IEIE Transactions on Smart Processing and Computing, vol. 6, no. 1, February 2017
https://doi.org/10.5573/IEIESPC.2017.6.1.039

IEIE Transactions on Smart Processing and Computing

A Study on an Integer Frequency Offset Estimation and Compensation for DOCSIS 3.1 Downstream

JaeHwui Bae, JinHyuk Song, Sang-Jung Ra, Dong-Joon Choi, Joon-Young Jung, and Namho Hur

Media Transmission Research Group, Media Research Division, Electronics and Telecommunications Research Institute, Daejoen, ROK {jhbae, song020, sjna, djchoi, jungjy, namho}@etri.re.kr

***** Corresponding Author: JaeHwui Bae

Received January 18, 2017; Accepted January 27, 2017; Published February 28, 2017

** Regular Paper*

** Extended from a Conference: Preliminary results of this paper were presented at the ICCE-Asia2016.*

***Abstract*:** In this paper, we propose an integer frequency offset estimation and compensation method based on PLC preamble correlation in DOCSIS 3.1 Downstream system. The proposed method determines the PLC preamble subcarrier location recovered from PLC data and the one obtained from PLC preamble correlation. We showed the performance of PLC preamble detection in the received signal through the maximum value detection of PLC preamble correlation. Thus we can estimate and compensate for the integer frequency offset by computing the difference of PLC subcarrier locations.

***Keywords*:** Integer frequency offset, DOCSIS 3.1, PLC preamble correlation

1. Introduction

DOCSIS 3.1 DS(downstream) can be applied to increase the data rate of cable network comparable to the fiber network with 10Gbps [1]. DOCSIS 3.1 has high flexibility in allocating PLC(physical layer-link channel) which transmits OFDM parameters and downstream profile information [2]. For the 10Gbps data rate, 4096QAM should be used. Because 4096QAM has very small Euclidean distances between neighboring constellations, it can be distorted by even small degradations caused by the receiving signal processing. Therefore it is necessary to minimize the signal degradations in the receiving process. The reception of DOCSIS 3.1 DS signal requires high performance synchronization methods for the detection of the starting point of OFDM symbols, fractional and integer frequency offsets and PLC Preamble location. Especially the frequency offset estimation and compensation scheme is very important because it may result in the destruction of orthogonality among OFDM subcarriers and severely degrade the received signal. For FFO(fractional frequency offset) estimation, the cyclic prefix phase comparison method proposed by Beek et al can be used [3]. But for integer frequency offset estimation, an efficient method suitable for DOCSIS 3.1 DS is required.

In this paper, we propose an IFO(integer frequency offset) estimation method based on the PLC preamble correlation of DOCSIS 3.1 DS. It determines the locations of PLC subcarriers in the frequency axis by detecting the maximum value of PLC preamble correlation. The exact PLC subcarrier location allocated in the transmitter side can be found by recovering the PLC data. When these two PLC location values are compared, the integer frequency offset can be estimated. If the spectrum of the received signal is shifted according to the estimated value, the integer frequency offset can be compensated for. We showed the performance of the proposed method with a typical OFDM STO(symbol timing offset) value in AWGN channel.

2. Overview of DOCSIS 3.1 Downstream

DOCSIS 3.1 system is developed for 10Gbps data transmission through the cable network. DOCSIS 3.1 DS system uses high order QAM modulation such as 4096QAM for 10Gbps data rate. DOCSIS 3.1 DS has SPs (scattered pilots) for channel estimation and equalization and CPs (continuous pilots) for the sampling clock synchronizations etc [2]. The SPs repeat for every 128 OFDM symbols. The CPs exist at the same subcarrier

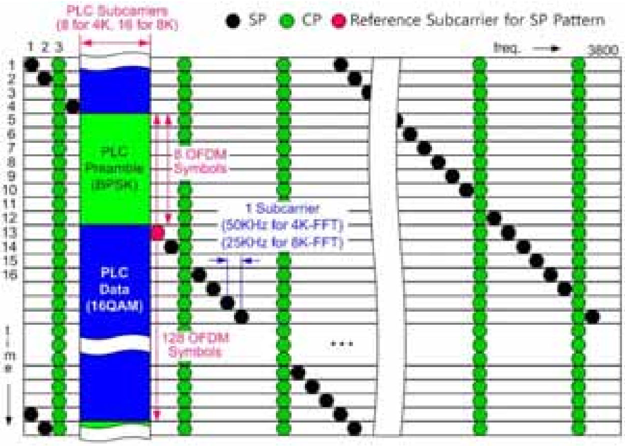


Fig. 1. Pilot Patterns of DOCSIS 3.1 DS 4K-FFT mode.

locations for every OFDM symbol. There are two SP patterns: one for 4K FFT and one for 8K FFT. Although these pilots occur at different frequency locations in different OFDM symbols, the patterns repeat after every 128 OFDM symbols, i.e. it has a periodicity of 128 OFDM symbols along the time dimension.

