A Comparison of PHY Layer on the Ecma-392 and IEEE 802.11af Standards

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Abstract— **Cognitive radio is widely expected to be a promising technology to efficiently exploit underutilized spectrum. Regulatory committees in many countries are taking into account the spectrum policy of dynamic spectrum access using this technology. The TV band is under consideration as a first step to share the spectrum resource. As a result, many activities to specify a standard using this band have been shown. In this paper, an overview on the physical layer of Ecma-392 standard and IEEE 802.11af draft standard is presented together with software simulated performance results. Furthermore, the effect of the frequency diversity on different number of subcarriers and channel bandwidth is analyzed and discussed.**

Keywords-component; Cognitive Radio, TV Whtie Space, Standard, PHY, IEEE 802.11af, Ecma-392

I. INTRODUCTION

The appearance of smart phones is causing the problems of a data traffic explosion and a lack of frequency resource. To enhance the system throughput, multiple-input and multiple-output (MIMO) scheme is included in almost all recent standards, and new spectral resource such as mm-Wave has been developed. Cognitive radio (CR), first proposed in [1], is also receiving significant attention as one of possible solutions to increase the efficiency of spectrum usage by discovering and exploiting unused frequency resource. Many regulatory domains are instituting the spectrum policy based on dynamic spectrum access using this technology and making the rule to enable the unlicensed users to share the spectrum while protecting the licensed users. At the first step, USA Federal Communications Commission (FCC) have opened the door to utilize TV broadcast bands, in which there are a large number of vacant TV channels in rural areas [2]. Finally, FCC issued the second report and order in Nov. 2008 to allow secondary usage of TV white space (TVWS) for fixed and portable devices [3]. UK Office of Communications (OFCOM), European Conference of Postal and Telecommunications Administrations, Finland and other government agencies have also made various rules to promote more efficient use of this valuable and useful spectral resource [4] ,[5].

In this context, many standard domains take an interest in the various usage cases using TV bands, which have better radio propagation property than existing bands for wireless communication services. The IEEE 802.22 standard for wireless regional area network (WRAN), of which service coverage is typically 30 km using high transmission power of 4 watt, is published in July 2011. Recently, the IEEE 802.22.b working group (WG) is specifying an amendment standard for supporting the smart grid network using WRAN. On the other hand, the standards for the personal and portable applications using low power have been developed under IEEE 802.11 and ECMA-International. To extend the coverage of wireless local area network (WLAN) service, as so-called Super Wi-Fi, IEEE 802.11af WG is making an amendment to the IEEE 802.11 standard satisfying the legal requirements for channel access in the TVWS [6]. Currently, draft standard is based on the IEEE 802.11n standard which specifies higher throughput (HT) operation [7]. Ecma-392 standard is published for the first time as a standard operating on TV bands in Dec. 2009 [8]. Its target applications are wireless home network and wireless internet access at campus, park, hotspot, etc., which are similar to 802.11af's. The major differences between two standards are incumbent protection mechanisms and channel bandwidth to be supported. Basically, both standards obtain an available channel list from TVWS database, which has information of unused TV channels geometrically, through internet access. Ecma-392 additionally supports the spectrum sensing functionality to periodically check the existence of incumbent signals on current operating channel. In the case of channel bandwidth, Ecma-392 has specified the operation in only single TV channel which can be one of three channel bandwidths (CBW) of 6 MHz, 7 MHz, or 8 MHz according to regulatory domain. In IEEE 802.11af draft standard, four bandwidths of 5 MHz, 10 MHz, 20MHz or 40 MHz are defined regardless of regulatory domain. It means that channel bandwidth can be adaptively changed when several adjacent TV channels are available. Recently, IEEE 802.11 af WG is considering 2MHz or 4MHz for minimum CBW and IEEE 802.11 ac draft standard as a base document of PHY layer.

To investigate comparison between Ecma-392 and IEEE 802.11af in more detail, this paper focuses on the physical layers and identifies their similarities and differences in a condition of single TV channel. In the case of IEEE 802.11af, we only consider the non-HT operation mode. Furthermore, the software simulated results in terms of packet error rate (PER) are presented to compare the performance of two standards depending on fast Fourier transform (FFT) size and CBW.

The remaining sections are organized as follows: The PHY layers specified by the two standards are presented in Section 2. In Section 3, the channel model that has been used in software simulation is described. Also, the results of PHY layer simulation for the two standards are provided in terms of PER performance vs. signal-to-noise ratio (SNR) under the different channel conditions. Finally, we conclude the paper in Section 4.

