform (DFT) based on *complex exponents* is used for basis functions for subcarriers. This allows to exploit well-developed Fast Fourier Transform (FFT) algorithms and finally to build affordable hardware implementation.

The main advantage of OFDM systems is their ability to maintain high data transmission rates in sophisticated signal propagation environments. However, since orthogonal transforms and coherent demodulation (QPSK) are used in OFDM, good time and frequency synchronization become the main factors for obtaining high performance of the communication system.

II. Basic

OFDM is a block transmission technique. In the baseband part of the communication system transmitter, complex-valued data symbols modulate N tightly packed discrete orthogonal waveforms $\varphi(n, k) = e^{j2\pi k \frac{n}{N}}$, where n is the subcarrier index (in the frequency domain) and k is the sample index (in the time domain). These waveforms can be considered also as base functions (BF) of transmit transformation. Subcarrier magnitude

modulation and transformation to time domain is given as:

$$s(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} d(n) \varphi(n, k), \quad k = 0, 1, \dots, N \quad (1)$$

where $d(n)$ is the information symbol to be transmitted. Note that operation (1) can be easily performed by means of inverse DFT. Continuous time representation of (1) is:

$$s(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} d(n) \varphi(n, t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} d(n) e^{j2\pi \frac{n}{T} (t - \frac{T}{2})} \quad (2)$$

where T is the length of OFDM symbol. Time domain waveform $s(k)$ sent over the communication channel becomes corrupted and is given by $r(k) = F(s(k))$. Received time-domain signal is transformed back into frequency domain by means of inverse transform and contains data symbols given as:

$$\hat{d}(k) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} r(k) \gamma(n, k), \quad n = 0, 1, \dots, N \quad (3)$$

where $\gamma(n, k) = e^{-j2\pi \frac{k}{N} n}$. Notice that DFT can be used to perform (3).

Two types of difficulties appear when signal (1) is transmitted over a time-dispersive channel. The channel time-dispersion and multipath propagation cause intersymbol interference (ISI) and lead to loss of orthogonality between individual subcarriers. Insertion of idle guard interval would solve the ISI problem, but will not avoid loss of subcarrier orthogonality. Peled and Ruiz in [11] proposed to use cyclic extension of OFDM symbols - cyclic prefix (CP). CP is last L samples of the symbol copied before the beginning of the symbol. This feature is based on the fact that cyclic shift in signal samples does not affect magnitude of signal spectrum. Cyclical shift of OFDM symbols causes shift of the phase spectrum and leads to phase rotation of data samples. If the CP length is larger than the channel length (the length of channel impulse reaction) then ISI can be omitted. A complete OFDM symbol with CP of length L can be defined in time domain as follows:

$$s(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} d(n) \varphi(n, k-L), \quad k = 0, 1, \dots, N+L-1 \quad (4)$$

In OFDM transmitter this signal is D/A converted, quadrature modulated, upconverted to RF and sent to communication channel.

Due to communication channel impairments and clock differences, the frontend of OFDM receiver is subject of various synchronization errors. Demodulation of received signal usually involves downconversion to intermediate frequency (IF), and if oscillator frequencies are not precise, this conversion causes carrier frequency offset. Moreover, demodulation introduces an additional phase noise.

N orthogonal carriers created in the OFDM transmitter must be properly demodulated in the OFDM receiver. A signal in the OFDM receiver, after down-conversion to

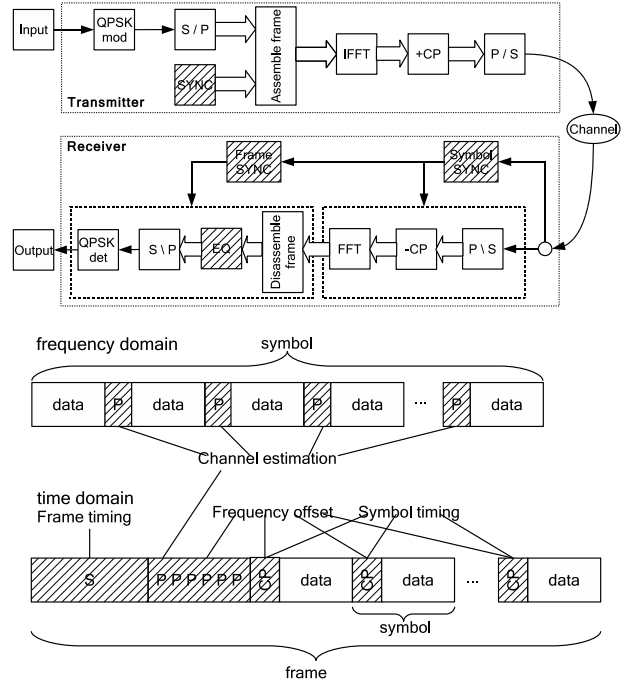


Figure 1 Diagram of OFDM-based communication system (top). Structure of OFDM signal (bottom). Synchronization related signals and subsystems are outlined.

baseband and automatic gain control (AGC), must be sampled and A/D converted. Sample clock of the A/D converter in the receiver must be with the same frequency as in the transmitter. A difference in sample clocks creates rotation of PSK constellation and must be corrected as well. Correction of the frequency offset and phase noise is discussed in section IV.

