A novel relative speed estimation technique in WAVE using pilot subcarriers

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Abstract—**Wireless access in vehicular environment (WAVE) is a technology developed for high data rate vehicle-to-vehicle and vehicle-to-infrastructure communications. Accurate estimation of speed of a vehicular node is essential in applications of WAVE such as collision avoidance systems and intersection safety applications. A novel speed estimation technique in WAVE is presented in this paper. The method estimates the relative speed of a vehicle using the Doppler shift which causes frequency offset in the received orthogonal frequency division multiplexed subcarriers. The frequency offset in the received subcarriers is calculated using a cross correlation metric between the transmitted pilot subcarriers and the received pilot subcarriers. The method gives good estimates of relative speed even at low signal to noise ratios and the simulations demonstrate that wide range of speeds (0 to 360 km/h) can be accurately estimated.**

Keywords-WAVE; OFDM; Doppler shift; relative speed estimation.

I. INTRODUCTION

Wireless access in vehicular environment (WAVE) is a short range wireless communication technology that provides a solution to the intelligent transportation systems which are being developed around the world. An important objective of WAVE is to minimize vehicle accidents via the deployment of applications such as collision avoidance and intersection safety systems [1]. In WAVE a vehicle regularly broadcasts 'state' information such as its position, speed, heading direction and steering angle to other vehicles and neighboring access points known as road side units (RSUs). These regularly received 'state' messages are used in estimating the position of a vehicle relative to other vehicles in WAVE applications. These are also used in determining the position when forwarding packets (or other information) to vehicles by RSUs. In all the above applications it is important that accurate speed information is available.

An extensive body of research is available in the literature on speed estimation of mobile users in communication systems [2-4]. In [2], two dimensional Wiener filtering is used to estimate the mobile user's velocity in an orthogonal frequency division multiplexing (OFDM) based communication system. In [3], a double sampling rate signal processing technique is introduced to estimate mobile speed. In [4] an autocovariance function is used to estimate the mobile speed in a broadband wireless communication system. However, only a few research studies have addressed the estimation of a vehicle's speed in WAVE. The standards that govern WAVE are not clear on how a vehicle's speed is to be determined. To obtain speed, WAVE systems can use vehicle speedometer measurements, however the regulatory standards only enforce an accuracy of $\pm$10% for speedometers [5], therefore these measurements are not reliable. Global positioning system (GPS) receivers can also used to obtain speed. But these measurements have limited accuracy as well. Also GPS does not work in places where there is no direct line of sight to GPS satellites such as tunnels and urban canyons [6].

The physical layer communication of WAVE uses OFDM symbols. The wireless channel in WAVE is highly dynamic and the use of OFDM eliminates effect of inter symbol interference caused due to a dispersive channel. The OFDM symbols are sensitive to carrier frequency offset (CFO) which causes inter carrier interference (ICI) in the received OFDM subcarriers. CFO is caused due to two factors. It is caused as a result of the Doppler shift due to relative motion between the transmitter and the receiver and due to local oscillator (LO) mismatch. In this paper, we present a novel method that exploits the effect of Doppler shift on OFDM symbols in order to obtain an estimate of the vehicle's speed. We only consider the frequency offset due to Doppler shift in our analysis. We use the cross correlation properties between the transmitted and received pilot subcarriers to calculate the relative speed of a vehicle operating in WAVE. Presently in WAVE the frequency offset is estimated using a sequence of training symbols [7]. In our proposed method only the four pilot subcarriers in the WAVE OFDM symbol is used to estimate CFO. The simulation results demonstrate that the proposed method gives good estimates to a wide range of speeds varying from 0 to 360 km/h. The technique gives good estimates of speed even at low signal to noise ratios (SNRs). This paper is arranged as follows: Section II outlines the system description of WAVE, Section III presents an analysis of the proposed speed estimation method and Section IV presents the simulation results. Finally, in Section V conclusions are presented.

