ORTHOGONAL FREQUENCY DIVISION MULTIPLEX SYNCHRONISATION TECHNIQUES FOR WIRELESS LOCAL AREA NETWORKS

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ABSTRACT

A range of frequency acquisition, frequency tracking, symbol synchronisation and frame synchronisation techniques are proposed and evaluated for employment in 155 Mbit/s, 60 Ghz local area networks. The algorithms are based on two correlation functions, exhibit a moderate implementational complexity and high robustness against channel noise.

1. INTRODUCTION

The fundamental principle of orthogonal multiplexing originates from Chang [1], and over the years a number of researchers have investigated this technique, which is portrayed in depth in Reference [2]. Despite its conceptual elegance, until recently its employment has been mostly limited to military applications due to implementational difficulties. However, it has recently been adopted as the new European satellite-based Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB) and Digital Terrestrial Broadcasting (DttB) standard. In this contribution we report on its applicability for Wireless Local Area Networks (WLANs) in the 60 GHz frequency range in the context of the Pan-European MEDIAN project [3], providing a wireless extension of the 155 Mbit/s Asynchronous Transfer Mode (ATM) network.

The Orthogonal Frequency Division Multiplexing (OFDM) technique is a form of Code Division Multiplexing, using a set of $N \in \mathbb{N}$ mutually orthogonal signals $c_n(t)$ in order to transmit a number of data-symbols in parallel over a period of time given by the symbol duration T_s. Here we refrain from detailing the associated modulation aspects and refer the reader for a deeper discussion on the topic to [2]. Instead, we focus our attention on a range of synchronisation techniques, which are required for supporting coherent operation.

Section 2 introduces the multiple access frame structure, Section 3 provides a brief synchronisation over-

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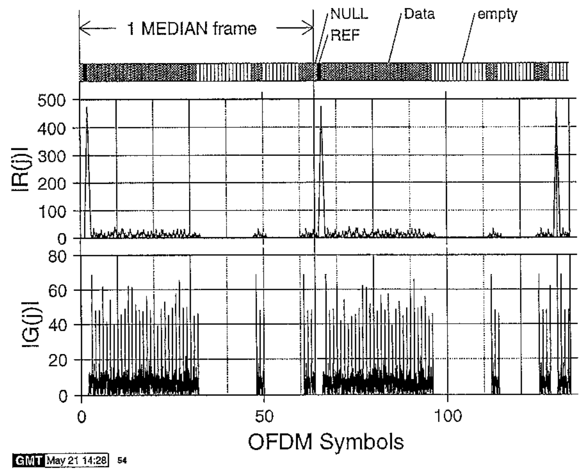


Figure 1: Time synchronisation: Plots of $R(j)$ and $G(j)$ for two consecutive MEDIAN frames under perfect channel conditions

view, while Section 4 describes the properties of the correlation functions used in the frequency acquisition, frequency tracking, symbol synchronisation and frame synchronisation techniques of Sections 5 and 6.

2. MULTIPLE ACCESS FRAME STRUCTURE

The proposed multiple access frame structure is depicted at the top of Figure 1, and is constituted by a Null-, a Reference- and 62 Data-symbols. Let us initially consider the role of the Reference symbol.

The reference symbol shown in Figure 2 was designed to assist in the operation of the synchronisation scheme and consists of repetitive copies of a synchronisation pattern SP of N_s pseudo-random samples. Note therefore that there are three hierarchical periodic time-domain structures in the proposed framing scheme, the short-term intrinsic periodicity in the reference symbol of Figure 2, the medium-term periodicity associated with the quasi-periodic extension of the OFDM symbols and the long-term periodicity of the OFDM

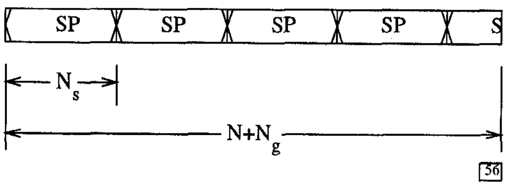


Figure 2: Reference symbol, consisting of consecutive copies of a synchronisation pattern (SP) in the time domain

frame structure, repeating the reference symbol every 64 OFDM symbols as portrayed in Figure 1. The long–term reference symbol periodicity is exploited to maintain OFDM frame synchronisation, while the medium–term synchronism of the cyclic extension assists in the process of OFDM symbol synchronisation. A detailed discussion of this Figure will be provided during our further discourse. Let us initially consider the macroscopic structure of the synchronisation system in the next Section.

