行政院國家科學委員會專題研究計畫　成果報告

採用 OFDM 的 IEEE 802.11a 無線區域網路的有效頻率偏移預估策略的探討

計畫類別：個別型計畫
計畫編號：NSC93-2213-E-216-027-
執行期間：93 年 08 月 01 日至 94 年 07 月 31 日
執行單位：中華大學電機工程研究所

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報告類型：精簡報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫可公開查詢

中　華　民　國 94 年 10 月 12 日

行政院國家科學委員會補助專題研究計畫成果報告

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計畫編號：NSC 93 – 2213 – E – 216 – 027
執行期間：93年08月01日至94年07月31日

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中　華　民　國　94　年　10　月　12　日

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中文摘要

關鍵詞: 正交頻率多工、IEEE802.11a、載子頻率偏移預估、短前導、引導符元

正交頻率多工具有抗拒頻率選擇衰竭及時間離散性頻道的能力，可以緩和系統對等化器複雜度的嚴峻需求，因此被 IEEE802.11a 的無線區域網路工作小組採用為傳輸技術標準。在眾多會影響正交頻率多工通訊系統效率的因素之中，同步的議題具有主導的地位。不準確的同步會產生符元間干擾及載子間干擾，這將降低系統的效能，或甚至癱瘓系統的正常功能。

正交頻率多工系統的同步對象可概略區分成時間，頻率或相位上。一個正交頻率多工接收機爲了完成同步工作所採取的一般步驟是先使用一些策略分別或同時預估上述標的物的偏移量，然後藉著一些方法去修正或調整該標的物至可被接受的程度。而用來評估預估策略優劣的重要效能參數之一是預估所衍生的變化量。

在此計畫中，我們將焦點放在適合 IEEE802.11a 無線區域網路標準內正交頻率多工的有效率的新載子頻率偏移預估策略的開發。更確切的說，我們利用此標準的框架結構中十個短前導，提出了簡單且能精確的預估粗略載子頻率偏移的兩層預估新策略。此新策略的重要特性之一，除了能達到低變化量外，在於它能解決執行粗略載子頻率偏移預估時常遭遇的曖昧問題，因此在頻率偏移很大的情況下仍能正常運作。針對上述新策略，我們推導出評估其變化性的數學公式及 Cramer Rao 下限的數學公式，並用模擬結果來驗證這些公式的正確性。同時，我們也檢視了多路徑衰竭效應與某些系統參數變化對新策略效能的影響。最後，我們藉著和其他學者提出的一些既有策略的比較，以彰顯新策略的優勢。

Abstract

Keywords: OFDM, IEEE802.11a, Carrier Frequency Offset Estimation, Short Preamble, Pilot Symbol

Orthogonal Frequency Division Multiplexing (OFDM), characterized by its capability of combating frequency selective fading and time dispersive channels, thus mitigating the stringent requirements of complex equalizer, has been adopted as the standardized transmission technique by the IEEE 802.11a Wireless Local Area Network (WLAN) working group. One of the major issues that will dominate the efficiency of a communication system employing OFDM techniques is synchronization. Inaccurate synchronization will cause Inter-Symbol Interference (ISI) as well as Inter-Carrier Interference (ICI). This will degrade the system performance, or even worse will result in malfunction of the system.

Synchronization of an OFDM system can be roughly classified as in time, in frequency or in phase. A general procedure for an OFDM receiver to accomplish the synchronization task is to estimate the specified offset for the above objects using some algorithms, individually or jointly, and then correct or adjust the corresponding parameter to an acceptable level via some means. One of the major performance measures for an estimating algorithm is the concomitant variance resulted from estimation.

In this project, we focus on development of new efficient carrier frequency offset estimation algorithms for the standardized OFDM-based IEEE 802.11a WLAN. Specifically, we have proposed a new and simple two-level estimation scheme that can accurately estimate the coarse carrier frequency offset using the ten short preambles accommodated at the start of each frame. A significant feature of this scheme is that it can resolve the ambiguity problem associated with coarse frequency offset estimation and thus can operate properly in a situation with large frequency offsets. For the new scheme, mathematical analyses for the evaluation of variance, as well as formula for the Cramer Rao bound under AWGN channels have been derived. Simulations are conducted to validate the analyses. Effects of multipath fading as well as system parameter variations on the performance have been examined. Superiority of the new scheme to some existent algorithms is demonstrated via performance comparisons.