II. SYSTEM DESCRIPTION

This section provides a brief introduction to the WAVE system. Fig. 1 illustrates the main parts of a WAVE system. WAVE is based on the 5.9 GHz band, where 75 MHz has been set aside for dedicated short range communications amongst RSUs and on board units (OBUs) that are present in vehicles. The physical layer communication between the OBUs and RSUs uses OFDM.The physical and the medium access control layers of WAVE are as specified in the IEEE 802.11p which is

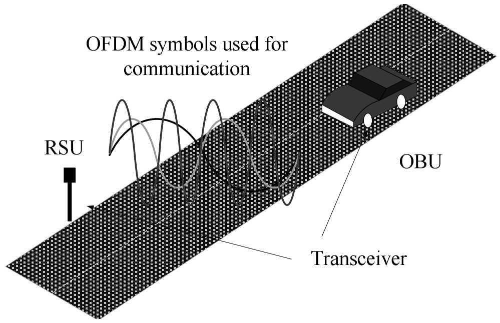

Figure 1. Parts of a WAVE system

based on the IEEE 802.11a (wireless local area network) standard [8]. The IEEE 802.11p standard specifies an OFDM symbol with 64 subcarriers out of which 48 are used to carry data, four are pilot subcarriers and the rest are null subcarriers. One of the purposes of the pilot subcarriers is to make coherent detection robust against channel noise and phase offset [7]. The pilot subcarriers are binary phase shift keying (BPSK) modulated using a pseudo-binary sequence to avoid the generation of spectral lines [7].

Fig. 2 shows the block diagram of a typical OFDM system. At the transmitter high speed serial data are first divided into parallel low bit rate streams which are then mapped on to subcarriers according to IEEE 802.11p standard. The mapped subcarriers, $a_{0,i},\ldots,a_{N-1,i}$ are modulated with a N - point inverse discrete Fourier transform (IDFT) to obtain time-domain samples, $b_{0,i},\ldots,b_{N-1,i}$ where $N=64$ denotes the number of subcarriers. These time-domain samples are then converted from parallel-to-serial, digital-to-analog and low-pass filtered. The signal, $x(t)$ is modulated next onto a high frequency carrier, $\exp(j2\pi f_c t)$, and sent across the channel. At the receiver the down-converted time domain signal $y(t)$ is low-pass filtered, analog-to-digital and serial-to-parallel converted before being demodulated back to the frequency domain by the discrete Fourier transform (DFT). The frequency domain signals, $z'_{0,i},\ldots,z'_{N-1,i}$ at the output of the DFT block is sent through a single tap equalizer and is finally converted to data via subcarrier demapping module.

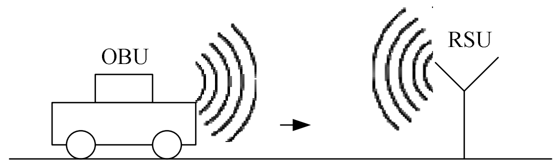

Figure 3. Case considered

III. Analysis of Proposed Speed Estimation Method

This section provides an analysis of the proposed method. The relative speed of a vehicle results in Doppler shift which causes CFO in the subcarrier frequency of the received OFDM symbols. The relative speed, v can be calculated using the formula $v=(\Delta f)\lambda$, where λ is the wave length of the signal and Δf is the Doppler shift. The case considered in this paper is shown in Fig. 3, where an OBU is directly moving towards a RSU, in this case the spatial angle between the incoming signal and the direction of travel of the vehicle is zero. The channel noise in the analysis is assumed to be additive white Gaussian noise.

Next, we will show that by taking the cross correlation between the received and transmitted pilot subcarriers, the normalized frequency offset, ΔfT can be estimated, which in turn can be used to estimate relative speed, v.