2.1 Pilot Patterns of DOCSIS 3.1 DS

We explained the 4K-FFT mode for convenience. An example of pilot patterns for 4K-FFT mode is shown in Fig. 1. The SP pattern is synchronized to the PLC. (Ed- already defined above) The first OFDM symbol after the PLC preamble has an SP in the subcarrier just after the highest frequency subcarrier of the PLC preamble marked as red circles in Fig. 1. The SPs are placed at the same subcarrier location for every 128 OFDM symbols along the time axis and every 128 subcarriers along the frequency axis [2]. From symbol to symbol, SPs are shifted by one subcarrier position in the increasing direction of the frequency axis. SPs are not placed both in the exclusion band and in the PLC band (Ed- I've presumed that you don't mean "SPs are not placed in the exclusion band but rather in the PLC band"). When the location of an SP coincides with that of a CP, it is treated as a CP and not as an SP.

The pilot pattern of 8K-FFT mode has almost the same SP pattern allocation as 4K-FFT mode except that pilots are stepped by two subcarriers from one OFDM symbol to the next [1]. By inserting SP subcarriers with 2 subcarriers span, the SPs of 8K-FFT do not cover all subcarrier locations. To solve this problem, the entire 8K-FFT SP locations can be shifted by one subcarrier location after 64 subcarriers. As a result, the SPs cover all subcarrier locations and the periodicity of the 8K FFT SP pattern becomes 128.

2.2 PLC Subcarriers in DOCSIS 3.1 DS

The PLC in DOCSIS 3.1 DS transmits the modulation parameter information such as QAM order, interleaving depth, guard interval length, and PLC subcarrier location etc [2]. The PLC has a repetition period of 128 OFDM symbols, as shown in Fig. 1. The PLC consists of PLC Preamble of 8 OFDM symbols with BPSK and PLC data of 120 OFDM symbols with 16QAM.

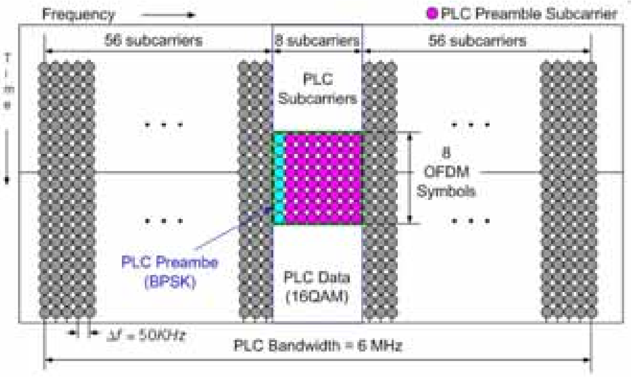


Fig. 2. PLC subcarrier structure of 4K-FFT mode in DOCSIS 3.1 DS.

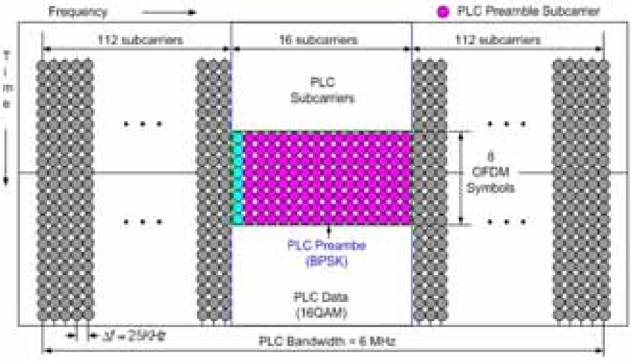


Fig. 3. PLC subcarrier structure of 8K-FFT mode in DOCSIS 3.1 DS.

The PLC has 8 subcarriers for 4K-FFT, as shown in Fig. 2, and 16 subcarriers for 8K-FFT, as shown in Fig. 3. For 4K-FFT mode, the subcarrier spacing Δf is 50KH . There are $120(=\left(6\times10^{6}\right)/(50\times10^{3}))$ subcarriers in 6MHz PLC band and 56 subcarriers in both sides of PLC subcarriers. The 8 PLC subcarriers are located in the center, as shown in Fig. 2. For 8K-FFT mode, the subcarrier spacing Δf is 25KHz. There are $240(=\left(6\times10^{6}\right)/(25\times10^{3}))$ subcarriers in 6MHz PLC band and 112 subcarriers in both sides of PLC subcarriers. The 16 PLC subcarriers are located in the center, as shown in Fig. 3.

3. Proposed Integer Frequency Offset Estimation and Compensation

In this section, we explain the conventional IFO estimation method used for other cable TV systems such as DVB-C2. Also we explain the proposed IFO estimation method for DOCSIS 3.1 DS in detail and explain why the conventional method used for DVB-C2 cannot be used for DOCSIS 3.1 DS.