研究計畫成果

We have completely accomplished the targets described in the proposal of this project including:

1. Using short preambles to propose a new simple and accurate two level coarse carrier frequency estimation scheme for 802.11a WLAN.
2. A new algorithm has been proposed to resolve the ambiguity problem associated with conventional coarse carrier frequency estimation algorithms. The scheme can operate properly in a large frequency offset range.
3 .Performance of the scheme in terms of estimation variance has been mathematically derived and validated by MATLAB simulations.
4. The Cramer Rao lower bound of the new scheme has been mathematical analyzed.
5. Effects of parameter variations and multipath fading on the performance are examined.
6. Superiority of the new scheme to some existent algorithms has been demonstrated via performance comparison.
7. Contributions arises from this project have been presented at one conference, IEEE International Conference on Communications (ICC’2005) [1], and submitted to two SCI journals, IEEE Transactions on Vehicular Technology and Transactions on Wireless Communications [2], [3].

In addition, support from this project has also enabled us to extend our research topic from carrier frequency offset estimation, which is the focus specified in this project, into sampling time offset estimation area. Preliminary results will be presented at Asian/Pacific Electro-Magnetic Conference (APEMC’2005) scheduled in December 2005 [4], [5].

[1] In-Hang Chung and Ming-Ching Yen, “Use of Diverse Delayed Correlation for an ML Carrier Frequency Offset Estimator in OFDM-Based IEEE 802.11a WLANs,” in Proc. IEEE International Conference on Communications (ICC’2005), pp. 2548-2552, Seoul Korea, May 2005.

[2] In-Hang Chung and Ming-Ching Yen, “On the Performance of Carrier Frequency Offset Estimation Algorithms Using an Maximum Likelihood Method with Delayed Correlation for OFDM-Based IEEE 802.11a WLANs,” submitted to IEEE Trans. Vehicular Technology, Jan. 2005.

[3] In-Hang Chung and Ming-Ching Yen, “A Maximum Likelihood Method with Two-Branch Delayed-Correlation for the Carrier Frequency Offset Estimation of OFDM-Based IEEE 802.11a WLANs,” submitted to IEEE Trans. Wireless Communications, July 2005.

[4] In-Hang Chung and Chung-Yi Chiang, “Using the FFT for the Interpolation of OFDM-Based IEEE 802.11a WLAN,” to be presented at Asian/Pacific Electro-Magnetic Conference (APEMC’2005), Taipei, December 2005.

[5] In-Hang Chung, Chi-Kuang Hwang and Ming-Fong Tzeng, “An Adaptive Sampling Time Offset Estimation Scheme Using Two Values of Correlation for OFDM-Based 802.11a WLAN,” to be presented at Asian/Pacific Electro-Magnetic Conference (APEMC’2005), Taipei, December 2005.

The following paper [1] in the proceedings of IEEE ICC’2005 summarizes major contribution arises from support of this NSC project.

Use of Diverse Delayed Correlation for an ML Carrier Frequency Offset Estimator in OFDM-Based IEEE 802.11a WLANs

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Abstract*— Estimation of Carrier Frequency Offset (CFO) is an important issue in the design of a WLAN receiver that employs OFDM techniques. In this paper, a new and efficient CFO estimation scheme that uses the ten short training symbols specified in the IEEE 802.11a standard will be proposed. This scheme, which we call DDC-ML, makes use of a Diverse Delayed Correlation (DDC) skill in the ML estimator. We will show that by using DDC-ML to estimate the CFO both large range and low variance of estimation error (VOER) can be attained. For AWGN channels under moderate Signal to Noise Ratio (SNR) conditions, a mathematical analysis will be developed to evaluate the VOER resulted from a CFO ML estimator that uses Delayed Correlation (DC-ML). The analysis will be corroborated via simulations, and compared with the formulated Cramer-Rao Lower Bound (CRLB). An optimum parameter combination for DC-ML estimator that can achieve minimum VOER will be obtained. VOER for the DDC-ML operated in a multipath environment will also be investigated via simulations. In addition, a new Ambiguity Resolution Algorithm (ARA) for the DDC-ML will be introduced and probability of false resolution will be presented. Performances of DC-ML and DDC-ML are compared in terms of probability of estimation error.

