Symbol Synchronization for Wirelss LAN Systems

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무선 LAN 시스템에서의 심볼동기

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ABSTRACT

The performance of a symbol timing estimator for orthogonal frequency division multiplexing (OFDM) systems is analyzed. The expected value and the variance of the timing metric at the correct symbol timing are derived. The performance degradation of the timing estimator due to multipath fading and fractional timing offset is also presented.

요 약

무선 LAN 시스템을 위한 심볼동기에 대하여 연구되었다. OFDM 방식의 LAN 시스템에서 정확한 심볼동기 시점에서의 시간 metric의 평균값과 분산을 이론적으로 구한다. 또한 채널의 다중경로 페이딩과 시간 부분 편차에 의한 심볼동기 성능 저하가, 컴퓨터 시뮬레이션에 의한 방법으로 아울러 분석되었다.

I. Introduction

For instance, next generation wireless LAN (WLAN) standards such as IEEE 802.11a[1],and high Performance LAN type 2 (HiperLAN/2) system have accepted OFDM as their physical layer specifications. Because of the packet switched nature of WLAN systems, synchronization has to be acquired during a very short time after the start of the packet. Synchronization in OFDM includes packettiming synchronization, symbol synchronization, and carrier frequency synchronization. To achieve the rapid synchronization, current WLAN standards include a preamble in the start of the packet. The first task of the receiver is to find an approximate estimate of the start of an incoming packet. After the estimate of the start edge of the packet, the symbol timing algorithm refines the estimate to sample level precision. Symbol synchronization refers to the task of finding the precise position of the fast Fourier transform (FFT) window.

Schmidl and Cox present a robust method using a training signal with two identical halve to find the symbol timing [2]. The method takes advantage of the periodicity of the training signal. The conjugate of a sample from the first half is multiplied by the

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corresponding sample of the second half. This approach is called the delay and correlation algorithm. However, WLAN receivers have knowledge of the preamble available to them, which enables the receiver to use simple correlation based symbol timing algorithm. Symbol timing can be preformed by calculating the correlation of the received signal and a known reference [3]. The structure of this estimator is similar to the structure of Schmidl and Cox's estimator. In this paper, we analyze the characteristics of the correlation timing estimator using the known training signal.

II. OFDM system Description

The samples of transmitted baseband OFDM symbol can be given by

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N_u-1} X(k) \exp(j2\pi kn/N), \quad -N_g \le n \le N-1, \tag{1}$$

where $X(k)$ is modulated data symbol on the nth subcarrier, N is the number of inverse fast Fourier transform (IFFT) points, $N_u\ (\le N)$ is the number of subcarriers, N_g is the number of guard samples, and the sampling period is T_u/N with $1/T_u$ being subcarrier spacing. Consider a discrete-time multipath channel characterized by

$$h(n) = \sum_{l=0}^{L-1} h_l\, \delta(n - \tau_l) \tag{2}$$

where $\delta(n)$ represents dirac-delta function, $\{h_l\}$ complex path gains, $\{\tau_l\}$ path time delays which are assumed in multiple of OFDM samples, and L the total number of paths. Then the received samples, assuming perfect sampling clock, can be given by

$$r(n) = \exp(j2\pi nv/N) \sum_{l=0}^{L-1} h_l\, x(n - \tau_l + \varepsilon) + w(n) \tag{3}$$

where v is the carrier frequency offset normalized to subcarrier spacing, ε is timing offset in units of OFDM samples and $w(n)$ is the sample of zero mean complex gaussian noise process with variance σ_W^2. In the guard interval preceding the OFDM symbol, there is a certain range that is not affected by the previous symbol because of the channel time dispersion. As long as the FFT window starts from this range, the orthogonality among the subcarriers will not be destroyed. A symbol timing error within this interval will only introduce a phase rotation in every subcarrier symbol at the FFT output. For coherent system, this phase rotation is compensated in channel equalization which sees it as a channel introduced phase shift [4].