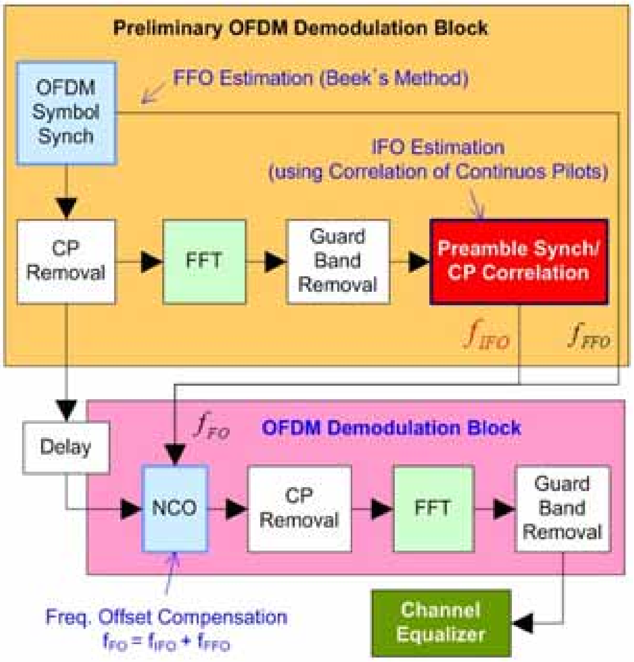


Fig. 4. Block Diagram of the Conventional IFO estimation method for DVB-C2.

3.1 Conventional IFO Estimation Method for DVB-C2

The conventional IFO estimation method for DVB-C2 is based on the correlation of the preamble pilots which are in preamble OFDM symbols [4]. Preamble OFDM symbols are inserted for every C2 frame to determine the starting point of C2 frame in the receiver side [5]. The preamble pilot is a known information. Therefore, when preamble OFDM symbols are detected, it is possible to correlate the preamble pilots to the received preamble OFDM symbols and determine IFO by detecting the maximum correlation value location in frequency axis [4].

Preamble OFDM symbols can be detected in frequency domain after FFT block, as shown in Fig. 4. The FFO can be obtained by Beek's method when OFDM symbol synchronization is obtained [3]. IFO and FFO are summed and compensated with NCO(numerically controlled oscillator). When the frequency offset f_{FO} is compensated for, the demodulation of the received signal is started by applying the 2nd FFT block, as shown in Fig. 4. As explained above, the conventional IFO estimation method requires two FFT blocks, which may result in the heavy complexity increase in the receiver.

To apply the conventional IFO estimation to DOCSIS 3.1 DS, the CP pattern has to be known information to the receiver. Although the CP pattern of DOCSIS 3.1 DS is not known information, it is closely related to the location of PLC subcarriers defined in DOCSIS 3.1 specifications [2]. The CP pattern can be recovered when the PLC subcarrier location is found after PLC synchronization. The CP pattern is recovered according to the procedures defined in DOCSIS 3.1 specification [6]. But if the PLC subcarrier location is shifted by IFO, then the CP pattern is also shifted and the correlation gives a shifted maximum correlation point. It is difficult to determine IFO if the PLC subcarrier location defined in the transmitter is not known.

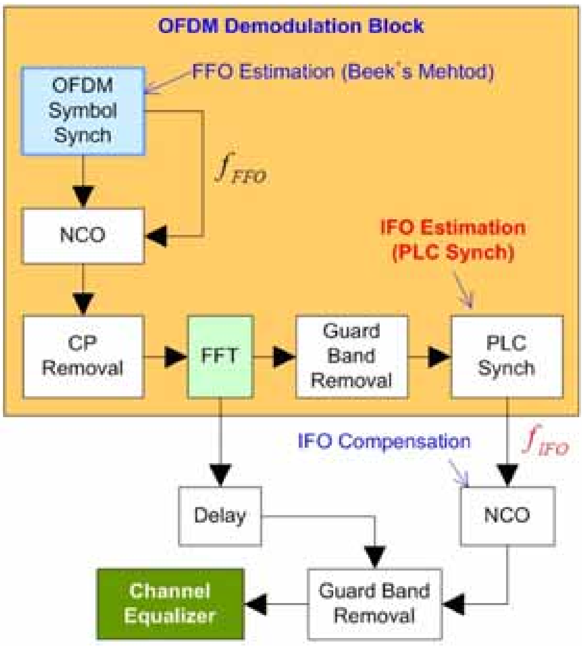


Fig. 5. Block Diagram of the Proposed IFO estimation method for DOCSIS 3.1 DS.

