Synchronization Algorithms and Preamble Concepts for Spectrum Pooling Systems

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Abstract— **Public mobile radio spectrum has become a scarce resource while wide spectral ranges are only rarely used. Here, we consider a new strategy called Spectrum Pooling (SP) enabling public access to these spectral ranges without sacrificing the transmission quality of the actual license owners. By temporarily leasing their spectrum during idle periods the license owners could tap new sources of revenue. We favor a modified wireless LAN as rental system. Especially OFDM based WLANs like IEEE802.11a and HIPERLAN/2 are suitable for an overlay system like SP as they allow a very flexible frequency management on a carrier-by-carrier basis. The modifications of these standards comprise many areas of the physical and MAC layer. In this paper, we show by simulation results that the existing preambles and synchronization methods are insufficient for SP. We derive new concepts that fit the special needs of an SP scenario. We focus on frequency and frame synchronization in the presence of multiple narrow-band interferers which is an appropriate transmission model for the licensed users in our context. Simulation results show that the proposed preamble and synchronization concepts perform well.**

Keywords— **Synchronization, Spectrum pooling, WLAN, IEEE 802.11a, HIPERLAN/2, OFDM**

I. INTRODUCTION

THE success of future wireless systems will depend on the concepts and technology innovations in architecture and in efficient utilization of spectral resources. There will be a substantial need for more bandwidth as wireless applications become more and more sophisticated. This need will not be satisfied by the existing frequency bands being allocated for public mobile radio even with very evolved and efficient transmission techniques. Measurement campaigns have shown that wide ranges of potential spectral resources are used only very rarely. In our approach that we call Spectrum Pooling, different spectrum owners (e.g. military, trunked radio etc.) bring their frequency bands into a common pool from which rental users (RUs) may rent spectrum. The notion Spectrum Pool was first mentioned in [1]. Interesting aspects of the spectral efficiency gain that is obtained with the deployment of SP were discussed in [2].

A potential rental system (RS) needs to be highly flexible with respect to the spectral shape of the transmitted signal. Spectral ranges that are accessed by licensed users (LUs) have to be spared from transmission power. OFDM modulation is a candidate for such a system as it is possible to leave a set of subcarriers unmodulated and thus providing a flexible spectral shape that fills the spectral gaps without interfering with the LUs. A detailed description of this approach is given in [3].

Furthermore, SP systems are not supposed to compete with existing and upcoming 2G and 3G standards. They are rather meant to be a complement in hot spot areas with a high demand for bandwidth (e.g. airports, convention centers etc.). Hence, it is straightforward to apply modified versions of OFDM based wireless LAN standards like IEEE802.11a and HIPERLAN/2 [4]-[6]. There are many modifications to consider in order to make wireless LANs capable of SP. They range from front end to higher layer issues. In this paper, we focus on the preamble concepts and the frame and frequency synchronization techniques which are identical for both considered standards. Synchronization in OFDM based wireless LANs has been investigated extensively [7]-[9]. Different kinds of wireless transmission effects were taken into consideration e.g. AWGN in [7] and multipath fading in [8].

A short overview on conventional synchronization techniques is given in section II. A whole new aspect occurs in an SP environment that has not been investigated yet: narrow-band interference. Every LU accessing a subband of the licensed system (LS) interferes with a subset of OFDM carriers. If this happens during the transmission of a preamble the frame detection probability decreases substantially and the standard deviation of the frequency offset rises. This effect is shown by simulation in section III. Possible improvements like the extension of the correlation length are proposed.

The degradation of the frame detection reliability is intolerable for the RS. Hence, new concepts have to be conceived and investigated. In section IV we derive a method that is based on adaptive digital filtering of the narrow-band interference and the migration from autocorrelation based to crosscorrelation based synchronization techniques. The performance of the proposed modifications is evaluated by simulation.