The preamble structure of the IEEE 802.11a system is illustrated in Fig. 1. The preamble is essential to perform start-of-packet detection, automatic gain control, symbol timing, frequency estimation, and channel estimation. The parts from t_1 to t_{10} are short training signals, that are all identical and 16 samples long. GI is a 32-sample cyclic prefix that protects the long training signals T_1 and T_2 from intersymbol interference (ISI) caused by the short training signal. The long training signals are identical 64 samples long OFDM signals.

A short training signal is produced by an inverse Fourier transform of the sequence of

Table 1 Short training signal p_m .

m	1	2	3	4	5	6	7	8
p_{mi}	0.1021	-0.2939	-0.0299	0.3168	0.2041	0.3168	-0.0299	-0.2939
p_{mq}	0.1021	0.0052	-0.1742	-0.0281	0	-0.0281	-0.1742	0.0052

m	9	10	11	12	13	14	15	16
p_{mi}	0.1021	0.0052	-0.1742	-0.0281	0	-0.0281	-0.1742	0.0052
p_{mq}	0.1021	-0.2939	-0.0299	0.3168	0.2041	0.3168	-0.0299	-0.2939

training symbol S, given by

$$S_{-26,26} = \{0,\ 0,\ 1+j,\ 0,\ 0,\ 0,\ -1-j,\ 0,\ 0,\ 0, \cdots\cdots,\ 1+j,\ 0,\ 0\}. \tag{4}$$

The fact that only spectral lines of $S_{-26,26}$ with indices which are a multiple of 4 have nonzero amplitude results in a periodicity of $T_{FFT}/4 = 0.8\ \mu\text{sec}$. The training signal $p_m = p_{mi} + jp_{mq}$ is given in Table 1. Detection of the presence of a packet can be done by correlating a short training signal with the next and detecting if the correlation magnitude exceeds some threshold [3]. After each interval equal to two short signal durations, the receiver gain can be adjusted

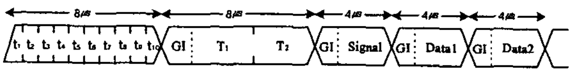

Fig. 1 IEEE 802.11a standard preamble.

after which symbol timing can continue. The short training signals are followed by long training signals. The long training signals make it possible to do fine frequency offset and channel estimations.

III. Estimation of Symbol Timing

Estimation of symbol timing is performed by calculating the crosscorrelation of the received complex signal r_m and the known reference p_m. Timing estimator takes as the start of the symbol the maximum point of the timing metric given by

$$M(d) = \frac{|P(d)|}{Q(d)} \tag{5}$$

where d is a time index corresponding to the first sample in a window of M samples and $P(d)$ is correlation metric given by

$$P(d) = \sum_{m=0}^{M-1} (r^*_{d+m}\, p_m) \tag{6}$$

where $(\ )^*$ represents conjugation and $Q(d)$ represents energy of OFDM signal and is included for normalization of the correlation metric and given by

$$Q(d) = \sum_{m=0}^{M-1} |r_{d+m}|^2 . \tag{7}$$

Let each complex sample $r_m = s_m + w_m = (s_{mi} + js_{mq}) + (w_{mi} + jw_{mq})$

$= r_{mi} + jr_{mq}$ be made up of a signal and a noise component. The real and imaginary parts of the noise component are independent with zero mean and equal variance. Let the variance of the real and imaginary components be:

$$E\{s^2_{mi}\} = E\{s^2_{mq}\} = \frac{\sigma_S^2}{2} \quad (8)$$

$$E\{w^2_{mi}\} = E\{w^2_{mq}\} = \frac{\sigma_W^2}{2} \quad (9)$$

so that the SNR is σ_S^2/σ_W^2. At the correct symbol timing, the received signal component s_{d_o+m} becomes

$$s_{d_o+m} = \sqrt{\frac{SNR}{1+SNR}}\, p_m \, . \quad (10)$$

Since $p_{mi} = p_{(m+8)q}$ and $p_{mq} = p_{(m+8)i}$, we obtain

$$\sum_{m=0}^{M-1}(s_{(d_o+m)i}\, p_{mq} - s_{(d_o+m)q}\, p_{mi}) = 0 \, . \quad (11)$$