***Keywords*—Carrier Frequency Offset, Cramer-Rao lower bound, DC-ML, DDC-ML IEEE 802.11a, OFDM**

I. Introduction

In OFDM, where a single high data stream is transmitted over a number of low rate subcarriers (SCs), was pioneered by Chang in 1966 [1]. Characterized by the capability of combating frequency selective fading or time dispersion in wireless channels, a receiver that employs OFDM can mitigate the stringent requirement of complex equalizers [2]. Since the proposition of using the DFT/IDFT, or FFT/IFFT, processor in a transceiver, instead of banks of sinusoidal modulators and demodulators, implementation complexity of OFDM modems has been greatly reduced [3]. This makes OFDM adopted as the transmission technique for various standardized networks or systems in diverse fields [2], including the IEEE 802.11a WLAN in the 5 GHz U-NII frequency band [4].

It is well known that an OFDM system is vulnerable to synchronization errors. Inaccurate synchronization will degrade the system performance as a result of inter-symbol interference (ISI) or inter-subcarrier interference (ICI) [5]. This paper deals with investigation of efficient algorithms that use the Maximum Likelihood (ML) principle to estimate the Carrier Frequency Offset (CFO) in an OFDM-based IEEE 802.11a system. It is assumed that the timing and sampling clock synchronization tasks have already been accomplished.

In this paper, we propose a new efficient CFO estimation scheme that uses the ML principle with Diverse Delayed Correlation (DDC-ML). This scheme uses the ten Short Training Symbols (STSs) specified in the 802.11a standard training structure to form the decision metric. Since the metric is calculated in time domain, the CFO estimation will be completed prior to the DFT/FFT demodulator. An important feature of DDC-ML is the application of DDC to the CFO estimation. This is motivated by the observation that use of ML with Delayed Correlation (DC-ML) in the CFO estimation, the range and accuracy trade-off can be controlled by varying the distance, D, between the samples that are taken correlation, or by varying the length of the correlation window (CW), G, as studied in [6]-[8] (referring to Fig. 1). Our numerical results will show that by using DDC-ML, instead of DC-ML, both large range of CFO ($\geq 1/2$ subcarrier spacing) and low Variance Of Estimation erroR (VOER) can be attained simultaneously.

In the following, VOER for DC-ML in a medium Signal to Noise Ratio (SNR) condition will be analyzed for AWGN channels. The analysis will be validated in the light of simulations and compared with the developed Cramer-Rao Lower Bound (CRLB). Numerical results showing the VOER performance will be presented. An optimum combination of (D, G) for the DC-ML estimator that can achieve minimum VOER will be obtained. VOER of DDC-ML in a multi-path environment will also be investigated via simulations. Furthermore, a new Ambiguity Resolution Algorithm (ARA) will be introduced for DDC-ML. Simulated performance of ARA showing probability of false resolution and probability

This work is supported in part by the National Science Council of Taiwan under contract No. NSC-93-2213-E-216-027 and in part by the Chung Hua University under contract No. CHU-93-TR-003.

of estimation error will be provided. Note that in addition to the proposition of DDC-ML and new ARA, this paper differs from [6]-[8] in some aspects. For instance, [6] and [7] studied pilot channels and the correlation was taken in the frequency domain (post-FFT). Moreover, the VOER and the CRLB were not formulated therein. In [8], which studied a DC-ML estimator that used STSs for an 802.11a system, the VOER was not formulated. In addition, the expression of CRLB developed in [8] is looser than ours.

The signal model and training structure of OFDM for the 802.11a will be described in section II. This is followed by the DDC-ML and the new ARA introduced in section III. Mathematical analyses for evaluating the VOER and the CRLB of DC-ML under AWGN channels will also be developed in this section. Various numerical examples will be presented and discussed in section IV. Finally, section V concludes this paper.

II. OFDM Signal Model and Frame Format of 802.11a

A. OFDM Signal Model

Consider an OFDM system that uses an N-point FFT/IFFT processor to transmit data over N SCs with SC spacing $f_s = 1/T_s$, i.e., the FFT interval is T_s. If the duration of the cyclically prefixed guard interval (GI) is T_G, the length of a full symbol is $T_b = T_s + T_G$. Let the sampling clock period be denoted by T. Then, $T = T_s / N$. If the complex-valued input data transmitted in the k-th SC with center frequency $f_k = k/T_s$ is denoted by X_k, the baseband discrete time signal for an OFDM block after the IFFT can be expressed as

$$s_m = \frac{1}{N}\sum_{k=0}^{N-1} X_k e^{j\frac{2\pi mk}{N}}, 0 \le m \le N-1. \tag{1}$$