II. CONVENTIONAL SYNCHRONIZATION TECHNIQUES

Synchronization has a large relevance in an OFDM system as this modulation technique is very sensitive to phase noise, frequency offset and timing errors. Here, we neglect the synchronization of the sampling time which is realized using a scrambler as proposed in the standards. As this is not affected by the SP-typical effects mentioned above, we do not consider sampling time issues. Carrier phase recovery is disregarded as well. The carrier phase is tracked with the use of pilots. These pilots are affected by narrow-band interference. So, the adaptive positioning of the pilots avoiding collisions with narrow-band interferers is an important task that is currently under investigation. However, we assume perfect knowledge of the carrier phase in this paper.

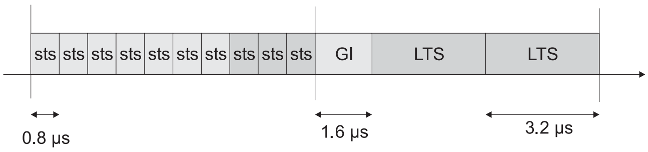

Fig. 1. Preamble structure of an IEEE802.11a data packet

The synchronization tasks that we would like to focus on now are frame and frequency synchronization based on preambles. There are many techniques for OFDM based wireless communications. A small range of all the options can be found in [10]. Fig. 1 depicts the preamble structure of an IEEE802.11a data packet. It consists of ten short training symbols (sts) and two long training symbols (LTS) separated by a guard interval (GI). The first seven sts are used for signal detection, automatic gain control and carrier sensing.

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The remaining three short training symbols serve as training symbols for a coarse estimation of the frequency and clock offsets. Using repeated short symbols of one forth of the original length yields a spectrum after the FFT where only every forth element differs from zero due to the periodicity of the signal in the time domain. This circumstance enables an estimation of the frequency offset that is larger than one carrier spacing. A detailed description of an OFDM receiver exploiting this shortened periodicity can be found in [11].

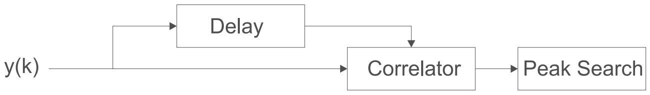

Fig. 2. Structure of the frequency offset estimator and frame detector

Fig. 2 shows a simplified structure of the frequency offset estimator and frame detector. The receiver correlates the received signal with a delayed version of the received signal. Using this autocorrelation method the beginning of the frame can be estimated as the autocorrelation will be significantly higher when the received preamble samples are pushed through the correlator. Ordinary data symbols cannot have this periodic structure and lead to a lower correlation value.

Hence, finding the beginning of the frame means finding the peak value at the output of the correlator. The samples of the received signal $y(k)$ are modulated by a frequency offset with respect to the transmitted signal $x(k)$. This is introduced by differing oscillator frequencies in the transmitter and the receiver. The phase of the samples grows continuously in consequence of this frequency offset Δf_c:

$$y(k) = x(k) \cdot e^{j2\pi\Delta f_c T_S k}, \tag{1}$$

where T_S is the sampling period. The correlation with the delayed version of same signal $y(k)$ yields:

$$\begin{aligned} K &= \sum_{k=0}^{N-1} y(k) \cdot y^*(k+N) && (2)\\ &= \sum_{k=0}^{N-1} x(k) \cdot e^{j2\pi\Delta f_c T_S k} \cdot x(k)^* \cdot e^{-j2\pi\Delta f_c T_S (k+N)}\\ &= \sum_{k=0}^{N-1} |x(k)|^2 \cdot e^{j2\pi\Delta f_c T_S k} \cdot e^{-j2\pi\Delta f_c T_S k} \cdot e^{-j2\pi\Delta f_c T_S N}\\ &= e^{-j2\pi\Delta f_c T} \cdot \sum_{k=0}^{N-1} |x(k)|^2, && (3) \end{aligned}$$

where $T = NT_S$ denotes the duration of the correlation. Now, the frequency offset can be calculated as follows:

$$\Delta f_c = \frac{1}{2\pi T} \arg K^*. \tag{4}$$

It is obvious that with the estimation equation (4) does not deliver frequency offsets which are larger than half a carrier spacing as it only ranges from $-\pi$ to π. Hence, equation (4) can not serve as estimator for the acquisition phase where frequency offset can become quite large. This may be the case when a station is turned on and the oscillator has no synchronization to the system at all. This is why IEEE802.11a provides the short training symbols. As mentioned before, the length of the training sequence is divided by 4 and (2) becomes:

$$\begin{aligned} K_{\frac{1}{4}} &= \sum_{k=0}^{\frac{N}{4}-1} y(k) \cdot y^*(k + \frac{N}{4})\\ &= e^{-j2\pi\Delta f_c T \cdot \frac{1}{4}} \sum_{k=0}^{\frac{N}{4}-1} |x(k)|^2, && (5) \end{aligned}$$

and the estimation equation for the frequency offset (4) turns into:

$$\Delta f_c = \frac{4}{2\pi T} \arg K^*_{\frac{1}{4}}. \tag{6}$$

Now, a wider range of frequency offsets can be estimated because of the factor 4 in (6). In this case, only 16 values instead of 64 are correlated. Hence, the estimation accuracy is quite poor. Applying a small trick [11] enables the combination of (4) and (6):

$$\Delta f_c = \frac{1}{T} \left\lfloor \frac{4}{2\pi} \arg K^*_{\frac{1}{4}} \right\rfloor + \frac{1}{2\pi T} \arg K^*. \tag{7}$$

If we want to apply these mathematical models on SP, we meet with an obstacle. It is not always possible to transmit short training symbols. The reduction of the symbol duration to $1/4$ of its original length implies that every forth carrier can potentially interfere with an LU. Furthermore, the suppression of subsets of carriers would destroy the temporal orthogonality of the short training symbols. Hence, the techniques proposed by the standard are not applicable to SP and new methods need to be derived.

III. SYNCHRONIZATION TECHNIQUES FOR SP BASED ON AUTOCORRELATION

The first approach we would like to present is the transition from short training symbols to full length (80 samples) training symbols. The preamble has to enable the estimation of the frequency offset. Therefore, two identical sequenced training symbols are necessary that are not separated by a guard interval.

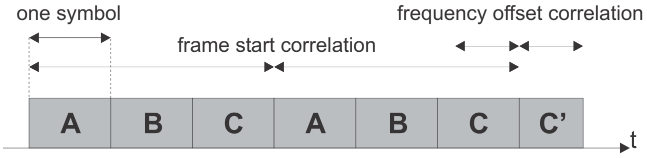

Fig. 3. Preamble for the estimation of Δf_c and frame start with long symbols

Fig. 3 shows the typical structure of such a preamble. In our example, it consists of three repeated symbols followed by a copy of the last samples of the last symbol. The symbols A, B and C are 80 samples long in the style of the IEEE802.11a symbol length. While C' comprises 64 samples. Basically, the symbols A, B and C do not even need to be correct IFFT generated OFDM symbols as their samples just pass through the correlator like in Fig. 2. It is sufficient to know the number of samples after which the sequence is repeated in order to set the right delay. Here, we considered pseudo random training sequences.

The problem with this method is that some OFDM carriers encounter interference when the LUs access their subbands. If the traffic volume in the LS rises, more and more OFDM carriers will be affected and the SNR for the correlation of the preamble will degrade. Fig. 4 shows this effect very clearly. In this

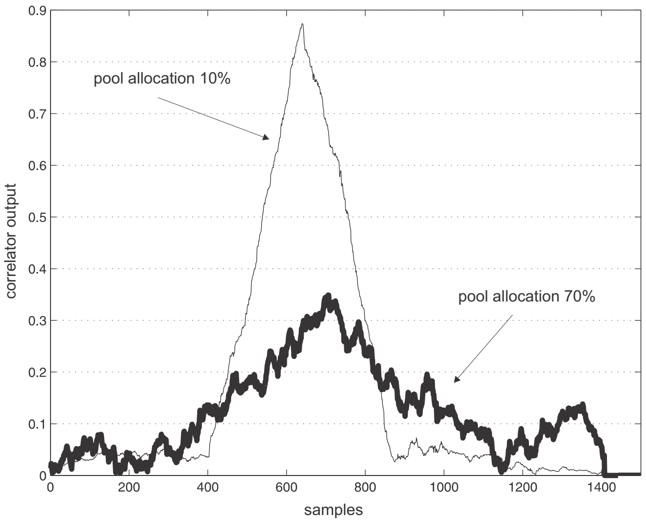

Fig. 4. Correlator output with a correlation length of 3 symbols and varying pool allocation