From (6) and (11), normalized timing metric at the correct symbol timing $M(d_o) = |P(d_o)|$ can be written as

$$\begin{aligned} M(d_o) &= \sum_{m=0}^{M-1} \left|(s_{d_o+m} + w_{d_o+m})^* p_m\right| \\ &= \sum_{m=0}^{M-1} \left|s^*_{d_o+m}\, p_m + p_m\, w^*_{d_o+m}\right| \\ &= \sum_{m=0}^{M-1} |(s_{(d_o+m)i}\, p_{mi} + s_{(d_o+m)q}\, p_{mq} \\ &\quad + p_{mi}\, w_{(d_o+m)i} + p_{mq}\, w_{(d_o+m)q}) \\ &\quad + j(p_{mq}\, w_{(d_o+m)i} - p_{mi}\, w_{(d_o+m)q})| \end{aligned} \quad (12)$$

The expected value of $M(d_o)$ can be calculated as

$$\begin{aligned} E\{M(d_0)\} &= E\left\{\sum_{m=0}^{M-1}(s_{(d_0+m)i}p_{mi} + s_{(d_0+m)q}p_{mq})\right\} \\ &= \sqrt{\frac{SNR}{1+SNR}} \, . \end{aligned} \quad (13)$$

At relative high SNR, when magnitude is taken, the imaginary part in equation (12) is small compared to the real part and can be neglected, so

$$\begin{aligned} M(d_0) &\approx \Big\{\sum_{m=0}^{M-1}(s_{(d_0+m)i}\, p_{mi} + s_{(d_0+m)q}\, p_{mq} \\ &\quad + s_{(d_0+m)i}\, w_{(d_0+m)i} + s_{(d_0+m)q}\, w_{(d_0+m)q})\Big\} \\ &\quad / \sum_{m=0}^{M-1}|r_{d_0+m}|^2 . \end{aligned} \quad (14)$$

For usable value of SNR, the variance of $M(d_0)$ can be given as

$$\begin{aligned} \sigma_M^2 &\approx E\left\{\frac{\left[\sum_{m=0}^{M-1}(s_{mi}\, w_{mi} + s_{mq} w_{mq})\right]^2}{\left[\sum_{m=0}^{M-1}|r_m|^2\right]^2}\right\} \\ &= \frac{\sigma_S^2\, \sigma_W^2}{2M(\sigma_S^2 + \sigma_W^2)^2} \, . \end{aligned} \quad (15)$$

IEEE 802.11a has M = 16, the number of samples in a short training signal. Fig. 2 shows the results of simulations performed on AWGN channel.

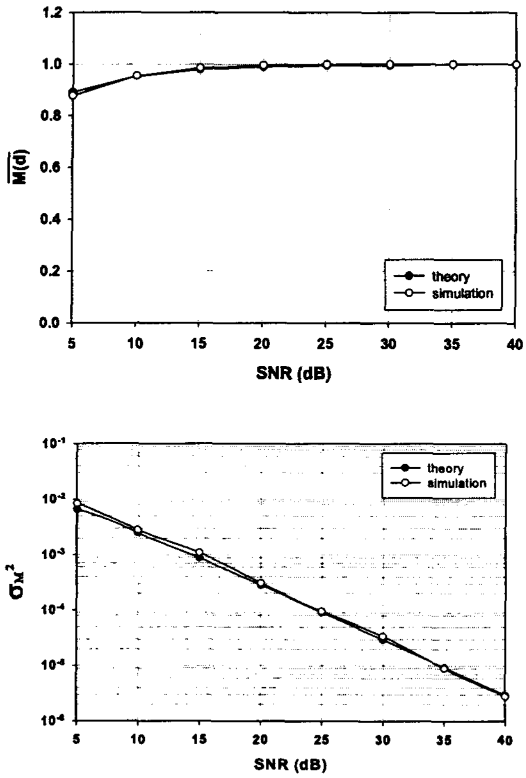

Fig. 2 Mean and variance of the timing metric at the correct symbol timing for the AWGN channel.