3. SYNCHRONISATION

The sychronisation system of a frame–based OFDM modem has to ensure both time and frequency synchronisation. The time synchronisation has to establish both the frame–timing and the FFT window alignment of the received sample stream. The task of the frequency synchronisation is to preserve the orthogonal properties of the sub-carriers, since a frequency error results in inter-carrier interference. Generally, this frequency synchronisation is performed in two steps in order to reduce the overall complexity. The frequency acquisition requires more computational complexity and more redundancy in the transmitted signal, while the frequency tracking employs algorithms with lower frequency capture ranges, but requires less complexity and redundancy. The block diagram of the synchronisation system is shown in Figure 3. The downsampling and clock recovery module **DS** has to determine the optimum sampling instant. The time synchronisation **TS** controls the frequency acquisition **FA** and frequency tracking **FT** as well as the time domain alignment of the FFT window, which is carried out by the **RP** block, removing the prefix, as suggested by the Figure. Since at the beginnning of the synchronisation process neither the frequency error nor the timing information are known, hence synchronisation algorithms must be found that are robust to initial timing- and frequency-errors. Following this rudimentary macroscopic synchronisation overview, in the next Section let us now introduce the required correlation functions, which can be invoked to quantify the time- and frequency synchronisation error.

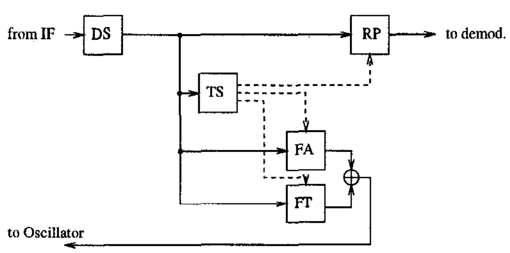


Figure 3: Block diagram of the synchronisation system: **DS**–down-sampling and clock recovery, **TS**–time synchronisation, **FA**–frequency acquisition, **FT**–frequency tracking, **RP**–remove cyclic extension prefix

4. TIME– AND FREQUENCY–SYNCHRONISATION BY AUTOCORRELATION

In what follows, we will show that both the frequency and the time synchronisation control signals can be derived from the received signal samples' cyclic nature, detected by means of autocorrelation techniques. The specific algorithms proposed for the symbol timing and fine frequency tracking were advocated for the MEDIAN system by P. Mandarini and A. Falaschi [4]. Originally, Moose [5] proposed an synchronisation algorithm using repeated data symbols, and methods for the frequency error estimation using the cyclic extension of OFDM symbols were presented by Daffara *et al.* [6] and Sandell *et al.* [7]. Frequency acquisition and frame synchronisation can be established on the basis of similar principles, aided by the dedicated reference symbol of Figure 2, as it will be highlighted during our forthcoming discussions.

Again, for the proposed algorithms no a-priori knowledge of the synchronisation sequences is required, since only the repetitive properties of the OFDM symbols and those of the so–called reference symbol of the proposed frame structure seen in Figure 2 are exploited. All the processing is carried out in the time domain, hence no FFT based demodulation of the reference symbol is necessary.

4.1. The Correlation Functions

The synchronisation algorithms rely on the evaluation of the correlation functions $G(j)$ and $R(j)$, where j is the index of the most recent input sample:

$$G(j) = \sum_{m=0}^{N_g-1} z(j-m) \cdot z(j-m-N)^* \qquad (1)$$

$$R(j) = \sum_{m=0}^{N+N_g-N_s-1} z(j-m) \cdot z(j-m-N_s)^* \qquad (2)$$

where $z(j)$ are the received complex signal samples, N is the number of sub-carriers per OFDM symbol, N_g is

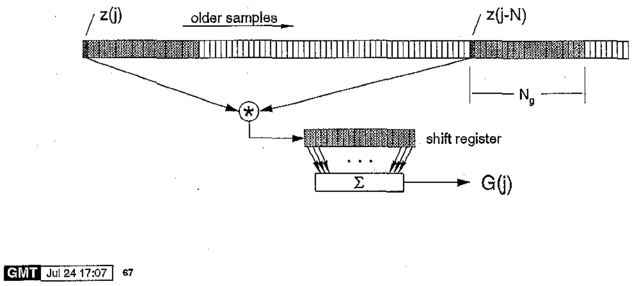


Figure 4: Schematic plot of the computation of the correlation function $G(j)$. The gray area represents the memory of the shift register

the length of the cyclic extension and N_s is the periodicity within the reference symbol, as seen in Figure 2. The asterisk * denotes the conjugate of a complex value.

