

# Coarse Frame Synchronisation for OFDM based Wireless Communication Systems

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## ABSTRACT

This paper presents a method to fast and easily detect the beginning of a frame which is based on a special frame synchronisation symbol. The method is primarily useful for OFDM systems but can be applied for other systems as well. The implementation can be done with a low power analogue circuit which generates an event that is independent from the remaining signal processing, thus allowing to switch of the unused circuitry. A digital solution is also given. It will be shown that the method is sufficiently reliable for most wireless communication systems under consideration.

## I. INTRODUCTION

The interest in the *asynchronous transfer modus* (ATM) has been growing over the last years due to its ability to efficiently deliver all kinds of multimedia services with only one technology. Another trend in communications is to provide wireless access to all kinds of networks which reduces infrastructure costs and gives the added value of mobility. Accordingly, big efforts were made during the last years to extend ATM for wireless transmission ([1], [2], [3], [4]). Standardisation activities for wireless ATM (W-ATM) systems are going on at the ATM Forum and at ETSI (cf. e.g. [6]).

The main challenges in W-ATM system design are the medium access control (MAC) protocol and the physical layer. Both layers must be designed together in order to optimise system performance. OFDM has been identified as a candidate physical layer technology. The main application area of OFDM so far has been broadcasting, e.g. Digital Audio Broadcast (DAB) and Digital Video Broadcast (DVB).

The frame synchronisation in both DAB and DVB systems is performed using the so called null symbol, i.e. no energy is transmitted within the duration of a symbol [7]. This is possible because the null symbol is unique within the structure on the air interface. Since W-ATM systems are bi-directional communication systems, some aspects of OFDM require further investigation. One critical issue that is caused by the structure of the MAC protocol is the frame synchronisation because it entails that the null symbol is not unique. The MAC under consideration, however, is not the actual subject of this contribution. Nevertheless, the knowledge of some of its basic

properties is necessary in order to understand the new requirement for the frame synchronisation.

The purpose of this contribution is to present a new approach to solve the above described problem. In the first section, the underlying MAC protocol is explained shortly, followed by a description of the frame synchronisation concept. Two different approaches for its realisation are presented, one digital and one analogue solution. For both concepts, the detection algorithm and the performance are given. A summary and an outlook concludes the paper.

## II. MAC PROTOCOL DSA++

In this section a brief overview of the DSA++ protocol is given, only emphasising those items which are important for further understanding. A more detailed description can be found in e.g. [8].

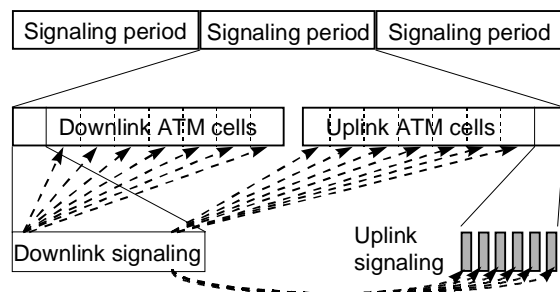


Figure 1. Basic MAC signalling scheme DSA++

The basic principle of the considered MAC protocol is shown in Figure 1. Downlink and uplink are separated by time division duplexing (TDD) and the channel is shared using a dynamic TDMA (time division multiple access) scheme. One down- and uplink together are called a signalling period (SP). The whole SP is determined by the downlink signalling (DS) at the beginning of each downlink phase which (1) announces the destination of the downlink ATM cells, (2) reserves uplink slots for ATM cells and (3) assigns short uplink signalling slots for the terminals. These short slots are used for capacity requests if a terminal has no reserved uplink slots for ATM cells that can be used to transmit capacity requests piggyback. They are shared by the terminals using random access. Between

every downlink and uplink phase, a transceiver turnaround interval (TTI) is inserted during which no power is transmitted.

If a terminal is not synchronised to the current structure on the air interface, e.g. after switch on or waking up from a power saving mode, it first has to find and evaluate the downlink signalling burst. Unfortunately, the null symbol preceding the downlink phase is not unique because the TTI occurs also prior to the uplink phase and a short uplink signalling slot may stay unused due to the random access scheme applied. Most alternative methods use some kind of correlation which must happen in real-time and, therefore, is power-consuming. This problem can be solved with the frame synchronisation scheme described below.

### III. FRAME SYNCHRONISATION CONCEPT

The frame synchronisation concept for OFDM based W-ATM systems introduced in this paper is based on a special frame synchronisation symbol (FSS) which is transmitted at the beginning of the downlink phase. The proposed synchronisation symbol is characterised by a spectrum which occupies only half of the bandwidth of a conventional data symbol, see Figure 2.