3.2 Proposed IFO Estimation Method for DOCSIS 3.1 DS

The proposed IFO estimation and compensation is based on PLC preamble correlation using PLC Preamble subcarriers of the Tx(transmitted) and the Rx(received). When the Tx and the Rx PLC Preambles coincide, the correlation is maximized [6]. So the detection of the maximum value can detect the location of the PLC subcarriers along the frequency axis in the received signal. Through the detection of PLC location from the received signal and the recovery of PLC location defined in Tx side, these two PLC locations can be compared and the IFO can be found. It requires one FFT block, as shown in Fig. 5.

The steps of the proposed method are as follows.

1. Step 1 - Detection of PLC Preamble subcarriers location in the received signal

For correlation, Tx and Rx PLC Preambles of 2D signal have to be converted in 1D signal, as shown in Fig. 6.

The same size of Rx signal with Tx PLC Preamble is applied for correlation. PLC Preamble has 8 OFDM symbols and 8 subcarriers for 4K-FFT, and 8 OFDM symbols and 16 subcarriers for 8K-FFT. The Rx signal selection window shifts along time and frequency axis, as shown in Fig. 7 for the 4K-FFT case. In time axis, the window moves from OFDM symbol 1~128, the PLC Preamble repetition period. In frequency axis, it moves N~(3800-N+1) for 4K-FFT and N~(7600-N+1) for 8K-FFT, where N is 4 for 4K- and 8 for 8K-FFT. The selected Rx signal is converted to 1D signal, as described in Step 1.

The detection of the PLC Preamble correlation

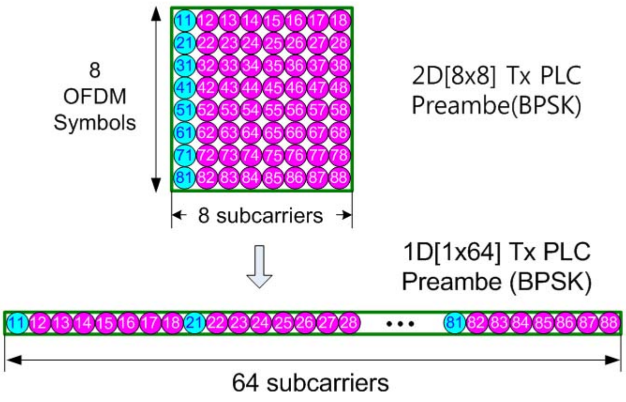


Fig. 6. Conversion of PLC preamble from 2D to 1D.

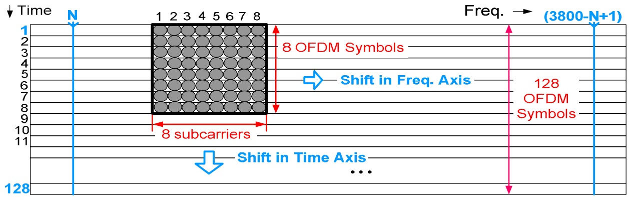


Fig. 7. Correlation window shifts in time and frequency for 4K-FFT.

maximum value is performed along both time and frequency axes. The correlation of PLC preamble is performed with real and imaginary terms of the received signal, respectively, and their results are summed. When the maximum of the summed correlation results is detected, the exact location of PLC preamble in the frequency axis can be found.

2. Step 2 –Extraction of PLC subcarrier location allocated in the transmitter side from PLC data

When the location of PLC preamble is detected from the received signal, the PLC data can be extracted and recovered. For the demodulation of the received DOCSIS 3.1 DS signal, it is necessary to know the applied OFDM modulation parameters and information of DS profile such as QAM order, time interleaving depth and, PLC subcarrier location, which are defined in the Tx side and stored in the OFDM channel descriptor and downstream profile descriptor [7]. They can be obtained by recovering the PLC data. For the IFO estimation, the information of PLC subcarrier location allocated in Tx side is needed and it can be obtained easily through the PLC data recovery.

3. Step 3 –IFO Computation

The detection of PLC Preamble correlation maximum value is performed in the ranges for time and frequency, as described in Step 2. The correlation is performed with a real term and an imaginary term [4]. The IFO can be computed by comparing the PLC subcarrier locations obtained from the PLC preamble correlation and recovered from the PLC data defined in Tx side. The difference between them is the desired IFO value.

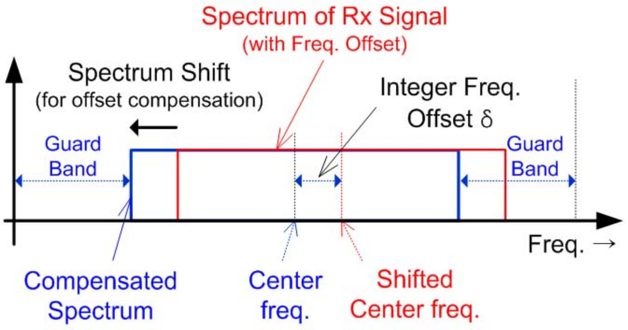


Fig. 8. IFO compensation by the spectrum shift before active subcarrier extraction.