After A/D conversion a signal in the OFDM receiver can be represented by stream of complex samples. Now for doing down-conversion to separate data substreams by means of FFT, the beginnings of OFDM symbols must be found. The beginnings of OFDM symbols are determined by symbol clock, which is derived from the receiver's sample clock and can differ from pure symbol clock. Additionally, if burst transmission scheme is used, symbol clock, as well as frame clock, must adapt to incoming synchronization symbols and pilots instantly. Because of using the CP, symbol boundary estimation can be assumed as easy task. A small error in symbol boundary estimation appears as phase rotations of data symbols and can be corrected by the frequency domain equalizer. A large error resulting in symbol capture outside symbol boundaries causes severe reception errors.

Separated data substreams are PSK or QAM detected and sent out of OFDM receiver. Further processing usually involves decoding and error correction which is out of coverage of this paper.

By summarizing what has been said above, four main synchronization tasks to be handled in OFDM based communication systems are:

- symbol timing
- frame timing
- carrier frequency estimation and correction

- channel estimation

All these tasks are discussed in details in the following sections.

III. Symbol timing synchronization

An OFDM signal consists of N orthogonal subcarriers modulated by N parallel data streams. In systems with CP, an OFDM signal sent into the communication channel is given by formula (1). OFDM symbols $d(n)$ could be received by bank of matched filters. However the alternative, a DFT-based scheme is used in practice. For successful demodulation of signal, the boundaries of OFDM symbols must be found. In non-dispersive environment received OFDM symbol is given by:

$$r(k) = s(k - \theta)e^{j2\pi\epsilon k} + \xi(k) \quad (5)$$

where s is transmitter signal from (1), θ is the integer timing delay to be estimated, ϵ denotes the difference of receiver and transmitter oscillators and ξ represents additive white Gaussian noise.

Approaches for finding unknown time and frequency offsets may be divided into two groups. First are those that use inserting of some kind of “time stamp” or “pilot” into OFDM signal. Insertion of additional data symbol implies reduction of data rate. A second approach is based on redundancy of OFDM symbols. Namely, the cyclic prefix (CP) can be used to determine the boundaries of OFDM symbols. In OFDM transmitter CP is appended to each OFDM symbol to fight against echoes, and transmitted signal can be described by (4). It is possible to find the place where an OFDM symbol is likely to start by different means. In [12] authors propose to use the difference between received signal and its copy delayed by N samples:

$$v(m) = \sum_{k=m}^{m+L-1} |r(k) - r(k+N)|, m \in \{0, \dots, \theta, \dots, N+L-1\} \quad (6)$$

Then the estimated symbol delay can be found using:

$$\hat{\theta} = \arg \min_{\theta} \{v(\theta)\} \quad (7)$$

Authors in [13] propose to use the correlation of the received samples and delayed copy of them:

$$y(m) = \sum_{k=m}^{m+L-1} r(k)r^*(k+N), m \in \{0, \dots, \theta, \dots, N+L-1\} \quad (8)$$

where r^* denotes complex conjugate. In this case symbol delay can be found using:

$$\hat{\theta} = \arg \max_{\theta} \{y(\theta)\} \quad (9)$$

Moreover, the phase of the statistic at the time $m = \hat{\theta}$ is related to the frequency offset. In [14] it is shown that the carrier frequency offset can be estimated by:

$$\hat{\epsilon} = -\frac{1}{2\pi} \angle y(\hat{\theta}) \quad (10)$$

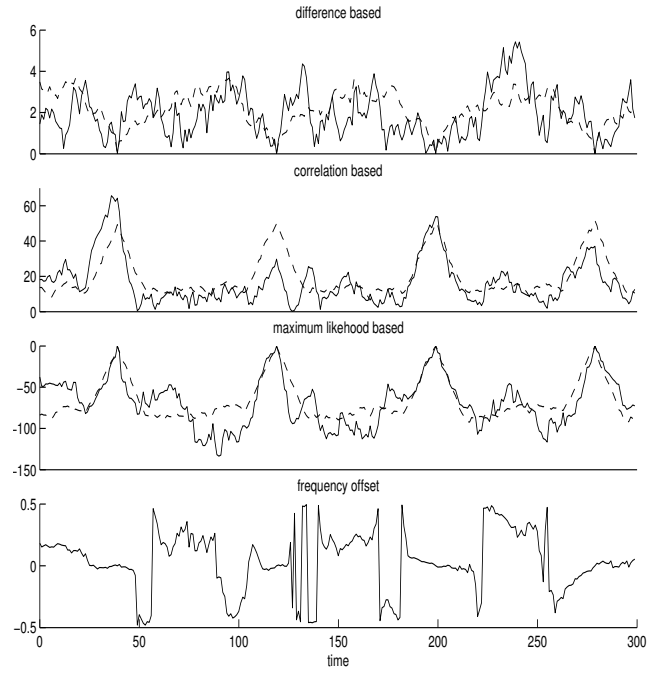


Figure 2 Symbol boundary detection using different methods. Dashed lines display symbol-based averaging output over 8 symbols.

where \angle means the angle of complex-valued argument. The concept of using statistics based on pairwise correlation of received signal and its delayed copy due to the cyclic prefix is patented as US patent [15].

The most efficient joint *maximum likelihood* (ML) estimator of time and frequency offset has been proposed by Van de Beek [16]. This estimator is based on statistic (8) together with additional statistic:

$$u(m) = \frac{1}{2} \sum_{k=m}^{m+L-1} |r(k)|^2 + |r(k+N)|^2 \quad (11)$$

The joint estimate of symbol timing delay in this case is:

$$\hat{\theta}_{ML} = \arg \max_{\theta} \{ |y(\theta)| - \rho u(\theta) \}, \quad (12)$$

where ρ is the correlation coefficient given by SNR. Frequency offset estimate formula (10) still remains valid.

In dispersive environment with multipath propagation the received signal (5) becomes:

$$r(k) = \sum_{l=1}^M \alpha_l s(k - \tau_l - \theta) e^{j\frac{2\pi\epsilon k}{N}} + \xi(k), \quad (13)$$

where L is the number of paths, α_l and τ_l are channel fading and path delay of the l -th path, respectively. For such a received signal, the methods described above give only approximate positions of OFDM symbols. In multipath fading channels the CP part is strongly damaged by previous symbol. As a rule, it leads to erroneous estimation of symbol positions. As a simple solution continuous averaging of $\hat{\theta}$ can be used. Such a solution is proposed in [17]. In the simplest case

peaks from CP autocorrelator are averaged on cyclic basis (average between current sample i and sample $i + N + L$). Moving sum unit are used for this purpose. Since synchronization system must contain unit calculating (12), averaging can be applied directly to $\hat{\theta}$ or $\hat{\theta}_{ML}$.

An advanced synchronization mechanism is demonstrated in the model from [18]. The output of CP-based symbol timing ML estimator is fed to the control loop which manages frequency of receiver A/D sampler. Such solution ensures continuous and adaptive timing offset tracking. An implicit averaging of timing occurs in proportional-integral-derivative controller (PID controller). The output of ML estimator is used for coarse symbol timing only. The slope of channel phase estimate (see section V) is exploited to provide fine symbol timing adjustments.

Another solution aimed to reduce symbol timing variance is proposed in [19]. Symbol timing estimation in that paper is based on the observation that in case of time-dispersive channel, correlation function (11) is the sum of correlation functions over separate paths l . It is shown that correct timing moment is in the point where combined correlation function just starts to decrease. However, this point coincides with correlator output maximum and if symbol timing estimator uses maximum search algorithm as stated in (12) (but not threshold scheme) it gives correct output as well.

In papers [20-22] an iterative algorithm based on expectation-maximization (EM) [23] is proposed to solve the problem of symbol delay and phase rotation estimation. The algorithm rapidly converges to the true ML estimation of unknown parameters. The algorithm iterates back and forth, using the current timing and phase estimates to decompose the observed data better and thus improves the next timing and phase estimates.

Pulse shaping has been proposed for improving sidelobe suppression in [24]. In paper [25] the model described in [16] is extended to a more general model that covers also arbitrary pulse shapes and interference from neighboring time slots. In the corresponding OFDM system first N_{SH} samples and last N_{SH} samples are multiplied with raised cosine. Results of simulations in [25] show that it is possible maintain and even improve (by approx. 10% in a channel with fading) the quality of synchronization in systems with pulse shaping.