In WAVE, the pilot subcarriers carry known signals that are inserted in each OFDM symbol at the transmitter. Let $a_{p,i}$ denote a pilot subcarrier at the transmitter of the i^{th} OFDM symbol, where $p\in\{7,21,43,57\}$. The received pilot subcarrier is

$$z'_{p,i} = z_{p,i} + n_{p,i} \quad , \tag{1}$$

where $z_{p,i}$'s are the received subcarriers without the effect of noise and $z'_{p,i}$'s are the received subcarriers after being affected by noise terms, $n_{p,i}$ ($n_{p,i}$ is a sample of complex zero mean Gaussian noise of variance $\sigma_N^{\ 2}$). The m^{th} received subcarrier of the i^{th} OFDM symbol, $z_{m,i}$ can be written as [9]

$$z_{m,i} = \exp(j\theta_0)\sum_{l=0}^{N-1} c_{l-m} a_{l,i} \quad , \tag{2}$$

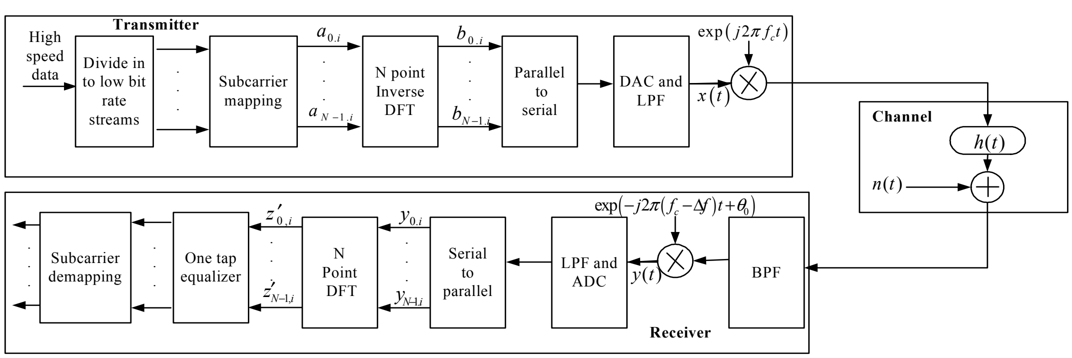

Figure 2. An OFDM system

where,

$$c_{l-m} = \frac{1}{N} \frac{\sin \pi(l-m+\Delta fT)}{\sin \frac{\pi(l-m+\Delta fT)}{N}} \exp j\pi \frac{(N-1)(l-m+\Delta fT)}{N} . \quad (3)$$

In (3) Δf is the frequency offset due to Doppler shift, $a_{l,i}$ is the transmitted subcarrier, T is the IDFT period, θ_0 is the phase offset between the carrier phase at the start of the received symbol and the phase of the receiver local oscillator and $c_{-N+1},\ldots c_0,\ldots,c_{N-1}$ are the complex weighing factors. ΔfT denotes normalized frequency offset. When there is no CFO, $z_{m,i} = \exp(j\theta_0) a_{m,i}$, the received subcarrier will only undergo a phase rotation of the wanted subcarrier. When there is ICI the weighted sum of all c_{l-m} values other than c_0 will make the other subcarriers interfere with the wanted subcarrier, $a_{m,i}$. In this paper $\theta_0 = 0$ is assumed as the phase offset can be corrected using a phase offset correction algorithm [10].

Let $X = \left[a_{7,i}, a_{21,i,} a_{43,i}, a_{57,i}\right]$ be the vector of transmitted pilot subcarriers and $Y = \left[z'_{7,i}, z'_{21,i,} z'_{43,i}, z'_{57,i}\right]$ be the vector of received pilot subcarriers. Now, the cross-correlation between the received pilots and transmitted pilots is defined as

$$R_{XY}(k) = \begin{cases} \sum_{i=0}^{4-k-1} x_{i+k} y_i^* & \text{for } k \geq 0 \\ R^*_{YX}(-k) & \text{for } k < 0 \end{cases} , \quad (4)$$

where x_i and y_i are elements of vectors X and Y respectively, and $k = 0, \pm 1, \pm 2, \pm 3$ is the position index. Since noise terms, $n_{p,i}$ are independent and identically distributed (i.i.d.) variables, $E\left\{a_{p,i}.\left(z_{p,i}+n_i\right)\right\} = E\left\{a_{p,i}.z_{p,i}\right\}$, where $E\{\cdot\}$ denotes the expectation operator. It is observed that the statistical mean of the cross correlation between the transmitted and received pilot symbols is not affected by the noise in the wireless channel.