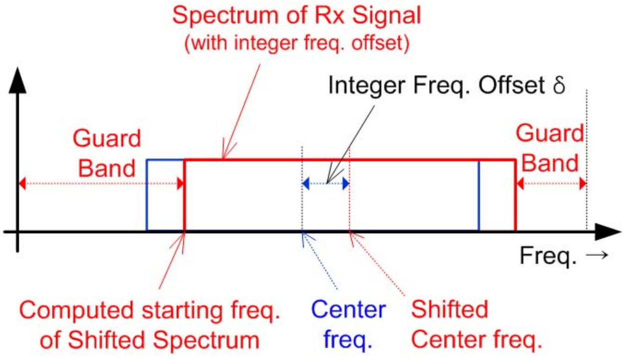


Fig. 9. IFO compensation by extracting the active OFDM subcarrier from the computed starting frequency of the received spectrum.

4. Step 4– IFO Compensation

For the compensation of IFO, we presented two methods as typical ways.

A. Shifting of the received spectrum according to the estimated integer frequency offset

When the spectrum of the received signal is shifted according to the estimated integer frequency offset, then the location of the received spectrum shall be adjusted to the original position allocated in the transmitter side. Through this processing, the integer frequency offset is compensated for. For the guard band removal, the same numbers of subcarriers for both sides are eliminated, as shown in Fig. 8.

B. Start point computation of the received spectrum with IFO

Before the compensation of integer frequency offset, the received spectrum will be like the red one which is shifted according the estimated integer frequency offset, as shown in Fig. 9. When the starting point of active subcarriers in the shifted spectrum is computed, then the active subcarriers of an OFDM symbol can be obtained by extracting the 3800 subcarriers for 4K-FFT and 7600 subcarriers for 8K-FFT, respectively.

The proposed IFO estimation method requires PLC preamble correlation to determine the PLC preamble location in frequency axis. When PLC synchronization is performed on the PLC preamble correlation, as explained in [8], then the PLC preamble correlation can be used for PLC synchronization and IFO estimation simultaneously. The detection of PLC preamble location is obtained during the PLC synchronization process, in that point the proposed method has advantages in computation complexity.

4. Simulation Results and Analysis

In computer simulation, we focused on the detection of the PLC subcarrier location in the received signal. When the PLC subcarrier location is detected, then the PLC data can be restored and the PLC subcarrier location allocated in transmitter side-the exact PLC subcarrier location-can be also found. Therefore, it is important to determine the PLC subcarrier location in the received signal. The experiments of PLC preamble detection in time and frequency axes were performed already and showed good performances with low SNR in AWGN [6, 8]. In this paper, we focused on the PLC subcarrier location detection performance based on PLC preamble correlation by applying several predefined integer frequency offsets.

4.1 PLC Preamble Auto-correlation Characteristics

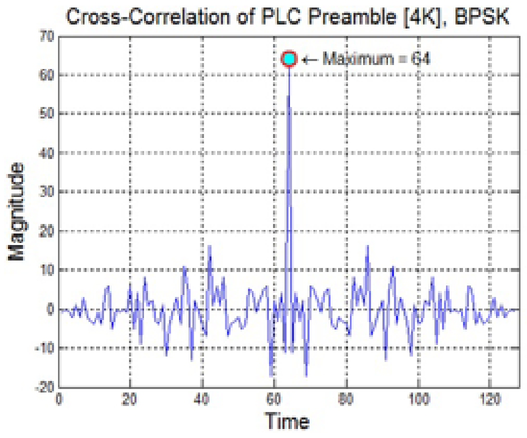
The correlation characteristics of BPSK modulated PLC preamble have maximum correlation values 64 (8x8) for 4K-FFT and 128(=8x16) for 8K-FFT, as shown in Fig. 10.

4.2 Integer Frequency Offset Estimation

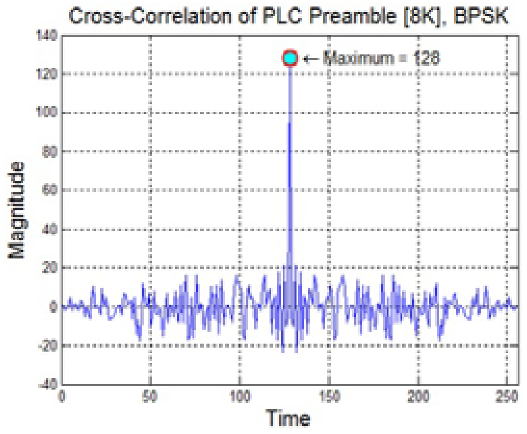
In performance analysis, the applied SNR is 15dB in AWGN channel considering the 16QAM PLC data reception and OFDM symbol timing offset STO=255 as a typical value. The applied FFO is FFO= 6.4×10^{-3} as an example for VCXO with 1ppm tolerance in $f_c = 300$ MHz, but when Beek's method is applied the mean squared error between the applied FFO and the estimated one can be reduced to $\hat{\varepsilon}\le10^{-5}$ [3]. The locations of PLC subcarriers are 348~355 for 4K-FFT and 688~703 for 8K-FFT. Through computer simulation, we examined the locations of the detected PLC subcarriers according to the predefined integer frequency offset values +2~-2. The exact PLC location can be found after PLC data recovery. Therefore, when the PLC subcarrier location in the received signal is found, the estimation of integer frequency offset becomes possible.