Assume that the wireless channel experiences an AWGN noise with power spectrum density σ_n^2. Further assume that the receiver can correctly identify the symbol boundary and the sampling clock is perfectly synchronized with that of the transmitter. If a frequency offset Δf and phase offset θ will be induced between the transmitter and the receiver, the received discrete time signal can be written as

$$r_m = \left(\frac{1}{N}\sum_{k=0}^{N-1} X_k e^{j\frac{2\pi mk}{N}}\right) e^{j(\frac{2\pi m\Delta k}{N}+\theta)} + n_m$$

$$= s_m e^{j(\frac{2\pi m\Delta k}{N}+\theta)} + n_m, \tag{2}$$

in which $\Delta k = T_s \Delta f = \Delta f / f_s$ is the normalized CFO with respect to SC spacing and n_m is the sampled AWGN noise with $E\{|n_m|^2\} = \sigma_n^2$. Let the average energy of a symbol be $E\{|s_m|^2\} = \sigma_s^2$. Then, $\text{SNR} = \sigma_s^2 / \sigma_n^2$.

B. Training Structure of 802.11a OFDM Signal Model

In the 802.11a standard [4], a 20 MHz bandwidth is divided into N = 64 SCs with spacing f_s = 312.5 kHz, or $T_s = 3.2\ \mu s$. Only 52 of the 64 SCs will carry messages, in which 48 SCs are used for the transmission of data. The other 4 SCs which carry pilot signals can be used for the detection of residual frequency offsets and phase noises. From the training structure shown in Fig. 2, we can see that an OFDM frame contains a $16\mu s$ preamble field, a $4\mu s$ signal field, and a data field with variable duration depending on the number of data symbols. The preamble field, which consists of ten repeated STSs, each with duration T_{short} = 0.8 μs, as well as two repeated Long Training Symbols (LTSs), each with duration T_{long} = 3.2μs, is used for synchronization. Note that there is a 1.6 μs guard interval GI2 preceding the LTS. Also note that while an LTS block consists of 53 SCs (including a zero value at dc), each STS block only contains 12 SCs. It is assumed that the system is not oversampled, i.e., $1/T$ = 20 MHz. Thus, there amounts to 16 samples in an STS.

III. Description of the Scheme

According to the 802.11a, the CFO must be estimated and recovered prior to the start of GI2 using the ten STSs, $t_1 \sim t_{10}$. Moreover, the CFO must be compensated to within $\pm 1/2$ SC spacing, i.e., $\pm$156.25 kHz, in this region so that the remaining CFO can be tracked by the LTSs, the GIs, or pilot symbols. The maximum allowable CFO specified in the 802.11a is $\pm 20\ ppm$. If the maximum carrier frequency of 5.8 GHz is assumed, the maximum CFO that can be tolerated is $5.8\,\text{GHz} \times (\pm 20\,ppm) \times 2 = \pm 232\,\text{kHz}$. Furthermore, the maximum CFO that can be estimated using the STS is $\pm 1/(2T_{short}) = \pm 625\,\text{kHz}$, which is a $\pm$ double of the SC spacing, 312.5 kHz. This paper concentrates on the estimation of CFO for 802.11a using the ten STSs $t_1 \sim t_{10}$.

A. Estimation of CFO Using DC-ML

Since existence of a CFO will induce phase rotation of an OFDM signal, we can estimate it by observing the phase difference resulted from correlation of a sampled signal and its delayed replica. To achieve high estimation accuracy, we usually take correlation from a sequence of samples and their replicas (called moving average). Referring to Fig. 1 and using (2), we can form the metric for DC-ML, as

$$ML(d) = \frac{1}{G}\sum_{m=0}^{G-1} r_{d+m}^{*}\, r_{d+m+D}, \tag{3}$$

in which * stands for complex conjugate, G is the CW size and D is the delay of the correlation, both measured in the number of samples. If the estimate of Δk is denoted by $\Delta\hat{k}$, then $\Delta\hat{k}$ can be obtained as

$$\Delta\hat{k} = \frac{N}{2\pi D}\arg ML(d), \tag{4}$$

where arg represents argument. One may note that the symbol time offset can also be jointly estimated by observing the peak of $|ML(d)|$, as adopted in [10]. But this will not be discussed in this paper. Let $\Delta\tilde{k} = \Delta\hat{k} - \Delta k$ denote the CFO ER. Assume that the estimator is efficient so that $2\pi D\Delta\tilde{k}/N << 1$. Further assume that the SNR is moderately high (this is the real case for reliable communications). Following the procedures described in [9], we can obtain the $\Delta\tilde{k}$ as