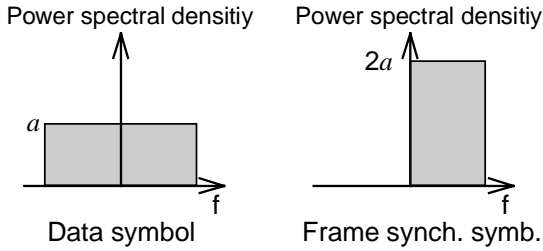


Figure 2. Power spectral density of data and frame synchronisation symbol

In an OFDM system with  $N$  subcarriers, such an FSS can be easily realised by either using the lower or upper  $N/2$  subcarriers, respectively. Since the energy of the data symbols is generally equally distributed over the available bandwidth  $B$ , the following basic detection algorithm can be applied:

1. The received signal is spectrally divided into upper (+) and lower (-) frequency band according to the used and unused subcarriers of the FSS.
2. In each frequency band the signal energy is continuously evaluated using either a sliding time window or successive, non-overlapping time windows of defined length.
3. The ratio of the signal energy in both frequency bands serves as an indicator for the FSS. Once this ratio is above or below a certain threshold, the beginning of a new frame is assumed.

This kind of frame synchronisation algorithm can be realised either in a more digital or more analogue way. In the following both methods are explained and compared with respect to

complexity and performance. Beforehand, some aspects concerning the FSS are discussed.

#### A. Frame Synchronisation Symbol.

Besides the demand that the whole energy of the FSS is concentrated on the lower or upper  $N/2$  subcarriers, the amplitude and phases of these subcarriers can in principle be chosen arbitrarily. Taking into account the frequency-selective fading in broadband wireless transmission, the energy should be equally distributed over the range of used subcarriers to maximise the average signal energy in the receiver.

Another aspect of importance is the envelope of the time signal. It is well known that OFDM has a highly dynamic signal envelope which requires a linear power amplifier in the transmitter. Since the linearity is limited to a certain power region, a large input backoff factor (IBO) is required to keep signal distortions low. Given a certain IBO factor, the envelope of the FSS should be designed not to overdrive the power amplifier thereby avoiding any distortions at all. This can be achieved by tuning the phases of the subcarriers appropriately.

Since there is a large degree of freedom in the design of the FSS, this symbol could additionally be used for frequency or clock synchronisation.

#### B. Analogue Processing

Frame synchronisation with analogue processing in the receiver is depicted in Figure 3.

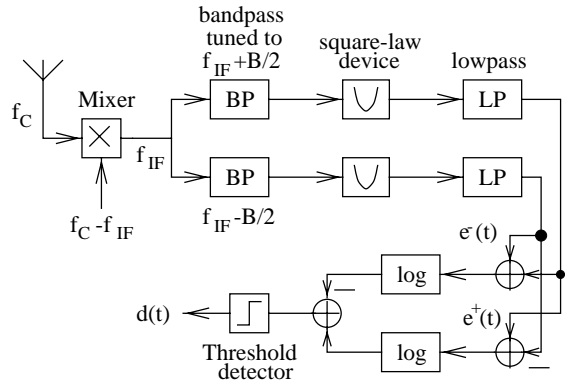


Figure 3: Block diagram of analogue frame synchronisation

The incoming signal is first down-converted to an intermediate frequency  $f_{IF}$  and then split into two branches. In both branches the signal is filtered passing either the frequencies  $[f_{IF} - B/2 : f_{IF}]$  or  $[f_{IF} : f_{IF} + B/2]$ . After that, squaring yields the instantaneous baseband signal power in each branch which is smoothed by lowpass-filtering. Since lowpass filtering realises a weighted integration, the output signals  $e^-(t)$  and  $e^+(t)$  are proportional to the signal energy within a sliding time window the length of which can be controlled by the cut-off frequencies of the lowpass filters.

Detection of the FSS can in principle be performed on a Maximum Likelihood basis but this is quite difficult to realise in an analogue way and additionally requires knowledge of the

channel and noise statistics. Therefore, further processing of the signals  $e^+(t)$  and  $e^-(t)$  has been optimised in a more heuristic way. Obviously, the ratio  $e^+(t)/e^-(t)$  is suitable for detecting the FSS since it is expected to be  $\approx 1$  in case of a data symbol or a time period without signal energy, and to be large/small in case of an FSS symbol. (depending which frequency band is used by the FSS). Further investigations have shown that evaluation of the quotient

$$\begin{aligned} d(t) &= \log \left[ \frac{e^+(t) - e^-(t)}{e^+(t) + e^-(t)} \right] \\ &= \log[e^+(t) - e^-(t)] - \log[e^+(t) + e^-(t)] \end{aligned} \quad (1)$$

leads to better results. In Eq. (1) it is assumed that the FSS uses the upper frequency band, i.e.  $d(t) \approx 0$  in case of an FSS and  $d(t) \ll 0$  in any other case. If  $d(t)$  exceeds a certain threshold an FSS is assumed to be detected.