The simulation results for 4K-FFT mode are shown in Fig. 10. The applied integer frequency offsets vary from +2 to -2 for (a)~(e), respectively. The maximum values of PLC correlation are found on the shifted location to the integer frequency offset, as shown in (a)~(e) of Fig. 11.

For 8K-FFT mode, the results are shown in Fig. 11. They show similar results with 4K-FFT mode. So when the detection of the PLC subcarrier location is possible whether it is shifted by the integer frequency offset or not, then the integer frequency offset can also be estimated by the detection of the shifted PLC subcarrier location and the comparison with the PLC location recovered from PLC data.



(a) PLC Preamble correlation characteristics of 4K-FFT



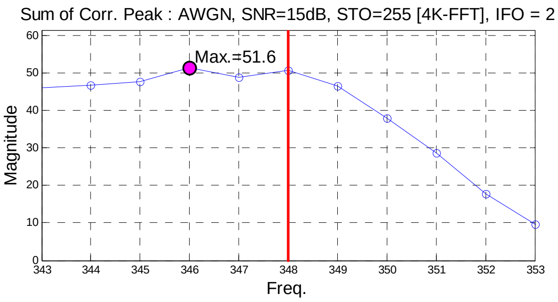
(b) PLC Preamble correlation characteristics of 8K-FFT

Fig. 10. PLC Preamble correlation characteristics of 4K- and 8K-FFT modes.

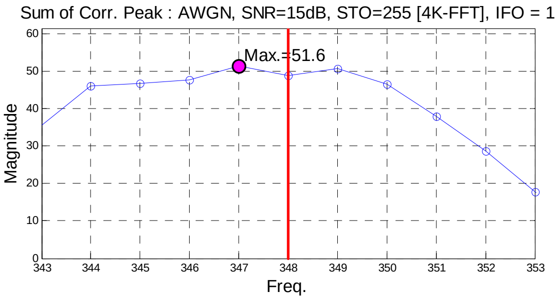
5. Conclusion

In this paper, we proposed an integer frequency offset estimation and compensation method based on the PLC preamble correlation for DOCSIS 3.1 DS. The PLC subcarrier location in the received signal can be found by detecting the maximum PLC preamble correlation value. When the locations of PLC subcarriers are found, the PLC subcarrier locations allocated in the transmission side can be found by recovering the received PLC data. By comparing these two PLC subcarrier locations, the integer frequency offset can be estimated and compensated for.

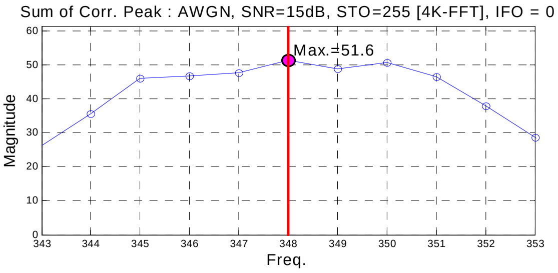
The proposed method also has advantages in terms of computation complexity. The PLC preamble correlation is performed during the PLC synchronization. Therefore, IFO estimation can share the correlation process with PLC