$$\Delta\tilde{k} \approx \frac{N}{2\pi DG\sigma_s^2}\left\{\mathrm{Im}\sum_{m=0}^{G-1}\left[s_m^{*}e^{-j(\frac{2\pi(m+D)\Delta k}{N}+\theta)}n_{m+D}\right.\right.$$

$$\left.\left.+s_m e^{j(\frac{2\pi m\Delta k}{N}+\theta)}n_m^{*}+n_m^{*}n_{m+D}e^{-j\frac{2\pi D\Delta k}{N}}\right]\right\}, \quad (5)$$

in which Im denotes the imaginary part of the specified complex number. From (5), it is not difficult to find that $E\{\Delta\tilde{k}\}=0$, i.e., the estimator is unbiased.

B. Variance and CRLB of DC-ML

When SNR is moderately high, we find that the VOER, $\mathrm{var}\{|\Delta\tilde{k}|\}$, can be approximately written as (the complete derivation procedure are omitted due to space limitation)

$$\mathrm{var}\{|\Delta\tilde{k}|\} = \begin{cases} \dfrac{N^2}{4\pi^2 D^2 G}\left[\dfrac{1}{\mathrm{SNR}}+\dfrac{1}{2(\mathrm{SNR})^2}\right], & \text{when } D \ge G \\ \dfrac{N^2}{4\pi^2 D G^2}\left[\dfrac{1}{\mathrm{SNR}}+\dfrac{G}{2D(\mathrm{SNR})^2}\right], & \text{when } D < G \end{cases}. \quad (6)$$

To determine the CRLB of the DC-ML for AWGN channels, we let $f(\vec{r}|\Delta k)$ denote the joint probability density function (pdf) of the sampled sequences in the observation window, for a given Δk. Expressions of $f(\vec{r}|\Delta k)$ will depend on the relationship of D and G. In case that $D \ge G$, $f(\vec{r}|\Delta k)$ can be written as

$$f(\vec{r}|\Delta k) = \prod_{m=0}^{G-1} f(r_m, r_{m+D}|\Delta k), \quad (7)$$

where $f(r_m, r_{m+D}|\Delta k)$ is the conditional joint pdf of the two samples, r_m and r_{m+D}, given Δk. Using (2), we find

$$f(r_m, r_{m+D}|\Delta k) = \frac{\exp\left\{-\dfrac{|r_m^*|^2 - 2\rho\,\mathrm{Re}\left[e^{-j2\pi D\Delta k/N} r_m^* r_{m+D}\right] + |r_{m+D}|^2}{(\sigma_s^2+\sigma_n^2)(1-\rho^2)}\right\}}{\pi^2(\sigma_s^2+\sigma_n^2)^2(1-\rho^2)}, \quad (8)$$

in which Re represents the real part, and the correlation coefficient ρ is defined as

$$\rho = \left|\frac{E\{r_m^* r_{m+D}\}}{\sqrt{E\{|r_m|^2\}}\sqrt{E\{|r_{m+D}|^2\}}}\right| = \frac{\sigma_s^2}{\sigma_s^2+\sigma_n^2} = \frac{SNR}{SNR+1}. \quad (9)$$

When $D < G$, $f(\vec{r}|\Delta k)$ can be expressed as

$$f(\vec{r}|\Delta k) = \prod_{m=0}^{D-1} f(r_m, r_{m+G}|\Delta k). \quad (10)$$

The $f(r_m, r_{m+G}|\Delta k)$ in (10) has similar form to the $f(r_m, r_{m+D}|\Delta k)$ used in (8), with ρ modified accordingly. Using (7)-(10) to establish the log-likelihood function and following the procedures described in [10], we obtain

$$\mathrm{CRLB} = \begin{cases} \dfrac{N^2}{4\pi^2 D^2 G}\left[\dfrac{1}{\mathrm{SNR}}+\dfrac{1}{2(\mathrm{SNR})^2}\right], & \text{for } D \ge G \\ \dfrac{N^2}{4\pi^2 D G^2}\left[\dfrac{1}{\mathrm{SNR}}+\dfrac{1}{2(\mathrm{SNR})^2}\right], & \text{for } D < G \end{cases}. \quad (11)$$