$G(j)$ is used for both frequency tracking and OFDM symbol synchronisation, expressing the correlation between two sequences of N_g samples length spaced by N in the received sample stream, as shown in Figure 4. The second function, $R(j)$, is the corresponding expression for the reference symbol, where the period of the repetitive synchronisation pattern is N_s, as seen in Equation 2 and Figure 2. In this case, $(N_g + N - N_s)$ samples are taken into account for the correlation, which are spaced by a distance of N_s samples. Having defined the necessary correlation functions for quantifying the time- and frequency synchronisation error, let us now concentrate on how the synchronisation algorithms rely on their evaluation.

5. FREQUENCY TRACKING AND OFDM SYMBOL SYNCHRONISATION

In this Section we consider details of the frequency tracking and OFDM symbol synchronisation algorithms which make use of $G(j)$, as defined by Equation 1.

5.1. OFDM symbol synchronisation

The magnitude of $G(j_{max})$ is maximum, if $z(j_{max})$ is the last sample of the current OFDM symbol, since then the guard samples constituting the cyclic extension and their copies in the current OFDM symbol are perfectly aligned in the summation windows. Figure 1 shows the simulated magnitude plots of $G(j)$ and $R(j)$ for two consecutive MEDIAN frames, with $N = 512$ and $N_g = N_s = 50$, under perfect channel conditions. The observed correlation peaks of $|G(j)|$ can be easily identified as the last sample of an OFDM symbol. The simulated accuracy of the OFDM symbol synchronisation in an AWGN channel is characterised in Figure 5. Observe in the Figure that for SNRs in excess of about 7dB the histogram is tightly concentrated around

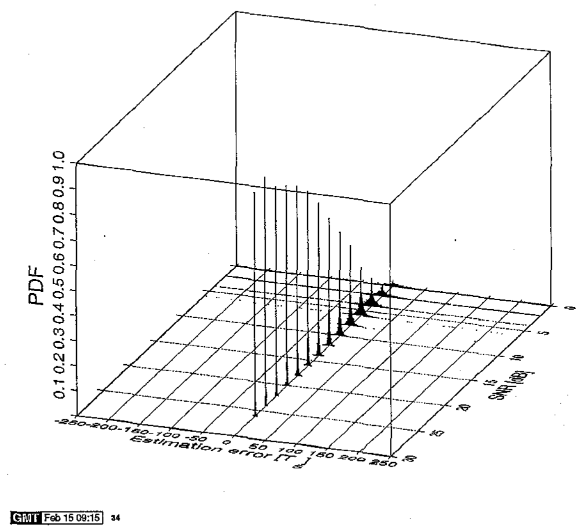


Figure 5: Histogram of the symbol timing estimation errors normalised to the sample interval T_s in an AWGN channel for $N = 512$ and $N_g = 50$ with no low-pass filtering of the estimates

the perfect estimate, typically resulting in OFDM symbol timing estimation errors below $\pm 20T_s$. However, as even slightly misaligned time domain FFT–windows cause phase errors in the frequency domain, this estimation accuracy is not sufficient. To improve the OFDM symbol timing synchronisation, the estimates must be low–pass filtered. Let us now concentrate on the issues of frequency tracking.

5.2. Frequency tracking

A carrier frequency error of δf results in an evolving phase error $\Psi(j)$ of the received samples $z(j)$:

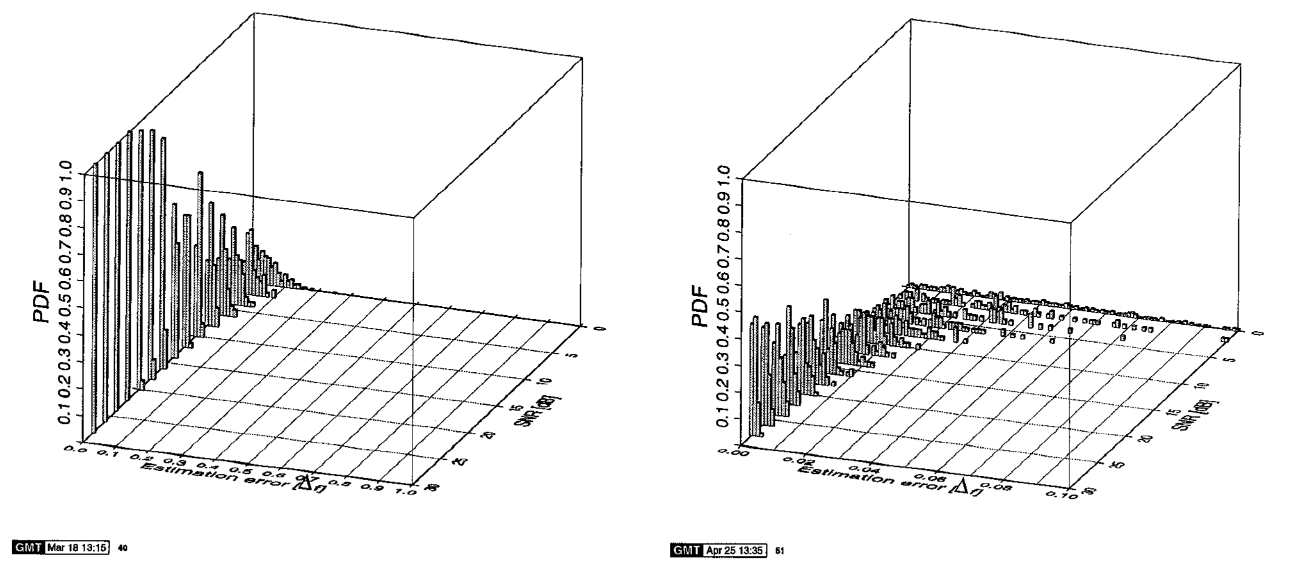
$$\Psi(\delta f, j) = 2\pi\delta f \cdot j \cdot T_s \quad (3)$$

$$= 2\pi\frac{j\delta f}{N\Delta f}. \quad (4)$$

Clearly, the phase error difference between two samples $z(j_1)$ and $z(j_2)$ is a function of the frequency error and their time delay, and is given by $\Psi(\delta f, j_2) - \Psi(\delta f, j_1) = \Psi(\delta f, |j_2 - j_1|)$. If the original phase difference between the two symbols $z(j_1)$ and $z(j_2)$ is known, and all other phase distortion is absent, the phase difference error can be used to determine the frequency error δf.

As the time–domain samples of the cyclic extension or the guard interval are known to be a copy of the last N_g data samples of the OFDM symbol, the frequency error can be estimated using each of these N_g pairs of identical samples. To improve the estimation accuracy in noise, averaging can be carried out over the N_g estimates.

The phase of $G(j)$ at $j = j_{max}$ equals the averaged phase shift between the guard time samples and



(a) frequency acquisition

(b) frequency tracking

Figure 6: Histogram of the simulated frequency estimation error for the frequency acquisition and frequency tracking algorithms using $N = 512$ and $N_s = N_g = 50$ over AWGN channels

the corresponding data samples of the current OFDM symbol. As the corresponding sample pairs are spaced by N samples, rearranging Equation 4 leads to the fine frequency error estimation δf_t given by:

$$\delta f_t = \frac{\Delta f}{2\pi} \cdot \measuredangle G(j_{max}). \tag{5}$$

Because of the 2π ambiguity of the phase, the frequency error must be smaller than $\Delta f/2$. Therefore, the frequency acquisition must ensure a rough frequency error estimate with an accurracy of better than $\Delta f/2$.

Assuming perfect estimation of the position j_{max} of the correlation peak $G(j_{max})$, as we have seen in Figure 1, the performance of the fine frequency error estimation in an AWGN environment is shown in Figure 5.1. Observe that for AWGN SNR values above 10dB, the estimation error histogram is concentrated to errors below about $0.02\Delta f$, where Δf is the sub-carrier spacing.

Having resolved the issues of OFDM symbol synchronisation and fine frequency tracking, let us now focus our attention on the aspects of frequency acquisition and frame synchronisation.