Simulation results of the CP based symbol timing estimators described here are given in figure 2. The impact of the averaging can be observed in the same graphs.

IV. Carrier frequency estimation

OFDM systems are sensitive to the carrier frequency offset. A small frequency offset causes phase rotation of received data symbols with frequency equal to the difference of transmitter's and receiver's oscillator frequencies. They can be corrected by the frequency

domain equalizer. Large frequency offsets cause translation of OFDM subcarriers and lead to the loss of subcarrier orthogonality.

Difference in carrier frequencies caused by difference in oscillator frequencies (conversion from radio frequency (RF), A/D sampler) causes rotation of constellation obtained after DFT in receiver. Classical frequency estimation methods involve measurements of pilot symbol phase rotation speed. Such method is described, for example, in [3]. Proposed synchronization scheme for wireless LAN is based on correlation of time-domain images of two equal successive pilot symbols used for channel estimation (see section V). A pilot symbol (symbol whose all subcarriers $d(n)$ are pilots with magnitude 1) in time domain can be represented by inverse DFT given by (2). Let T be symbol period and Δf_c carrier frequency offset. Phase offset during one symbol is given as:

$$\phi = \Delta f_c T \quad (14)$$

If there is no frequency offset, the correlation between two symbols is given by:

$$J_0 = \sum_{k=0}^{N-1} r(k)r^*(k+N) = \sum_{k=0}^{N-1} |r(k)|^2 \quad (15)$$

where $r(k)$ denotes received pilot samples and $r^*(k)$ denotes complex conjugate. In fact this is a similar operation to CP correlation described by (8). If frequency offset is present, the correlator output is:

$$J = J_0 e^{-j2\pi\phi} \quad (16)$$

So phase offset can be estimated:

$$\phi = \frac{1}{2\pi} \angle \left(\frac{J^*}{|J|} \right) \quad (17)$$

where \angle denotes the angle of complex argument. This method works for $\phi < 1$ only. For coarse frequency offset estimation, authors of [3] propose to correlate frame sync symbols (short symbols) in adjacent frames:

$$G = \sum_{k=0}^{\frac{N}{4}-1} r(k)r^*\left(k + \frac{N}{4}\right) = e^{-j2\pi\frac{\phi}{4}} \sum_{k=0}^{\frac{N}{4}-1} |r(k)|^2 \quad (18)$$

$$\frac{\phi}{4} = \frac{1}{2\pi} \angle \left(\frac{G^*}{|G|} \right) \quad (19)$$

Since the correlator uses four times shorter signals there is no ambiguity of determining ϕ even in case of large frequency offsets (100ppm). Due the same reason the method is less accurate.

The same effect can be achieved by correlating cyclic prefix and beginning of any data symbol. According to formula (10), the frequency offset can be found by taking the angle of correlator output signal at moments when it

achieves the magnitude maximum. This method in details is described in section III. Simulation results shown in section VII prove usability of this concept.

By combining coarse and fine frequency estimation we can obtain required performance:

$$\phi = \frac{4}{2\pi} \angle \left(\frac{G^*}{|G|} \right) + \frac{1}{2\pi} \angle \left(\frac{J^*}{|J|} \right) \quad (20)$$

V. Channel estimation

In an OFDM link separate carriers are modulated by some form of *phase shift keying* (PSK) or *quadrature amplitude modulation* (QAM). To decode binary information modulated by these techniques, details of the reference phase and amplitude are required. In a real communication system with delay, multipath and reflection, phases and amplitudes of the received subchannels are randomly changing. To cope with this problem two different approaches exist. One could use differential modulation (DPSK or DQAM) and measure changes between successive symbols. This technique lets to avoid equalization, but the price of this simplicity is reduced throughput. Another approach is coherent detection, which uses estimates of the reference amplitudes and phases to determine boundaries for the constellation of each subchannel.

OFDM channel estimation is relatively simple due the flat fading characteristics of single OFDM subcarriers. The aim of the channel estimator is calculation of complex attenuation of each subcarrier. The output of channel estimator is used for driving *channel equalizer* (frequency domain equalizer).