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TABLE I. OFDM PARAMETERS

Parameters	Values	
	Ecma-392 (6MHz)	IEEE 802.11af Non HT_CBW5
Sampling Rate	48/7 MHz	5 MHz
FFT size	128	64
# of N_U, N_D and N_P subcarriers[a]	102, 98, 4	52, 48, 4
Subcarrier spacing (Δ_f)	53.571 kHz	78.125 kHz
Signal bandwidth	5.518 MHz	4.14 MHz
FFT period (T_{FFT})	18.667 μs	12.8 μs
Guard interval	0.58 μs(T_{FFT}/32)	3.2 μs (T_{FFT}/4)
	1.16 μs(T_{FFT}/16)	6.4 μs (T_{FFT}/2)
	2.33 μs (T_{FFT}/8)	-

a. N_U, N_D and N_P : number of used, data and pilot subcarriers

TABLE II. DATA RATE AND TRANSMISSION MODE-DEPENDENT PARAMETERS

Mode	Modulation	Ecma-392			IEEE 802.11af Non HT_CBW5	
		RS Rate	CC Rate	Data Rate[a] (Mb/s)	CC Rate	Data Rate[b] (Mb/s)
1	QPSK	255,245,5	1/2	4.75	1/2	3.6
2	16QAM	255,245,5	1/2	9.49	1/2	7.3
3	64QAM	255,245,5	3/4	21.36	3/4	16.3
4	64QAM	255,245,5	5/6	23.74	5/6	18.1

a. GI = T_{FFT}/16, b. GI = T_{FFT}/4

II. PHYSICAL LAYER OF ECMA-392 AND IEEE802.11AF

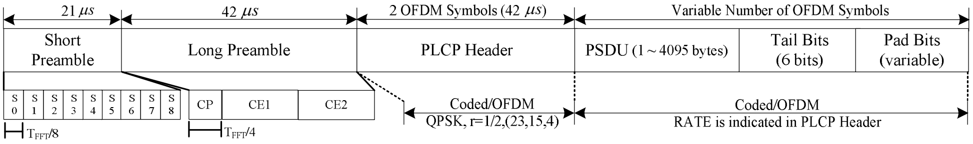
The PHY layers of both standards are very similar overall. Basically, the orthogonal frequency division multiplexing (OFDM) is used to combat frequency selective fading in both standards. OFDM is the most suitable modulation scheme for high-data-rate transmission. The two major differences in PHY layer are the CBW and FFT size. Ecma-392 supports only single channel operation, but IEEE 802.11af can operate on different CBW using multiple TV channels. This section presents with focusing on the single TV channel operation of 6 MHz CBW for Ecma-392 and 5 MHz CBW for IEEE 802.11af. The FFT sizes relating to the number of subcarriers to be used for data transmission are 64 and 128 in IEEE 802.11af and Ecma-392, respectively. The 64-FFT for 802.11af is used for backward compatibility of 802.11 standards to enable sharing the modem chip set only changing the clock rate. The 128-FFT for Ecma-392 is designed by considering the system performance and maximum system throughput which is related to the FFT size and guard interval (GI). When the FFT size is getting larger, the overhead in an OFDM symbol with the same duration of GI can decrease but performance can be degraded due to increasing the effect of inter carrier interference (ICI).

Table Ⅰ describes OFDM parameters per single TV channel. It is found that the FFT period and subcarrier spacing are derived from the FFT size and channel bandwidth. The typical GIs are 1.16μs for Ecma-392 and 3.2μs for IEEE 802.11af. They are enough long to deal with the delayed multipath up to root-mean-square delay spread of 250ns because the length of GI in OFDM system is generally designed by four times of RMS delay spread. Therefore, the GI of IEEE 802.11af makes throughput degradation due to a little excessive design more than 1μs. From the Table Ⅱ which presents data rates of four transmission modes, it is observed that the Ecma-392 has higher throughput than IEEE 802.11af by smaller duration of GI even though it includes the reed-solomon (RS) code with additional redundancy of parity bits. The signal bandwidth is also related to the data rate. Ecma-392 with larger bandwidth can obtain more throughput and better spectrum utilization per one TV channel than IEEE 802.11af. However, it is expected that IEEE 802.11af can minimize the potential interference to incumbent service operating adjacent TV channel what is very important issue in CR system as a secondary service.