6. FREQUENCY ACQUISITION AND FRAME SYNCHRONISATION

The frequency acquisition and MEDIAN frame synchronisation are based on the same algorithms as the fine frequency and OFDM symbol synchronisation. However, instead of using the medium–term periodicity of the cyclic extension of the OFDM data symbols, the dedicated reference symbol with shorter cyclic period $N_s < N$ is exploited to improve the frequency capture range.

6.1. Frame synchronisation

Similarly to the OFDM symbol synchronisation, the magnitude of $R(j)$ in Equation 2 and Figure 1 is maximum, when the periodic synchronisation segments SP of length N_s of the reference symbol shown in Figure 2 perfectly overlap. Again, the magnitude of $R(j)$ for two simulated MEDIAN frames is shown at the top of Figure 1. The OFDM frame timing is synchronised with the peak of $R(j)$, which can additionally be taken into account for the OFDM symbol synchronisation.

6.2. Frequency acquisition

The frequency acquisition uses the same principle as the frequency tracking scheme of Section 5.2. Specifically, the phase of $R(j)$ at the last sample of the reference symbol j_{max} contains information on the frequency error:

$$\measuredangle R(j_{max}) = 2\pi \cdot \delta f_a \cdot N_s \cdot T_s = 2\pi \cdot \delta f_a \cdot \frac{N_s}{N \cdot \Delta f} \tag{6}$$

leading to

$$\delta f_a = \frac{N}{N_s} \frac{\Delta f}{2\pi} \cdot \measuredangle R(j_{max}). \tag{7}$$

Because the spacing between the sample pairs used in the computation of $R(j)$ is smaller than in the case

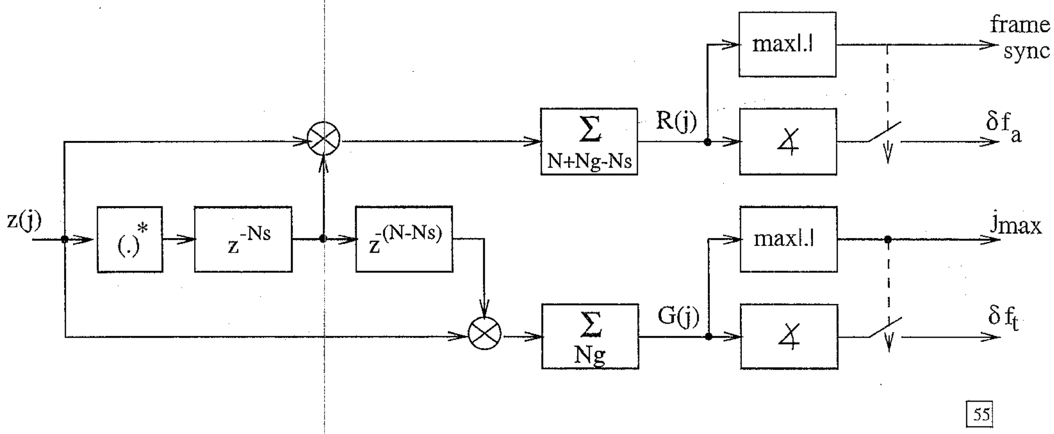


Figure 7: Block diagram of the synchronisation algorithms

of $G(j)$, which was used for the frequency tracking ($N_s < N$), the maximum detectable frequency error is now increased from $\Delta f/2$ to $N/N_s \cdot \Delta f/2$, where Δf is the sub-carrier spacing of the OFDM symbols. The simulated performance of the frequency acquisition algorithm for $N = 512$, $N_s = 50$ and perfect time synchronisation is shown in Figure 5.1 for transmissions over an AWGN channel. As seen in the Figure, the scheme maintains an acquisition error below $\Delta f/2$ even for SNR values down to 0dB, which exceeds the system's operational specifications.

7. SUMMARY AND CONCLUSIONS

In summary of our previous elaborations, Figure 7 shows the detailed block diagram of the synchronisation algorithms. The received samples are multiplied with the complex conjugate of the delayed input sequences, and summed up over $(N + N_g - N_s)$ and N_g samples, respectively. The magnitude maxima of the two sequences $G(j)$ and $R(j)$ are detected, and these trigger the sampling of the phase estimates $\measuredangle G$ and $\measuredangle R$ in order to derive the two frequency error estimations δf_a and δf_t. The algorithms are robust against the effects of noise and our future work is targeted at evaluating their performances over fading channels.

8. ACKNOWLEDGEMENT

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