example, we used a preamble containing three symbols A, B and C like in Fig. 3. The varying parameter is the pool allocation. It means the relative number of all OFDM carriers that are interfered with by LU accesses. The mean transmit power per OFDM carrier of the LUs was 3dB higher than one of the RUs (ΔP_{LU} = 3dB). The RS operated at an SNR of 25dB.

Two functions have to be fulfilled with the use of this correlator output. First, the reception of a valid preamble has to be detected. This could be done with a simple threshold stage at the output of the correlator. Unfortunately, the correlation peak diminishes when the pool allocation rises and the reliability of the preamble detection result will decrease.

Secondly, the exact start of the frame needs to be determined by finding the correlation peak. This could be realized in case of a pool allocation of 10% as we can see in Fig. 4. The correlation triangle is 480 samples wide as we have a correlation length of 240 samples (3 symbols at 80 samples each). Two dummy symbols were sent in advance. So, the expected peak is at sample 640 which agrees with the 10%-curve, but at a pool allocation of 70% the correlation curve is very noisy and the peak value is delayed. This delay is very crucial in an OFDM system. Each delayed sample shortens the effective length of the guard interval which is necessary for maintaining the orthogonality of the carriers in a multipath environment. In IEEE802.11a we have a guard interval length of only 16 samples. Hence, an error-free reception is impossible for a pool allocation of 70%. Fig. 5 shows how an extension of the correlation length could deliver better results under the same circumstances. The mean transmit power of the LUs is also important for the quality of the correlation curves.

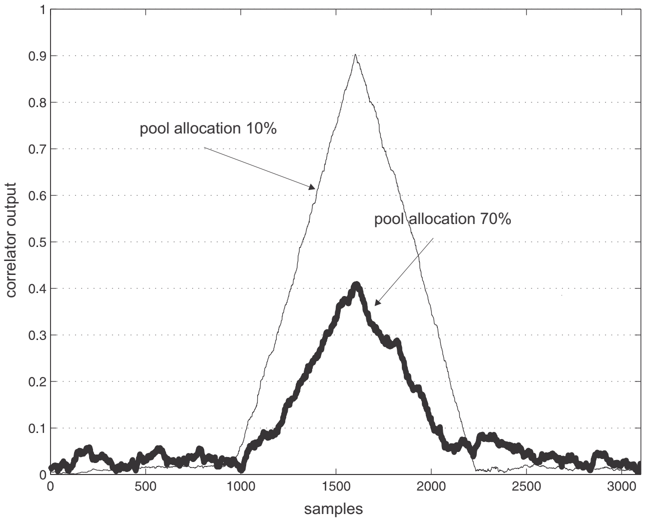

Fig. 5. Correlator output with a correlation length of 8 symbols and varying pool allocation