In order to perform channel estimation, the pilot tones must be inserted into certain subcarriers or even whole OFDM symbols. Since single subcarriers are nearly flat fading, channel estimation can be done in a straightforward way like it is done in single carrier systems. A modulation technique using pilot tones for channel estimation is called *pilot-symbol assisted modulation* (PSAM). There are basically several techniques of pilot symbol insertion:

- Pilot symbols are inserted in certain subcarriers of all OFDM symbols. When the correct symbol timing of OFDM receiver is established, the receiver extracts these subcarriers and measures pilot attenuation. These attenuations are interpolated with neighboring data subcarriers in channel equalizer.
- Dedicated symbols containing pilots in all subcarriers are inserted between information symbols. The attenuation of these symbols is measured in the receiver. The attenuation of successive symbols in received information is interpolated from pilot measures using time and frequency correlation properties of fading channel. This method requires an one additional synchronization level, since a mechanism to notify receiver about the time instants of pilot symbol transmission is required. Frame synchronization helping

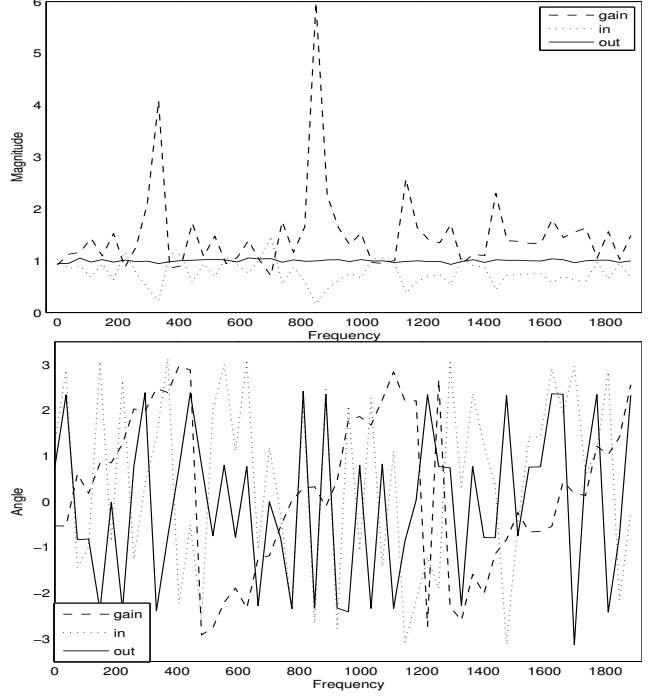


Figure 3 Simulation of equalization of 5-th OFDM data symbol containing random QPSK-modulated user data. Gains are estimated using channel estimator based on (24). Gain, in, out stands for equalizer gain, input signal, output signal, respectively.

to detect pilot symbol transmission times is discussed in section VI.

- Pilot symbols may be scattered, i.e. appear in particular subcarriers and particular frames only. In this case channel estimator must perform interpolation in both time and frequency. Such solution discussed in [26] is based on two Wiener FIR filters.

A discrete time signal transmitted over a communication channel using N subcarriers can be modeled using (1). The Fourier transform of discrete impulse response $h(k)$ of n -th frequency channel is given by:

$$H(n) = \frac{1}{\sqrt{\Delta}} \sum_{k=0}^{\Delta} h(k) e^{-j2\pi n \frac{k}{\Delta}} \quad (21)$$

where Δ is the length of channel impulse response (i.e. the length of the channel). A signal received on the n -th subcarrier can be expressed as:

$$r(k) = s(k) * h(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} H(n) d(n) \phi(n, k) \quad (22)$$

Note that equations (1) and (22) are similar, except that the n -th subcarrier modulates $H(n)d(n)$ instead of $d(n)$. Received data (disregarding additive noise) then has the form

$$p(n) = H(n)d(n) \quad (23)$$

Lets mark known pilot subcarriers sent by transmitter as $d_p(n)$ and received pilot subcarriers as $p_p(n)$. The channel estimate can be easily found using expression:

$$\hat{H}(n) = \frac{p_p(n)}{d_p(n)} \quad (24)$$

Formula (24) shows that all complex channel gains $\hat{H}(n)$ can be obtained by element-wise division of received pilot symbols by sent ones. Channel gains are used by channel equalizer to compensate amplitude and phase impairments caused by the communication channel. If we have estimated channel gains $\hat{H}(n)$ for all n , they can be applied directly. Sent symbols can be restored using formula:

$$d(n) = \frac{p(n)}{\hat{H}(n)} = \frac{\hat{H}(n)^*}{|\hat{H}(n)|^2} p(n) \quad (25)$$

Simulation of communication system utilizing such equalizer is presented in figure 3. Such, pilot symbol based, channel equalizer performs well in slowly changing communication channel. If channel characteristics are changing rapidly, insertion of additional pilot subcarriers is required. Since pilots are only on few subcarriers, frequency domain interpolation of channel gains is required. Moreover, if pilots are sparse (i.e. appear in certain subcarriers from time to time), time domain interpolation is necessary as well.