C. Estimation of CFO Using DDC-ML and ARA

Based on (4), the maximum CFO that can be estimated is $\Delta\hat{k} = \pm\pi(64/2\pi\times 16) = \pm 2$, or $\Delta f = \pm 625$ kHz, by using D = 16. In this case, however, the estimation accuracy will be worse, as can be inferred from (6). This stimulates our motivation to considering diverse delayed correlation for the CFO estimation, so that both the range and accuracy requirements can be fulfilled. A schematic block diagram of DDC-ML, which consists of two branches of DC-ML, is shown in Fig. 3. The (D_1, G_1) branch is designed for large estimation range and the (D_2, G_2) branch is devised for accuracy. Since the maximum CFO specified in the 802.11a standard is ± 232 kHz, we use $D_1 = 32$. For high accuracy, $D_2 > D_1$ is assumed. If the actual CFO is greater than the value of CFO corresponding to the maximum $\Delta\hat{k}$ obtained from (4) by using $D = D_2$, ambiguity may arise. To resolve this problem, we propose a simple ARA, as illustrated by the flow chart shown in Fig. 4 for D_1 = 32 and D_2 = 96. In this figure, f_{ecd1} and f_{ecd2} represent the CFO obtained from the (D_1, G_1) and (D_2, G_2) branch, respectively, and f_{ec} is the ultimate estimated CFO.

IV. Numerical Results and Discussion

For DC-ML in an AWGN channel with SNR = 5 and 20 dB, the VOER as a function of various combinations of D and G are depicted in Fig. 5. This figure shows that the analysis can accurately predict the VOER of DC-ML. Fig. 6 compares the VOER of DC-ML with the CRLB, as a function of SNR. It is found that in general the VOER approaches the CRLB asymptotically if SNR gets higher. The discrepancy between the attainable VOER and the CRLB becomes noteworthy when SNR is low and D is small.

In case that $D \ge G$, for a given N and SNR, we can find an optimum combination of D and G that will result in the minimum variance. Assume that for the purpose of counteracting the multipath effect, the first STS, t_1, is not used for the correlation operation. Then, $D + G = 144$. Classical calculus based on (6) shows that $D = 96$ will result in minimum VOER. On the other hand, if $D < G$, analytical value of D or G which can yield minimum VOER is not available, as it will depend on the SNR. However, if SNR >> 1, use of $G = 96$ will result in the minimum VOER. The above observations can be justified from the VOER characteristics plotted in Fig. 7.

For $\Delta f = 200$ kHz, we compare the simulated performance of DDC-ML under an AWGN channel and a Rayleigh fading channel in Fig. 8. The fading channel model employed is composed of 11 fading paths with time delay between adjacent paths $T_d = 50$ ns. Each path has a uniformly distributed phase over $[0,2\pi)$ and a Rayleigh distributed magnitude with average power decaying exponentially. The impulse response for the k-th path is described by $h_k = N(0,1/2\sigma_k^2) + j\,N(0,1/2\sigma_k^2)$, in which $\sigma_k^2 = \sigma_0^2 \exp\{-kT_d / T_{rms}\}$, $\sigma_0^2 = 1 - \exp\{-T_d / T_{rms}\}$, and $T_{rms} = 50$ ns. We can observe from Fig. 8 that, for the specified parameter and a given VOER, use of DDC-ML, instead of DC-ML, can achieve about 2dB SNR gain. Moreover, the benefit is more prominent in the multipath channel than that in the AWGN channel. For various values of CFO in the vicinity of 220 kHz, Fig. 9 plots the probability of false resolution versus SNR characteristics of the ARA in AWGN channels. This figure shows that the ARA can effectively resolve the ambiguity when SNR is moderately high. For $(D_1, G_1) = (32, 112)$ and $(D_2, G_2) = (96, 48)$, Fig. 10 displays simulated probability of estimation error versus SNR for the DC-ML and DDC-ML in AWGN channels. Superiority of DDC-ML over DC-ML can be clearly observed.