In order to calculate the CFO, $\text{imag}(R_{XY}(0))$ is used, which is given by

$$\begin{aligned} \text{imag}(R_{XY}(0)) = \text{imag}(&a_{7,\,i}\, z'^{*}_{7,\,i} + a_{21,\,i}\, z'^{*}_{21,\,i} \\ &+ a_{43,\,i}\, z'^{*}_{43,\,i} + a_{57,\,i}\, z'^{*}_{57,\,i}) \end{aligned} . \quad (5)$$

The function, $\text{imag}(R_{XY}(0))$ is related to ΔfT. The mean of it is as follows: (Appendix A)

$\mathrm{E}\{\text{imag}(R_{XY}(0))\} = \text{imag}(4c_0)^*$, now substituting (3)

$$= -\left(\left(\frac{4}{N}\right)\left(\frac{\sin \pi(\Delta fT)}{\sin \frac{\pi(\Delta fT)}{N}}\right)\sin\left(\frac{(N-1)\pi\Delta fT}{N}\right)\right) \approx -12.37\Delta fT \quad .$$

Therefore the metric, $\hat{m}$ used to calculate the CFO can be defined as follows

$$\hat{m} = \frac{1}{N_1}\sum_{n=1}^{N_1} \text{imag}\left(R_{XY}(0)_n\right) , \quad (6)$$

where N_1 is the number of OFDM symbols averaged. The metric $\hat{m}$ is related to ΔfT as follows: $\Delta fT \approx -\frac{\hat{m}}{12.37}$ (7). The relative speed of the vehicle can be found by using the formula $v = \Delta f \lambda$, which gives

$$v = \frac{-\hat{m}\lambda}{12.37T} . \quad (8)$$

The mean of the metric is as follows:

$$\begin{aligned} E\{\hat{m}\} &= E\left\{\frac{1}{N_1}\sum_{n=1}^{N_1} \text{imag}\left(R_{XY}(0)_n\right)\right\} \\ &= E\left\{\text{imag}\left(R_{XY}(0)\right)\right\} = \text{imag}(4c_0)^* , \end{aligned} \quad (9)$$

which is directly related to ΔfT.

The variance of the metric, $\hat{m}$ is given by

$$\text{var}(\hat{m}) = \text{var}\left(\frac{1}{N_1}\sum_{n=1}^{N_1} \text{imag}\left(R_{XY}(0)_n\right)\right) ,$$

which simplifies (Appendix B) to

$$\text{var}(\hat{m}) \approx \frac{1}{N_1^2}\sum_{n=1}^{N_1}\left(2\left(1-|c_0|^2\right) + 2\sigma_N^2\right) = \frac{2}{N_1}\left(1-|c_0|^2\right) + \frac{2\sigma_N^2}{N_1} , \quad (10)$$

where σ_N^2 is the noise variance. Since $\hat{m}$ is composed of a sum of large number of independent random variables the probability density function (PDF) of $\hat{m}$ can be approximated by a Gaussian distribution of mean and variance given by (9) and (10) respectively.

IV. Simulation Results

Monte Carlo simulations were run for 10,000 OFDM symbols to investigate the relationship between the Doppler shift and $\hat{m}$. Quadrature phase shift keying was selected as the modulation scheme of the data subcarriers and the simulated WAVE OFDM symbol consisted of 48 subcarriers with random data signals, four subcarriers with pilot signals modulated by BPSK and 12 null subcarriers as specified in the standard [7]. Only the four pilot subcarriers were used in determining the cross correlation metric $\hat{m}$.