### C. Digital Processing.

Alternatively to analogue processing, the spectral analysis can be performed by an FFT, using a non-overlapping sliding time window of length  $W$  samples. The signal vector  $s(k) = (s_1(k), \dots, s_w(k))$  at the output of the  $k$ -th FFT is utilised to calculate the signal power in the upper and lower frequency band:

$$p^+(k) = \sum_{i=0}^{W/2-1} |s_i(k)|^2 \quad (2)$$

and

$$p^-(k) = \sum_{i=W/2}^{W-1} |s_i(k)|^2 \quad (3)$$

Again, the FSS is detected by evaluating the term

$$d(k) = \log \left[ \frac{p^+(k) - p^-(k)}{p^+(k) + p^-(k)} \right] \quad (4)$$

for every successive block of  $W$  samples.

However, using the FFT for short time spectral analysis of the input signal only yields correct results if carrier frequency, sampling clock and symbol clock are synchronised. This is generally not the case at the time of frame synchronisation. The need of symbol synchronisation for frame synchronisation can be overcome by shortening the FFT window length from  $N$  to  $W=N/2$  samples and using an FSS with the same period (i.e. using only every second subcarrier in the upper or lower frequency band). In this case it is guaranteed that for every symbol at least one FFT-window exists which is not affected by ISI.

No measures can be taken to reduce the influence of sampling clock and carrier frequency offset on frame synchronisation. Since the incoming signal is spectrally broadened by windowing in time domain, the weighted side lobes of the window spectrum take effect in case of frequency errors thereby reducing the spectral difference between the FSS and a data symbol. Nevertheless, simulations have shown that still a good

performance of the digital frame synchronisation is achieved with realistic clock and frequency synchronisation offsets.

## IV. PERFORMANCE ANALYSIS

To describe the performance of the frame synchronisation concept, the probability  $P_c(i)$  of correct acquisition at the  $i$ -th appearance of a FSS and the probability  $P_f(i)$  of false acquisition before the  $i$ -th appearance of a FSS have been evaluated. These values were derived from the transition (conditional) probabilities for False Acquisition on Data,  $P_{FAD} = \text{Prob}(\text{FSS detected} | \text{OFDM symbol transmitted})$ , and True Acquisition on FSS,  $P_{TAF} = \text{Prob}(\text{FSS detected} | \text{FSS transmitted})$ , which have been measured in simulations for a large number of different channels.

Suppose that - after turning on the receiver -  $k$  conventional OFDM symbols precede the next FSS symbol. The one pass acquisition probability given a certain channel transfer function  $m$  is

$$P_c(1, k, m) = (1 - P_{FAD}(m))^k P_{TAF}(m) \quad (5)$$

Assuming a fixed frame length  $F$ , averaging over  $k$  and  $m$  yields

$$\begin{aligned} P_c(1) &= \frac{1}{FM} \sum_{m=1}^M \sum_{k=0}^{F-1} P_c(1, k, m) \\ &= \frac{1}{FM} \sum_{m=1}^M P_{TAF}(m) \frac{1 - (1 - P_{FAD}(m))^F}{P_{FAD}(m)} \end{aligned} \quad (6)$$

The probability  $P_N(1)$  of not detecting the FSS is therefore given by

$$P_N(1) = \frac{1}{FM} \sum_{m=1}^M (1 - P_{TAF}(m)) \frac{1 - (1 - P_{FAD}(m))^F}{P_{FAD}(m)} \quad (7)$$

Finally, the probability  $P_f(1)$  of false acquisition before the first appearance of the FSS can be evaluated from  $P_c(1)$  and  $P_N(1)$ :

$$P_f(1) = 1 - P_c(1) - P_N(1) \quad (8)$$

### A. Simulation Parameters

To evaluate the transition probabilities  $P_{FAD}$  and  $P_{TAF}$ , the following system and channel parameters were assumed.