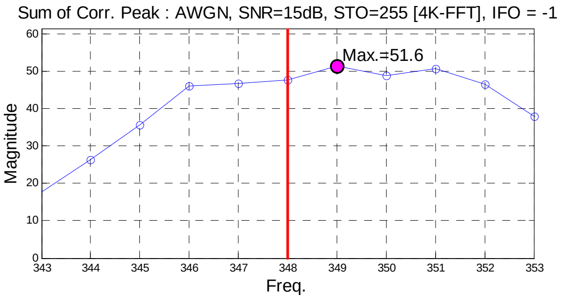
(a) IFO=2



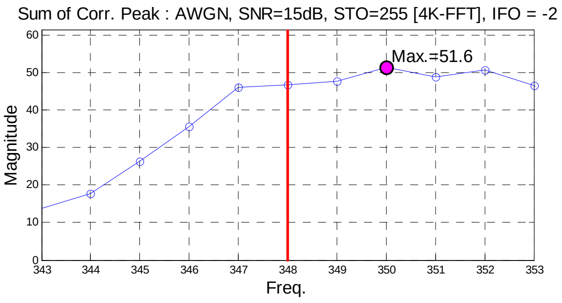
(b) IFO=1



(c) IFO=0

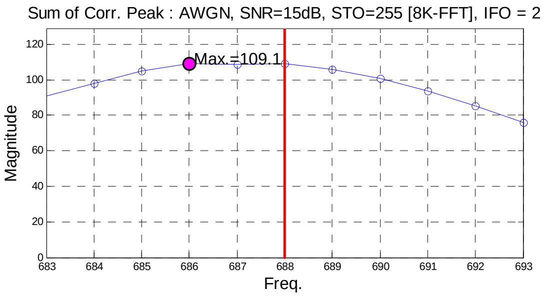


(d) IFO=-1

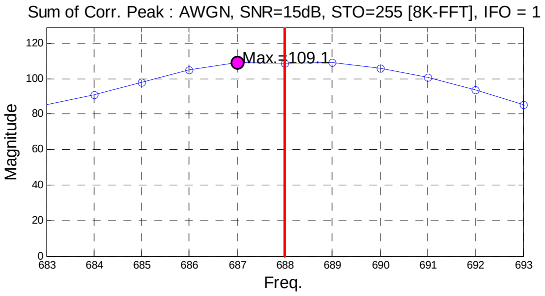


(e) IFO=-2

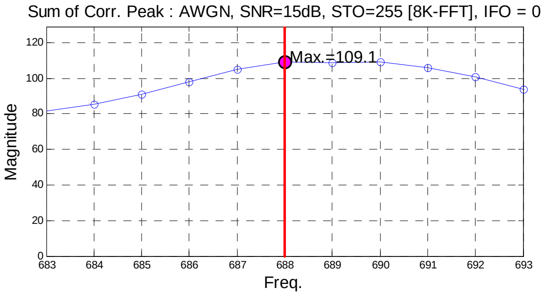
Fig. 10. PLC subcarrier location detection to IFO value for 4K-FFT.



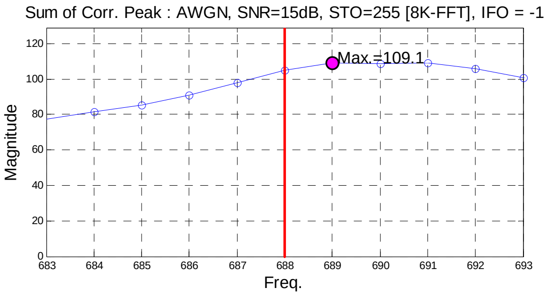
(a) IFO=2



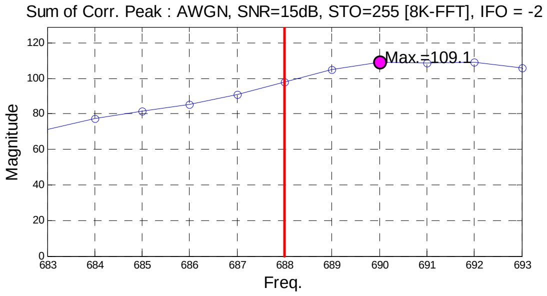
(b) IFO=1



(c) IFO=0



(d) IFO=-1



(e) IFO=-2

Fig. 11. PLC subcarrier location detection to IFO value for 8K-FFT.

synchronization and no other correlation process is needed [8].

Through the computer experiments, the proposed integer frequency offset estimation and compensation method showed good performances with low SNR in AWGN. In future research, performance analyses are needed in multipath channel with channel estimation.

Acknowledgement

This work was supported by the ICT R&D program of MSIP/IITP [2016-0-00106, Development of the RF-signal over IP Technology for the Smart Media Services based on Optical IP Network].

References

[1] Belal Hamzeh, Mehmet Toy, Yunhui Fu, James Martin, "DOCSIS 3.1: scaling broadband cable to Gigabit speeds," *IEEE Communications Maeazine*, Volume 53, pp. 108-113, March 2015 Article (CrossRef Link)

[2] CableLabs CM-SP-PHYv3.1-I03-140610, "Data-Over-Cable Service Interface Specifications 3.1 – Physical Layer Specification", June 2014. Article (CrossRef Link)

[3] J.J. van de Beek, P.O. Borjesson, M.L. Boucheret, D. Landstorm, J.M. Arenas, P. Odling, C. Ostberg, M. Wahlqvist, S.K. Wilson, "A time and frequency synchronization scheme for multiuser OFDM," *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1900-1914, Nov. 1999 Article (CrossRef Link)

[4] Jae-Ho Lee, Dong-Joon Choi, Nam-Ho Hur, Whan-Woo Kim, "The performance of frequency offset estimation in DVB-C2 receiver," *2013 15th International Conference on Advanced Communications Technology (ICACT)*, pp. 1106-1110, January 27, 2013 Article (CrossRef Link)