Fig. 4 presents the simulated graph of $\hat{m}$ against actual speed and the graph obtained from (8). A case where no channel noise is present is considered in this plot. It can be observed that a linear relationship exists between $\hat{m}$ and actual speed and that the simulation results closely follow the analytical values of equation (8). In a receiver if $\hat{m}$ can be

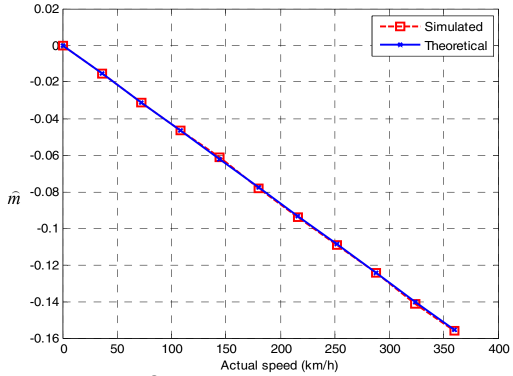

Figure 4. $\widehat{m}$ against actual speed (no noise present)

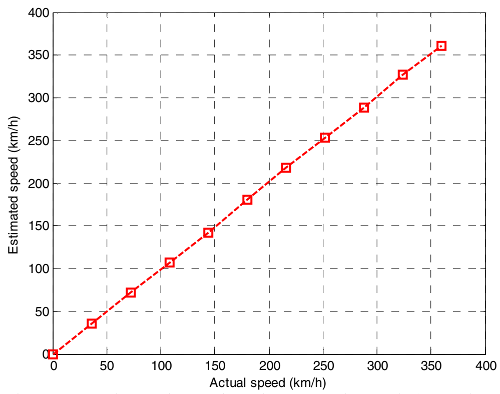

Figure 5. Estimated speed against actual speed (no noise present)

TABLE I. MEAN AND VARIANCE VALUES OF THE PDFS IN FIG. 8

	Mean	Variance
$\Delta fT = 0.01$	Simulated =- 0.1234 Theoretical =-0.1237	Simulated = 6.3955 x 10 $^{-5}$ Theoretical =6.3903 x 10 $^{-5}$
$\Delta fT = 0.02$	Simulated = -0.2474 Theoretical =-0.2471	Simulated = 6.5807 x 10 $^{-5}$ Theoretical =6.5875 x 10 $^{-5}$

calculated, the corresponding speed of the vehicle can be obtained using the graph. Fig. 5 shows a plot of estimated speeds against actual speeds for a case where no channel noise is present. It can be observed that estimated speeds obtained using (8) give good approximation to actual value of speeds. A wide range of speeds, 0 to 360 km/h can be accurately estimated. Fig. 6 shows the relationship between $\widehat{m}$ and actual speed for various SNRs. As $\widehat{m}$ is obtained by (6), when more OFDM symbols are averaged the estimated values tend to actual values and the metric becomes independent of noise. The slight variations seen are due to the randomness of noise. It can be seen that even for low SNRs the linear relationship between $\widehat{m}$ and actual speed still holds. Fig. 7 shows the analytical and simulated PDFs of the metric, $\widehat{m}$ for the $\Delta fT = 0.1$ case. It illustrates how the variance of the metric, $\widehat{m}$ increases as SNR is reduced and how the mean values, which is directly related to ΔfT, remains unchanged. Each $\widehat{m}$ value is obtained by averaging 1000 OFDM symbols, and then 1000 samples of $\widehat{m}$ are used to plot the simulated PDFs in Fig. 7 and Fig. 8. It can be observed in Fig. 7 and Fig. 8 that the analytical