System parameters:

- symbol duration:  $T=2.88\mu\text{s}$
- guard interval:  $T_g=0.32\mu\text{s}$
- subcarrier spacing:  $\Delta f = 390.62\text{KHz}$
- number of subcarrier:  $N = 64$
- Fixed frame length  $F=100$  Symbols

Channel parameters:

- maximum Doppler frequency:  $f_D=46\text{Hz}$
- maximum delay:  $\tau_{\max}=230\text{ns}$
- 4-path Rayleigh fading

### B. Analogue Processing

There are many parameters which influence the performance of the analogue frame synchronisation algorithm, such as shape and cut-off-frequencies of the applied lowpass and bandpass filters and the threshold used for detecting the FSS. Since this is a multidimensional optimisation problem, it is not possible to discuss the influence of every parameter in this paper and we therefore limit our considerations to the influence of the threshold only. For bandpass and lowpass filtering, 6<sup>th</sup> order Butterworth filters with a bandwidth of 9 MHz and 2<sup>nd</sup> order critical filters with a bandwidth of 300kHz have been used, respectively.

The one pass acquisition probability  $P_c(1)$  and the accumulated one and second pass acquisition probabilities  $P_c(1)+P_c(2)$  of the analogue frame synchronisation concept are depicted in Figure 4. The ratio  $E_s/N_o$  of the normalised OFDM symbol energy  $E_s=E/N$ , where  $E$  is the energy of an OFDM symbol and  $N$  the number of subcarriers, and the noise power spectral density  $N_o$  is treated as parameter ranging from 5 to 15dB.

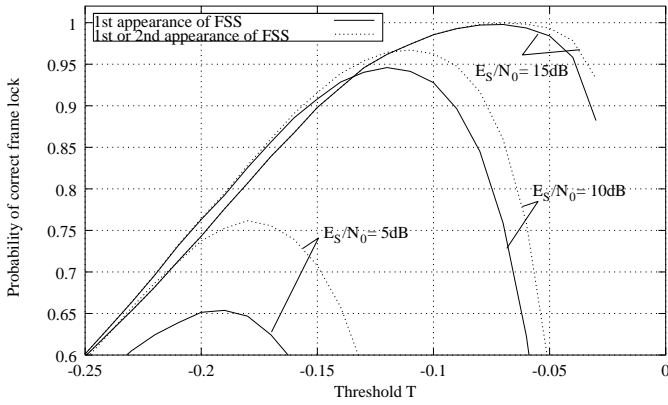


Figure 4: probability of correct frame synchronisation

It can be observed that the analogue frame synchronisation performs quite well at  $E_s/N_o=15\text{dB}$ , i.e. the one pass acquisition probability is about 99,7% at an optimised threshold of  $T=-0.07$ . At lower  $E_s/N_o$  values, the maximum achievable one pass acquisition probability decreases to 94,6% ( $E_s/N_o=10\text{dB}$ ) and 65.6% ( $E_s/N_o=5\text{dB}$ ).

To keep the probability of false frame lock small, the threshold should not fall much below  $T=-0.07$ , see Figure 5. Note that, in the simulated case, one FSS occurs in a frame of 100 symbols.

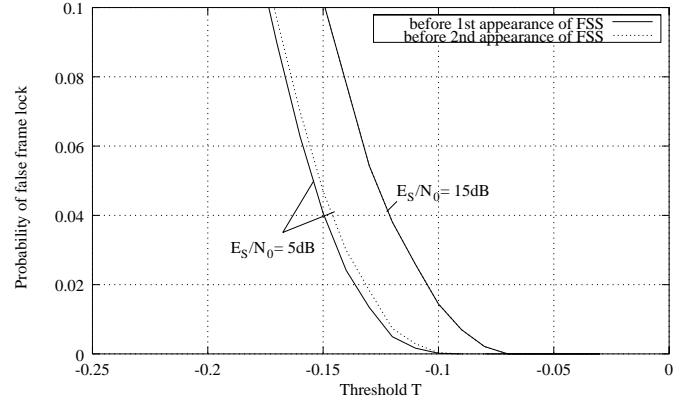


Figure 5: probability of false frame synchronisation

At  $T=-0.07$ , the probability of false lock before the second pass of the FSS lies below 0.1%. However, if  $E_s/N_o$  is small, such a threshold may result in very long acquisition times, cf. Figure 4. Considering practical W-ATM systems, this fact will probably be of minor importance since  $E_s/N_o$  values above 15dB are required anyway for reliable data transmission.

Another aspect of importance is the variance of the frame timing, i.e. the position of the detected with respect to the actual beginning of the frame. This is depicted in Figure 6.