V. Conclusions

In this paper, we have proposed a new CFO estimation scheme, called DDC-ML, for an IEEE 802.11a WLAN. An important feature of DDC-ML is that by using two branches of DC-ML, both low VOER and large estimation range can be attained concurrently. For AWGN channels, formulas for evaluating VOER and CRLB of DC-ML in a medium SNR condition have been developed. The analysis has been validated in light of simulations. For $D + G = 144$ and $D \geq G$, we have found that $D = 96$ will result in minimum VOER. In case that $D < G$ and high SNR, minimum VOER occurs at $G = 96$. VOER of DDC-ML in a multipath scenario has also been studied via simulations. In addition, a new ARA to resolve the ambiguity problem associated with CFO estimation has been presented. Numerical examples showing probability of false resolution have revealed that ARA can accurately resolve the ambiguity when SNR is high. Probabilities of estimation error for DC-ML and DDC-ML have also been investigated via simulations. Numerical results have shown that DDC-ML outperforms DC-ML both in AWGN and multipath channels.

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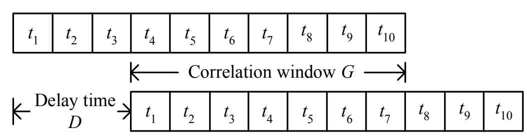

Fig. 1. Delay time and correlation window of DC-ML.

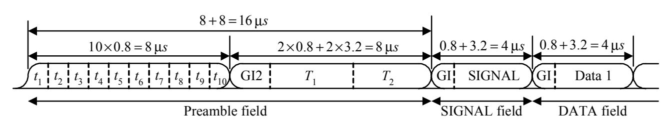

Fig. 2. Training structure of the IEEE 802.11a WLAN.

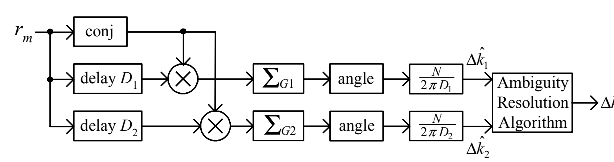

Fig 3. Schematic flow chart of DDC-ML.

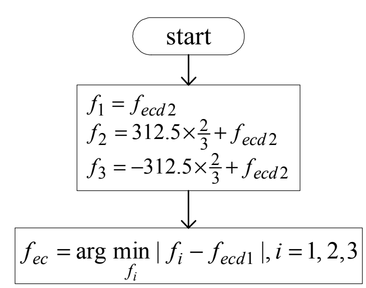

Fig. 4. Flow chart of ambiguity resolution algorithm for DDC-ML.

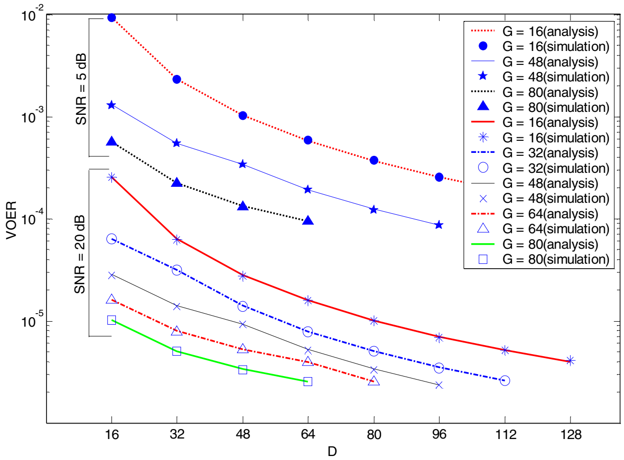

Fig. 5. Analytical and simulated VOER as a function of *D* for DC-ML for an AWGN channel, SNR = 5 and 20 dB.

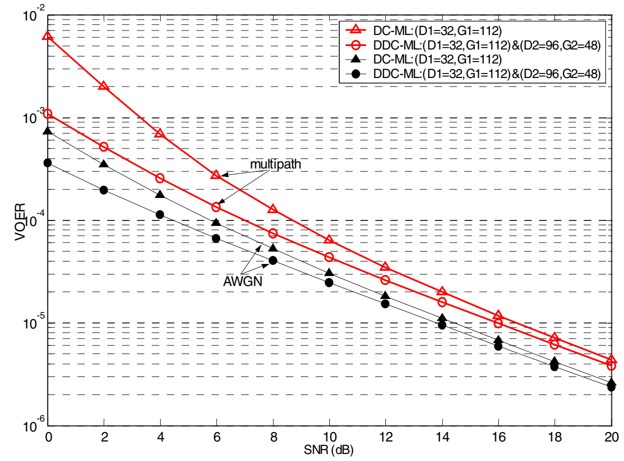

Fig. 8. Simulation results of DDC-ML with Δf = 200 kHz.