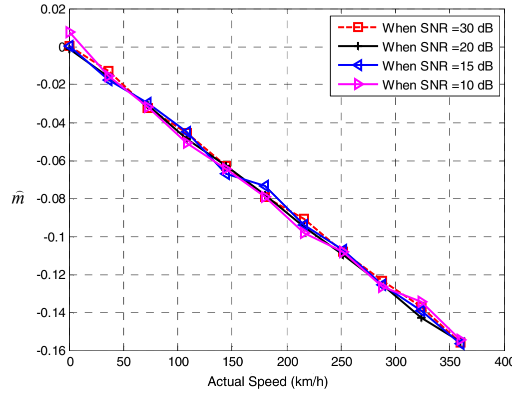

Figure 6. $\widehat{m}$ against actual speed for different SNRs

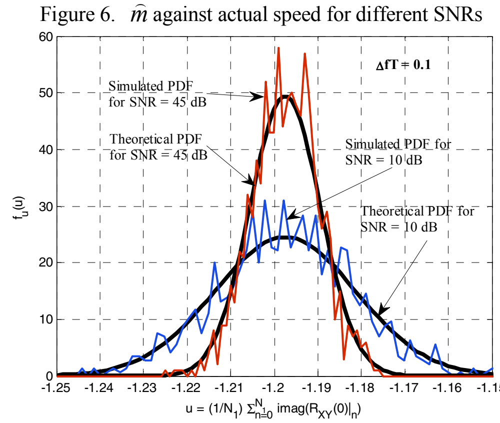

Figure 7. PDF for different SNRs, when $\Delta fT = 0.1$

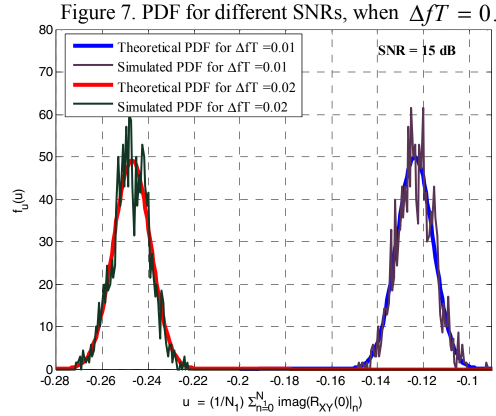

Figure 8. PDF for different ΔfT values, when SNR = 15 dB

PDFs which are drawn assuming a Gaussian distribution and the simulated PDFs follow each other closely; hence $\widehat{m}$ can be accurately approximated by a Gaussian distribution. Fig. 8 shows the PDF of $\widehat{m}$, for different values of ΔfT for a case where SNR is 15 dB. It is observed that as ΔfT changes the mean varies to reflect the relationship shown in (9). Table I gives the mean and variance values of the simulated and analytical PDFs of Fig. 8. The values in Table I show that the mean and variance of the metric obtained via simulations closely match the values obtained according to (9) and (10).

An advantage of the proposed method is that only four pilot subcarriers are used for frequency offset estimation unlike the present technique in WAVE which uses a sequence of training symbols [7]. The frequency offset caused by LO mismatch can be obtained by processing and analyzing the variations of CFO over a period of time. Only ΔfT due to Doppler shift is directly related to the relative speed, v hence it is estimated.

V. CONCLUSION

This paper presents a novel method that uses a cross correlation function between the transmitted pilot subcarriers and the received pilot subcarriers of OFDM symbols exchanged in the physical layer to estimate the relative speed of a vehicle in WAVE. The proposed technique uses the inherent characteristics of the received OFDM symbols to estimate the relative speed of a vehicle, hence is not dependent on a vehicle to send out its speed information. The exchange of fraudulent speed information by vehicles is eliminated by this method, thereby increasing the integrity of the speed information available to RSUs and OBUs. The method is able to estimate a wide range of speeds (0 to 360 km/h) using Doppler shift present in the received OFDM symbols and it gives good approximates even at low SNR values. The method only uses the four pilot subcarriers in the OFDM symbol to estimate speed and does not require training symbols.