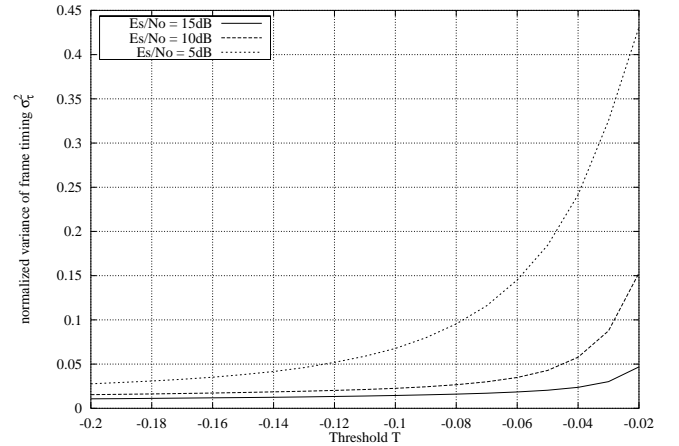


Figure 6: Variance of frame timing normalised to symbol duration

As expected, the variance of frame timing increases with increasing threshold, i.e. decreasing false lock probability. Considering again the threshold  $T=-0.07$ , the accuracy of the coarse frame synchronisation has a standard deviation  $\sigma_t$  of approximately 14% of an OFDM symbol duration which seems to be sufficient for further fine synchronisation.

### C. Digital Processing

The performance of the digital frame synchronisation is depicted in Figure 7 and Figure 8. In the simulations, a Gaussian distributed frequency offset of the receiver (with standard deviation of 1.5 times the subcarrier distance) was taken into

account to model an unsynchronised receiver.

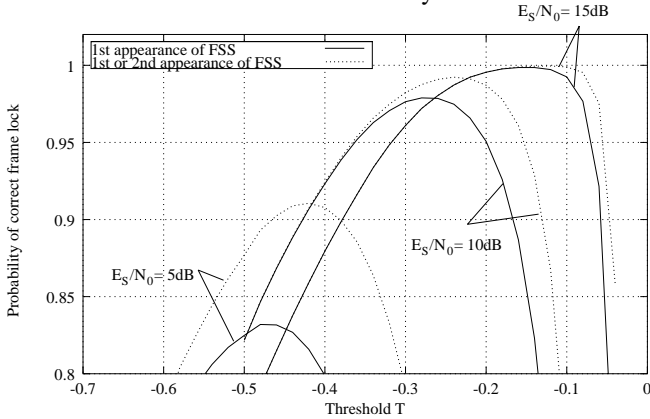


Figure 7: Probability of correct frame synchronisation

Compared to the analogue case, a slightly higher one and two pass acquisition probability can be observed, especially at low  $E_s/N_o$  ratios. The price to be paid is a worse frame timing due to the blockwise processing of the input signal. An appropriate threshold  $T$  is in the range of -0.12, as can be seen from Figures 7 and 8.

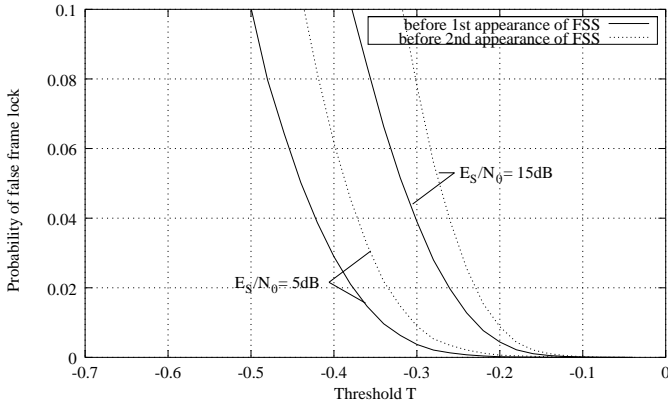


Figure 8: Probability of false frame synchronisation

## V. SUMMARY AND OUTLOOK

In this paper, a frame synchronisation algorithm is proposed which allows a simple and reliable frame synchronisation in an OFDM based wireless communication system. The algorithm is based on a special synchronisation symbol which is transmitted by the base station at the beginning of each frame. This symbol occupies only half of the available bandwidth and is therefore unique. Detection can be performed on the basis of the energy ratio in the upper and lower frequency band. The detection algorithm can be implemented either in a more digital or more analogue way. With optimised parameters both methods achieve a one pass frame synchronisation probability above 99% at moderate  $E_s/N_o$  ratios ( $\geq 15\text{dB}$ ).

To further improve the performance of the algorithm, it is possible to exploit additional information which indicates the occurrence of a frame beginning. In case of a TDMA TDD system, the null symbol is such an indicator which necessarily precedes the frame symbol and can easily be detected.

## ACKNOWLEDGEMENT

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