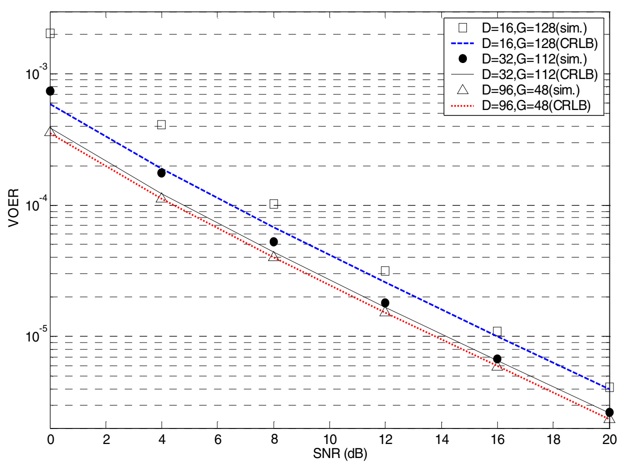

Fig. 6. Simulated VOER and the CRLB as a function of SNR for DC-ML in an AWGN channel.

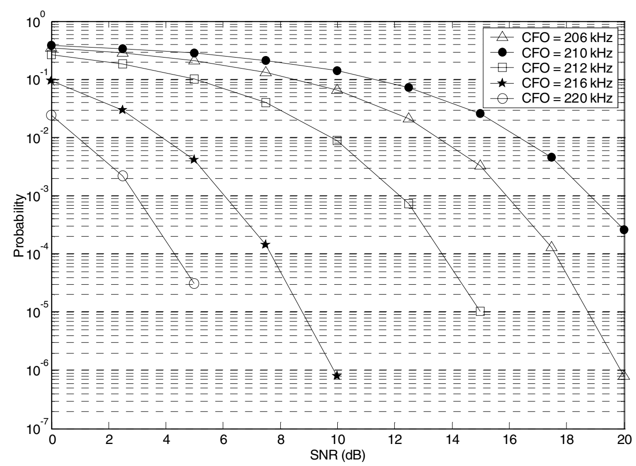

Fig. 9. Probability of false resolution of ARA versus SNR in AWGN channels.

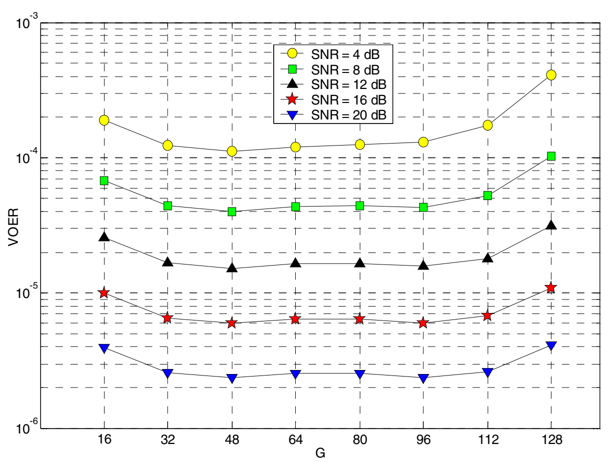

Fig. 7. VOER versus *G* characteristics of DC-ML for *D* + *G* = 144.

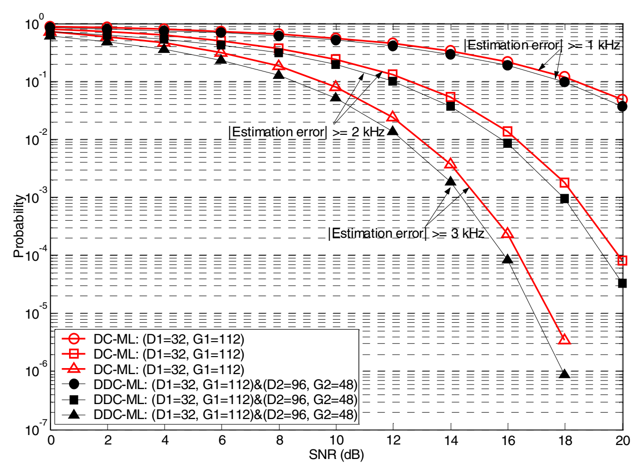

Fig. 10. Simulated probability of estimation error for DC-ML and DDC-ML with Δf = 200 kHz.