Notice that pilot spacing must satisfy the well-known *Nyquist sampling theorem*, which states that the sampling interval must be smaller than the inverse of the double-sided bandwidth of the sampled signal. The maximum Doppler spread B_d must be taken into account when calculating pilot spacing in the time domain $T_t < 1/B_d$, and the maximum delay spread B_τ must be taken into account when calculating pilot spacing in the frequency domain $T_f < 1/B_\tau$. For example, in the wireless LAN systems [6] pilots are transmitted continuously in subcarriers number -21, -7, 7, and 21, and the spacing between pilots is 4.375MHz. In these conditions, the maximum delay spread $B_{\tau max}$ to be allowed is 228 ns and the Doppler spread has no limitations.

Various strategies can be used to get the best least square (LS) estimate of channel. In paper [1] an overview of DFT based and *Singular value decomposition* (SVD) based estimators is given.

The optimal *linear minimum mean-squared error* (MMSE) estimate of H (minimizing $E \|\hat{H} - H\|^2$) is described in [27]. This estimator based on SVD and the theory of optimal rank reduction are of small practical value due the high complexity of implementation. However, it can be used as a basis for simplified solutions ([28], [29]).

Interesting results can be found in publication [30]. This paper addresses pilot tone selection and location in OFDM signal structure. A channel with the length Δ and N pilot subcarriers is considered. It is proven there that:

- in the absence of noise any Δ of N available pilot tones can be used for training to recover the channel exactly;
- in *time-invariant* channel the performance of scheme where all pilot tones are periodically inserted in one

symbol and of scheme where few pilot tones are in each symbol is the same;

- in *time-variable* channel it is better to transmit few pilot subcarriers in each symbol than to put pilots together in one symbol.

Pilots inserted into particular subcarriers are well suited to systems with continuous transmission, for instance, digital broadcasting. However, for packet switching systems such as wireless LAN there are difficulties with channel estimation at the beginnings of received packets. To avoid the loss of information, pilot symbols where all subcarriers are used as pilots must be transmitted at the beginning of each frame. For instance, in IEEE 802.11 [6] two pilot symbols (long symbols) are transmitted.

VI. Frame timing

There are several methods how to provide frame synchronization in an OFDM based communication system. The most obvious way is to introduce some kind of time stamp into OFDM signal time domain. In IEEE 802.11a based WLANs [6] special symbols (short symbols) are used to mark the beginnings of frames. The symbols are created in the following manner. Two equal successive frequency-domain symbols are generated using the pattern:

$$1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0.$$

After particular standard-specific subcarrier shifting, short symbols get transformed into time domain by means of inverse DFT. In time domain a short symbols have remarkable correlation characteristics (figure 4).

The OFDM receiver exploits these characteristics for searching the beginnings of OFDM frames. The receiver continuously correlates the incoming sample stream with the short symbol pattern. Due the periodic nature of these time domain symbols, when the short symbol is received, the correlator outputs 10 peaks with an interval of 16 samples. This pattern together with the 80 sample wide plateau (figure 5) generated by symbol timing autocorrelator (see section III) are used as flags for signaling the beginning of OFDM frame. In section VII the short symbol correlator (6) and symbol timing autocorrelators are simulated