VI. APPENDIX A

$E\{\mathrm{imag}(R_{XY}(0))\}$ is simplified as follows

$$E\{\mathrm{imag}(R_{XY}(0))\} =$$

$$\mathrm{imag}\left(\begin{array}{l}\left[\exp(j\theta_0)\right]^*\left[c_{-7}E\{a_{0,i}{}^*a_{7,i}\}+\ldots+c_0E\{a_{7,i}{}^*a_{7,i}\}+\ldots\right] \\ +\left[\exp(j\theta_0)\right]^*\left[c_{-21}E\{a_{0,i}{}^*a_{21,i}\}+\ldots+c_0E\{a_{21,i}{}^*a_{21,i}\}+\ldots\right] \\ +\left[\exp(j\theta_0)\right]^*\left[c_{-43}E\{a_{0,i}{}^*a_{43,i}\}+\ldots+c_0E\{a_{43,i}{}^*a_{43,i}\}+\ldots\right] \\ +\left[\exp(j\theta_0)\right]^*\left[c_{-57}E\{a_{0,i}{}^*a_{57,i}\}+\ldots+c_0E\{a_{57,i}{}^*a_{57,i}\}+\ldots\right] \\ +E\{a_{7,i}\ n_{p,i}\}+E\{a_{21,i}\ n_{p,i}\}+E\{a_{43,i}\ n_{p,i}\}+E\{a_{57,i}\ n_{p,i}\}\end{array}\right) \tag{11}$$

Assuming that all inputs are random and i.i.d.

$$E\{a_r{}^*a_p\} = E\{a_r{}^*\}E\{a_p\} = 0 \text{ for } r \neq p .$$

Since noise terms, $n_{p,i}$ are independent and i.i.d., $E\{a_{p,i}\ n_{p,i}\} = 0$. $a_7,\ a_{21},\ a_{43},\ a_{57}$ are pilot symbols that can take either $+1$ or -1 values, which are multiplied by a pseudo-binary sequence, hence (11) becomes

$$E\{\mathrm{imag}(R_{XY}(0))\} = \mathrm{imag}\left[\exp(j\theta_0)4c_0\right]^* . \tag{12}$$

Using the assumption that $\theta_0 = 0$, (12) becomes, .

$$E\{\mathrm{imag}(R_{XY}(0))\} = \mathrm{imag}\left[4c_0\right]^* \tag{13}$$

Substituting (3) in (13), then assuming that for small ΔfT values $\sin\pi\Delta fT \approx \pi\Delta fT,\ \cos\pi\Delta fT \approx 1,\ \ \sin\frac{\pi\Delta fT}{N} \approx \frac{\pi\Delta fT}{N}$ and $\cos\frac{\pi\Delta fT}{N} \approx 1$. Neglecting the higher order terms of ΔfT , and using the Taylor series (13) can be simplified to

$$\mathrm{imag}(4c_0)^* \approx -\left(\frac{N-1}{N}\right)(\pi\Delta fT) = -12.37\Delta fT . \tag{14}$$

VII. APPENDIX B

$\mathrm{var}(\mathrm{imag}(R_{XY}(0)))$ is simplified as follows,

$$E\{(\mathrm{imag}(R_{XY}(0)))^2\} \approx 2(1-|c_0|^2)+16\ (\mathrm{imag}(c_0))^2$$
$$+\ 4\ \mathrm{imag}(c_{36})\mathrm{imag}(c_{-36})+4\ \mathrm{imag}(c_{14})\mathrm{imag}(c_{-14})$$
$$+2\ \mathrm{imag}(c_{22})\mathrm{imag}(c_{-22})+2\ \mathrm{imag}(c_{50})\mathrm{imag}(c_{-50})+2\sigma_N{}^2$$

c_i's are very small for $i = \pm 14,\ \pm 22,\ \pm 36,\ \pm 50$, compared to c_0 which is the most prominent term, hence,

$$E\{(\mathrm{imag}(R_{XY}(0)))^2\} \approx 2(1-|c_0|^2)+16\ (\mathrm{imag}(c_0))^2+2\sigma_N{}^2 .$$

$$\therefore\ \sigma^2 = \mathrm{var}(\mathrm{imag}(R_{XY}(0))) = E\{(\mathrm{imag}(R_{XY}(0)))^2\}+$$
$$-(E\{\mathrm{imag}(R_{XY}(0))\})^2 \approx 2(1-|c_0|^2)\ +2\sigma_N{}^2$$

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