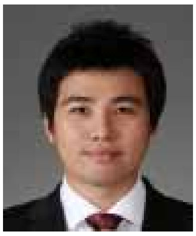
[5] ETSI EN 302 769 V1.2.1, Digital Video Broadcasting(DVB); Frame structure channel coding and modulation for a second generation digital transmission system for cable systems(DVB-C2), 2011-04 Article (CrossRef Link)

[6] JaeHwui Bae, JinHyuk Song, Sang-Jung Ra, Dong-Joon Choi, Namho Hur, "A Study on PLC Synchronization based on PLC Preamble Correlation for DOCSIS 3.1 Downstream," *IEEE 11th International Symposium on Broadband Multimedia Systems and Broadcasting*, June 2, 2016 Article (CrossRef Link)

[7] CableLabs CM-SP-MULPLv3.1-I02-140320, "Data-Over-Cable Service Interface Specifications 3.1 – MAC and Upper Layer Protocols Interface Specification," March 2014 Article (CrossRef Link)

[8] JaeHwui Bae, JinHyuk Song, Sang-Jung Ra, Dong-Joon Choi, Joon-Young Jung, Namho Hur, "Study on the influences of fractional frequency offset on PLC synchronization in DOCSIS 3.1," *2016 International Conference on Information and Communication Technology Convergence (ICTC)*, pp. 660-663 September 2016 Article (CrossRef Link)

JaeHwui Bae is currently a principal researcher of ETRI (Electronics and Telecommunication Research Institute) of Republic of Korea. He received B.S., M.S. and PhD degree from Electrical and Electronic Engineering from Kyungpook National University, Daegu, Republic of Korea, in 1991, 1993 and 2010. He joined ETRI since 2001 and participated research works related terrestrial TV broadcasting and cable TV broadcasting technology development. He is in the Media Transmission Research Group of Broadcasting Media Research Division. His major research fields are wireless transmission for digital broadcasting systems and data transmission over coaxial cable.



JinHyuk Song received the B.S. and M. S. degree from Sejong University, Seoul, Korea, in 2008 and 2010. Since 2010, he joined Department of Broadcasting System Research, ETRI (Electronics and Telecommunication Research Institute), Daejeon, KOREA, where he has been working on Media Research Division of Broadcasting·Media Research Laboratory. He is in the Media Transmission Research Group of Broadcasting Media Research Division. His research interests are in the areas of wireless communication system design, wide-band 10Gbps broadcasting infrastructure technology and digital broadcasting

Sang-Joong Ra (M'15) received the B.S. and M.S. degrees in computer engineering from the Chonnam National University, Korea, in 2002 and 2004. He joined in ETRI (Electronics and Telecommunications Research Institute) in 2004. Since 2004, he has participated in developing DOCSIS transmission system and the related data services. He is in the Media Transmission Research Group of Broadcasting Media Research Division. His current interest includes cable broadcasting, and OFDM system.

Dong-Joon Choi received the B.S., M.S. degrees in electrical and electronic engineering from Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1991, 1993. He is currently with the Broadcasting and Telecommunications Media Research Laboratory, Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea. He is currently a principal researcher of ETRI and has been working on digital TV broadcasting system technologies. He is in the Media Transmission Research Group of Broadcasting Media Research Division. His main research interests include cable broadcasting and communication, 3DTV, UHDTV.

Joon-Young Jung received the BS degree in electronic engineering from Yeungnam University, Daegu, Korea, in 1999, MS degree in electronic engineering from KAIST (Korea Advanced Institute of Science and Technology), Daejeon, Korea in 2001 and PhD degree in information and communication engineering form Chungnam National University, Daejeon, Korea in 2010. In 2001, he joined ETRI (Electronics and Telecommunications Research Institute), Daejeon, Korea where he has been working on digital TV broadcasting system technologies. Currently as a principal researcher, he is in the Media Transmission Research Group of Broadcasting Media Research Division. His main research interests include cable broadcasting and communication, 3DTV, UHDTV, and mobile TV.

Namho Hur (S'96–A'00–M'04) received the B.S., M.S., and Ph.D. degrees in electrical and electronic engineering from Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 1992, 1994, and 2000. He is currently with the Broadcasting and Telecommunications Media Research Laboratory, Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea. He is a managing Director of Broadcasting System Research Department in ETRI. He was an Executive Director of Association of Realistic Media Industry (ARMI) in Korea. ARMI was established to promote realistic media industry including 3DTV and UHDTV broadcasting industry. Also he is an adjunct professor with the Department of Mobile Communications and Digital Broadcasting, University of Science and Technology (UST) in Korea since 2005 September. For the collaborative research in the area of multi-view video synthesis and the effect of object motion and disparity on visual comfort, he was with Communications Research Centre Canada (CRC) from 2003 to 2004. His main research interests are in the field of next-generation digital broadcasting systems such as terrestrial UHD broadcasting system, UHD digital cable broadcasting system, mobile HD broadcasting system, and backward-compatible 3D-TV broadcasting systems for mobile, portable, fixed 3D audio-visual services.