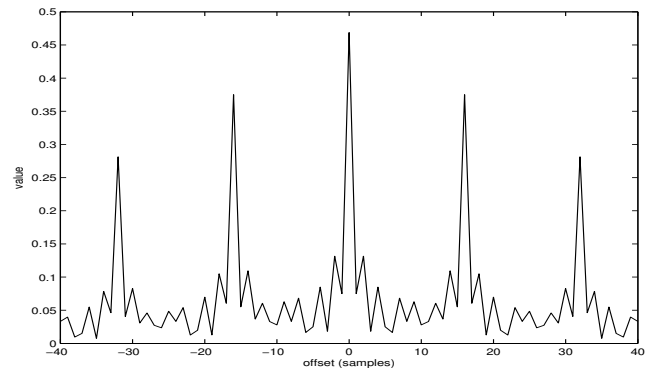


Figure 4: Autocorrelation function of short symbols used in IEEE802.11a

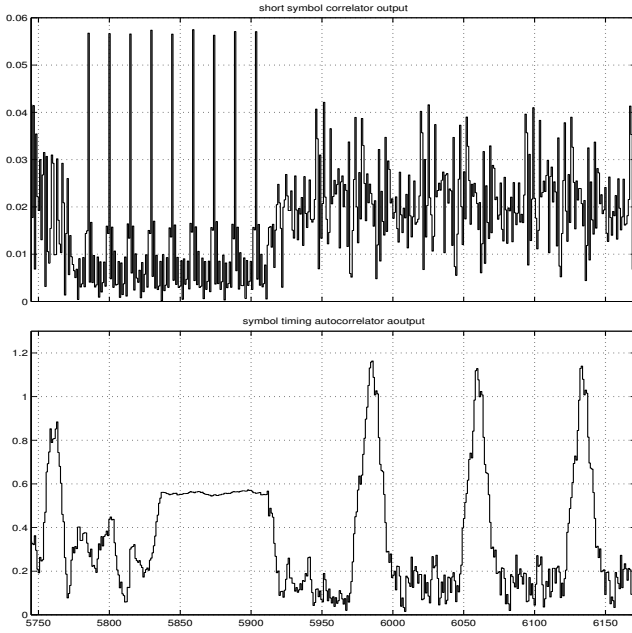


Figure 5. Timing-related correlator outputs: frame sync correlator (top), CP autocorrelator (bottom).

Actually, search of frame boundaries can be performed after symbol timing estimation (section III). In this case the short symbol correlator for 802.11a would correlate the short symbol pattern not with the stream of samples but with the whole 80-sample long OFDM symbol (containing 5 repeating short symbol patterns). Correlator output would generate 2 large peaks. However, this scheme is of low practical value since short symbols can be exploited for coarse frequency offset measurement before symbol timing estimation and automatic gain control (AGC).

In paper [31] an advanced scheme of frame and symbol timing is proposed. Authors introduce an additional synchronization frame - *burst frame* containing an additional guard interval and pilot tones to enable fast and precise symbol timing estimation during one OFDM symbol. In accordance with simulation results in [31] this scheme significantly outperforms classical synchronization schemes in multipath Rayleigh fading channel.

In widely-cited paper [32] by Schmidl and Cox, authors propose to use two special training symbols. The first symbol in time domain consists of two equal parts. It is generated by filling even subcarriers with pseudo noise (PN) sequence and setting odd subcarriers to zero. The symmetry of OFDM symbol makes it immune to carrier frequency offsets and makes possible fast detection of frame start. Moreover, values on even subcarriers allow to make channel measurements on these frequencies. The second symbol consists of two another PN sequences. They will help to measure remaining (odd) frequencies and calculate the frequency offset.

VII. Simulation results

Since we are working on practical implementation of communication system, numerous simulations are necessary to verify theoretical conclusions and join separate parts together into single system. For testing various aspects of synchronization, multiple *Simulink* models were created. Due to space limitations, simulation results of a few models only are presented here.

A Simulink model of communication system containing OFDM transmitter, AWGN channel and receiver was constructed. The simulated OFDM system uses 80 samples long symbols including CP of 16 samples. Frame sync symbols uses the same pattern as described in section VI. Pilot symbols for channel estimation use the same pattern as 802.11a WLAN systems [6]: 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 0, 1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, 1, 1, 1.

Three different symbol timing estimators - *difference based* (6), *simple autocorrelation* (8) and *maximum likelihood* (12) were compared. Figure 2 reflects simulation results.

Figure 3 demonstrates the work of channel estimator and channel equalizer. The transmitter sends 4 successive equal OFDM symbols carrying only pilots and after that sends 20 symbols with random data. The communication channel has static randomly valued complex gain and additive noise (SNR=12dB). The channel estimator estimates the channel gain using 4 measures of received pilot symbols (24). Measured complex channel gains (commonly referred to as Channel State Information (CSI)) are passed to the channel equalizer which does averaging of measures and calculation of transmitted QPSK data symbols in accordance with formula:

$$d(n) = \frac{\widehat{H}(n)^*}{|\widehat{H}(n)|^2} p(n) \quad (26)$$

By averaging over four OFDM symbols, the effects of noise on the channel estimation process can be reduced.

Finally, data transmission over a stationary channel

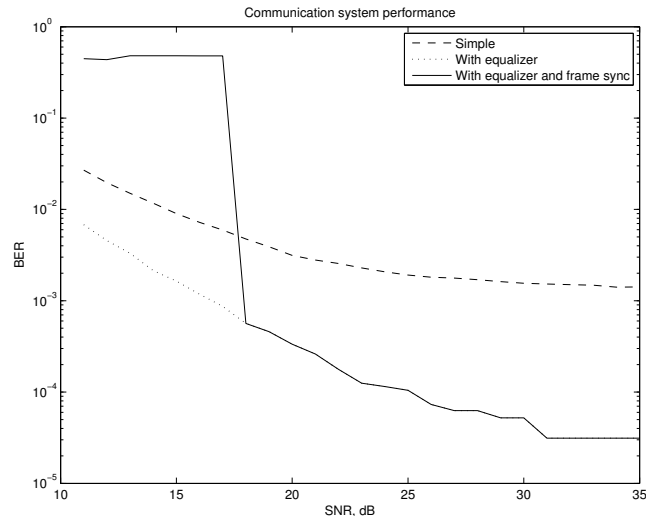


Figure 6 Performance of three different communication systems. Impact of equalizer and synchronization.