For usable value SNR, the mean is much greater than the variance. $M(d_o)$ can be approximated by a gaussian random variable since linear operations performed on a gaussian random variable will produce another gaussian random variable. Fig. 2 was made for the ideal case of a zero fractional timing offset between the received signal and the known signal. In the worst case, there is a timing offset of half a sampling interval. In this case, instead of one main peak per symbol, there are two equally strong peaks with a smaller amplitude than the single peak. Furthermore, the OFDM signal can be received through multipath channel. The multipath

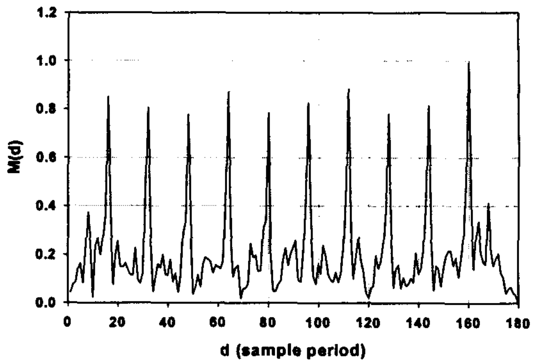

Fig. 3 Timing estimator output for the worst case fractional timing offset and the multipath channel (SNR = 10 dB).

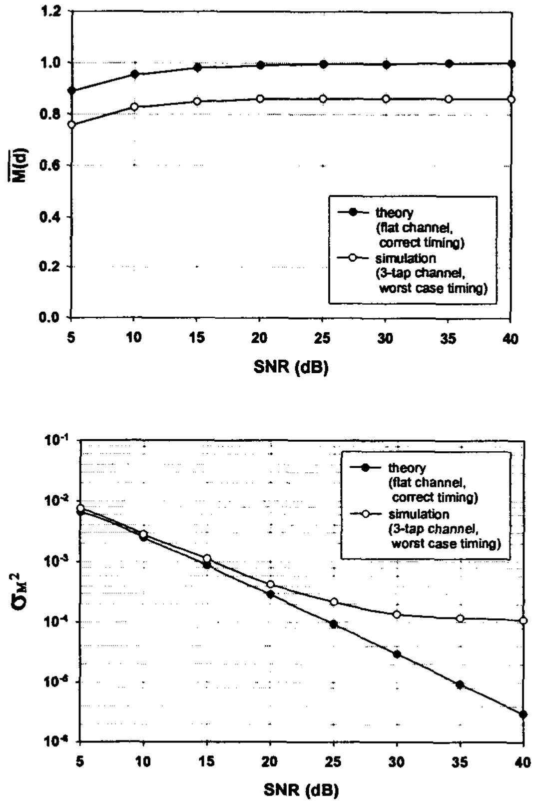

Fig. 4 Mean and variance at the correct symbol timing for the worst case fractional timing offset and the multipath channel.

channel is modelled as three paths with path delays τ_i of 0, 1, 2 samples and average path gains 0.696, 0.236, 0.068. Fig. 3 shows the simulated timing metric $M(d)$ for the worst case fractional timing offset and the multipath channel. Fig. 4 shows the mean and variance of the timing metric at the correct symbol timing for the worst case fractional timing offset and the multipath channel.

IV. Conclusions

The performance of a symbol timing estimation method for OFDM systems was analyzed. The expected value and the variance of the timing metric has been derived and simulation results show that the theoretical value is quite accurate for the ideal zero fractional timing offset and the AWGN channel. The performance degradation of the timing estimator due to multipath fading and fractional timing offset was also presented. The probability distribution derived in this paper can be used to determine the probability of not detecting a training sequence when one is present.

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