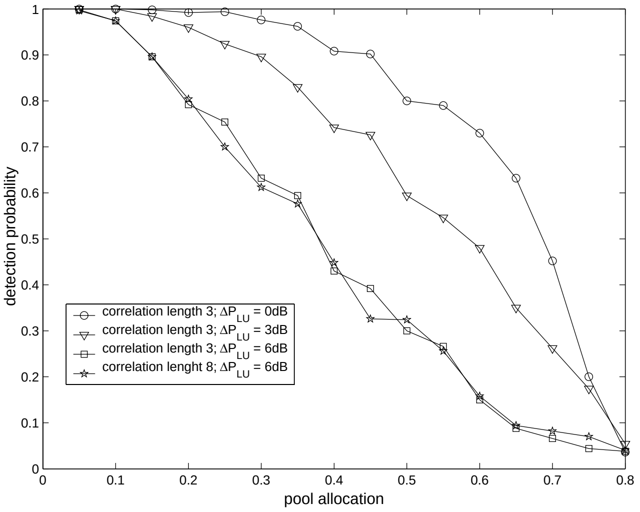

Fig. 6. Ratio of correctly detected preambles under different conditions

Now, we want to examine how the parameters frequency offset, mean LU transmit power, correlation length and pool allocation influence the requirements of a preamble. The mean LU transmit power is always normalized to the mean transmit power of the RUs. Simulations have shown that the frequency offset only has a negligible impact on the synchronization performance. This can be shown mathematically as we will see in section IV. In Fig. 6 the probability was calculated by simulation at which the absolute error of the estimated frame start was less than 8 samples i.e. a correct OFDM reception is still possible in the absence of multipath propagation. We can see that the reception ratio drops quickly when the pool allocation rises especially at a high transmit power of the LUs. The impact

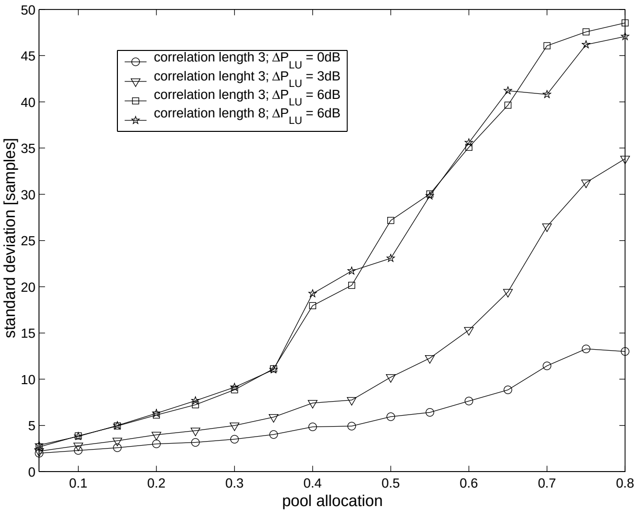

Fig. 7. Standard deviation of the estimation of the frame start

of the pool allocation and the mean LU transmit power on the standard deviation of the frame detection and the frequency offset estimation is depicted in Fig. 7 and Fig. 8, respectively. We learn from the curves that the extension of the correlation length does not yield significant improvements. The results are acceptable for low pool allocations, but at a pool allocation of 0.4 and mean LU transmit power difference of 6dB the detection ratio is as low as 50%. This is not tolerable for the RS. Hence, further improvements have to be derived.

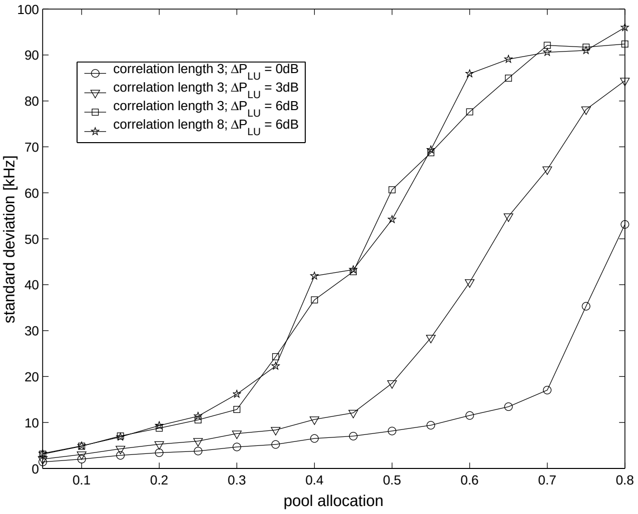

Fig. 8. Standard deviation of the estimation of the frequency offset

IV. SYNCHRONIZATION TECHNIQUES FOR SP BASED ON CROSSCORRELATION AND ADAPTIVE FILTERING

If we want to establish SP in pools with a high mean LU transmit power or a pool allocation that is greater than 20% for most of the time then we need to find an alternative solution to the methods presented in section III. The preamble is known a priori. Hence, one possibility is crosscorrelating the received samples with preamble sequences stored in the receiver instead of autocorrelating the received samples with a delayed version. Fig. 9 illustrates this procedure. Now, the repeated part (*C*-*C'*) is only used for the estimation of the frequency offset. Mathematically, the crosscorrelation of the original signal $x(k)$ and the received signal $y(k)$ which has encountered a frequency offset Δf_c and a phase shift φ can be described by the following equation:

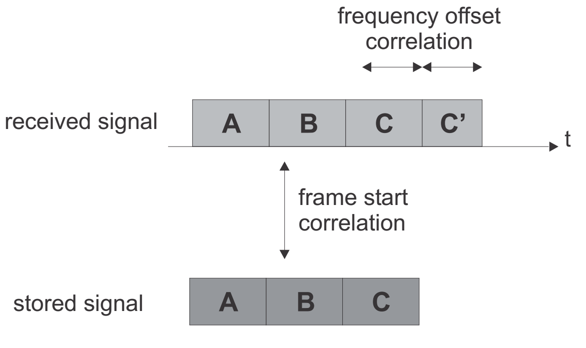

Fig. 9. Structure of the frequency offset estimator and frame detector

$$\begin{aligned} L &= \sum_{k=0}^{N-1} x(k) \cdot y^*(k) \\ &= \sum_{k=0}^{N-1} x(k) \cdot x^*(k) \cdot e^{-j2\pi\Delta f_c T_S k\ -j\varphi} \\ &= e^{-j\varphi} \sum_{k=0}^{N-1} |x(k)|^2 \cdot e^{-j2\pi\Delta f_c T_S k}, \end{aligned} \tag{8}$$

where T_S denotes the sampling period. As mentioned above, equation (8) cannot be used to estimate the frequency offset Δf_c. It even degrades the maximum value of L as every addend in (8) is rotated before the summation i.e. that a frame synchronization method based on crosscorrelation cannot be applied on the acquisition phase. However, it works fine for the tracking phase when a rough frequency offset estimation has already been conducted based on the techniques discussed in section II. One could also estimate the phase shift by solving (8) for φ. The frame start estimation can be realized by taking the absolute value of L

$$|L| = |\sum_{k=0}^{N-1} |x(k)|^2 \cdot e^{-j2\pi\Delta f_c T_A k}| \tag{9}$$

and finding the peak value. If the preamble was chosen with good crosscorrelation properties the output of the correlator will have a very sharp peak which is very advantageous for an exact determination of the frame start other than in Figs. 4 and 5 where we saw that the correlator output develops a triangular shape in case of an autocorrelation method. Hence, the crosscorrelation based techniques will deliver a much higher reliability in frame detection if the system has already been acquired.

A new point of view is introduced by the fact that the LUs bring in narrow band interference which the RS has to cope with. An OFDM transceiver features an FFT/IFFT function anyway. Hence, it is straightforward to use it as an adaptive digital filter or as a calculator for time varying coefficients of an FIR filter. This adaptive filter – realized either in the time domain or the frequency domain – cuts out the OFDM carriers that are subject to interference by transmitting LUs before the signal is actually fed into the correlator as depicted in Fig. 10. Therefore, the information which subbands of the LS are currently in use is required. Then, this spectral sequence of band-rejection and band-pass can be reproduced by the linear prefilter. Providing this information is task of the access point. It can perform spectral measurements or prompt other stations in the propagation area to perform measurements themselves and send the results back to the access point. The access point gathers all the measured data and broadcasts the carrier allocation back to the stations. The efficient implementation of these spectral measurements and the allocation broadcast are challenging tasks that are currently investigated. Here, we assume perfect knowledge of the carrier allocation and the filtering procedure mentioned above is applicable. However, it may happen that some LUs still disturb the synchronization of the RS even with a perfect periodic estimation of the carrier allocation in the access point

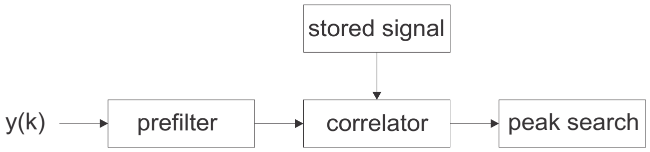

Fig. 10. Frame detector with crosscorrelator and adaptive prefilter