with random magnitude and phase characteristics is simulated. *Bit Error Rates* (BER) of three different communication systems are compared. All systems use parallel symbol transmission, i.e. data from transmitter to receiver are passed as 80-sample vectors. No symbol synchronization is needed. The first system does not have a channel estimator and equalizer at all. The second system has a channel estimator and equalizer and offers best results. Implicit frame synchronization happens, since the receiver and the transmitter start simultaneously and frame clocks are equal. The third model reflects a more real communication system where the transmitter and the receiver could start independently. The receiver detects the beginnings of frames using the short symbol detection method described in section VI. Simulation results show that the introduction of channel estimation gives a huge BER improvement. At SNR 30dB the BER improvement is more than 10 times. From figure 6 we also can notice that the frame synchronization scheme fails when SNR is less than 17dB at the input of the receiver.

VIII. Conclusion

A simple OFDM communication system model without synchronization can be built using modern modeling tools such as Simulink rather easy. However, the introduction of synchronization into the system significantly complicates the task. Multiple synchronization tasks in an OFDM system are mutually dependent and must be performed simultaneously with high level of accuracy.

- CP ML estimation (12) provides a robust method for coarse symbol timing and carrier frequency estimation.
- Fine tuning of symbol timing can be done using the slope of the channel phase estimate (10).
- Precise frequency synchronization can be provided using pilot symbol phase rotation measurements via pilot symbol autocorrelation (20).
- Channel equalization dramatically improves communication system performance. Slowly changing channel estimation and equalization can be done by means of pilot symbols sent in certain frame positions (24).
- Rapidly changing channels with fading and multipath certainly require utilization of pilot subcarriers [30].

Building an industry-grade OFDM synchronization system model requires introduction of series of automatic control loops for AGC, tracking of symbol timing and frame synchronization.

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A.Āboltiņš, D.Kļaviņš. Sinhronizācija uz OFDM balstītā sakaru sistēmā: īss pārskats.

Dotā raksta mērķis ir sniegt pārskatu par visiem sinhronizācijas uzdevumiem, kas parādās uz OFDM (ortogonālā frekvenču blīvēšana) balstītā sakaru sistēmā. Ir aprakstīti simbolu sinhronizācijas un frekvenču sinhronizācijas risinājumi sistēmās ar ciklisko prefiksu (CP). Ir aprakstīta vienkārša, uz pilot-toniņiem balstīta kanāla novērtēšanas sistēma, kā arī ir sniegti šīs sistēmas simulācijas

rezultāti. Ir salīdzinātas dažādu autoru piedāvātās alternatīvas kanāla novērtēšanas metodes. Ir doti pamata sinhronizācijas uzdevumu simulācijas rezultāti. Ir veikta sakaru sistēmu, kas izmanto dažādas sinhronizācijas metodes, simulācija programmā Simulink, un ir noteiktas bitu kļūdu intensitātes. Ir apskatīta aditīva trokšņa, daudzstaru izplatīšanās un Releja pāmīrumu ietekme uz sinhronizāciju. Ir izceltas OFDM sinhronizācijas mehānismu uzlabošanas metodes.

А.Аболтинш, Д.Клявинш. Синхронизация для системы связи основанной на OFDM: краткий обзор.

Цель данной статьи представить обзор и описание всех задач синхронизации возникающих в системах связи основанных на OFDM (мультиплексирование с ортогональным частотным разделением). Описаны решения символьной и частотной синхронизации в системах с циклическим префиксом (CP). Дано описание и представлены результаты симуляции простого метода оценки канала основанного на пилот-сигналах. Сравнены альтернативные способы оценки канала предложенные разными авторами. Представлены результаты симуляции главных задач синхронизации. Описаны результаты симуляции в программе Simulink систем связи использующих разные методы синхронизации, а также определены соответствующие интенсивности ошибок. Произведен обзор влияния аддитивного шума, многолучевого распространения и Рэлеевского замирания на синхронизацию. Выделены методы улучшения механизмов синхронизации OFDM.