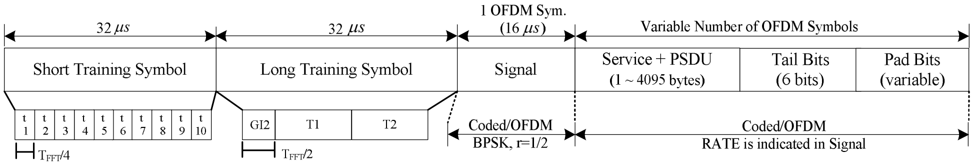
Fig. 1 shows the PHY protocol data unit (PPDU) frame formats and the reference configuration of transmitter (Tx). In both standards, the preamble and training symbols are transmitted at the front of the frame for the same purpose such as automatic gain control (AGC), frame detection, time and frequency synchronization, and channel estimation. Short preamble (SP) and short training symbol (STS) consist of nine and ten repetition symbols by allocating pilot signals to every eight and four subcarriers in the frequency domain, respectively. In comparison with 16μs duration of SPS in existing IEEE 802.11 standard well working in 2.4 GHz and 5 GHz such as [7], the time duration of SP or SPS in each standard has enough long to perform AGC and synchronization process with expecting good performance. Long preamble (LP) and long training symbol (LTS) are the same structure except for the time duration due to FFT size and sampling rate. The information about transmission parameters for PHY layer service data unit (PSDU) are transmitted on PLCP header or Signal field. The OFDM symbols are generated by Tx procedure defined in Fig. 1c. The differences of two standards are the RS code in Ecma-392 and the position of inserting pad bits.

A. Insertion of Pad bits

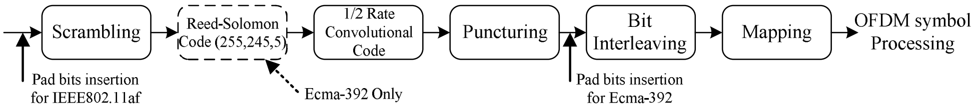
The pad bits are used to ensure that the number of PSDU data bits maps to an integer number of OFDM symbols. In IEEE 802.11af, the pad bits are inserted at the front of transmitter procedure. The number of them can be easily calculated by considering with modulation type and convolutional code (CC) rate, making the number of encoded bits be multiple of coded bits per one OFDM symbol [6]. On the other hand, the different insertion method for Ecma-392 is necessary because the number of data subcarriers of 98 cannot be divided by 3. In certain case such as QPSK and CC rate of 2/3, the number of code bits after RS encoder must become multiples of fractional number, 130.667 (=98*2*2/3). Therefore, the pad bits shall be inserted after RS-CC encoding and puncturing blocks when the total number of coded bits is not divided by the number of coded bits per one OFDM symbol. To avoid the high peak-to-average power ratio (PAPR) in time domain, all zero values of pad bits are scrambled with same method defined by following sub-section of B are used.



(a) Ecma-392 PPDU frame format



(b) IEEE 802.11af Non-HT_CWB5 PPDU frame format



(c) Transmitter PHY layer of Ecma-392 and 802.11af

Figure 1. PPDU frame formats and transmitter structure of Ecma-392 and IEEE 802.11af standard

B. *Data Scrambling*

Data scrambler prevents long runs of 1s and 0s in the input data being input to the remainder of the Tx blocks [9]. Otherwise, the high PAPR is appeared in OFDM symbol and it can cause the non-linear property of transmitted signal. The generation polynomials to generate a length 511 and 127 pseudo-random sequence for Ecma-392 and IEEE 802.11af are defined as Eq. (1) and Eq. (2), respectively. To initiate the scrambler, two bits among 9 bits in Eq. (1) are specified by the MAC in [8], which are incremented in a 2-bit rollover counter for each frame from 00 to identify it. Then 7 bits for remaining bits of Eq. (1) and for initialization vector of Eq. (2) are defined by all ones.

$$S_{Ecma\text{-}392}(x) = x^9 + x^4 + 1 \tag{1}$$

$$S_{802.11af}(x) = x^7 + x^4 + 1 \tag{2}$$

C. *FEC and Punctuing*

Ecma-392 adopted the concatenated coding scheme with RS code for the outer code and CC for the inner code. This is the reason to make error free or less for the high defined (HD) streaming service which is one of the initial target applications of Ecma-392. The RS encoder is based on a systematic (N=255, K=245, T=5) code using Galois field (GF) of 256. Both standards specify the same CC encoder with generation polynomials, g0=133 and g1=171. Puncturing is used to derive additional code rates from a base rate r=1/2 convolutional code.

D. *Bit Interleaver*

Bit interleaver to prevent burst error from being input to the Viterbi-decoder is based on the same block interleaver with two steps of Eq. (3) and (4) in both standards. But the parameters of the number of coded bits per subcarrier (N_{CBPC}) and one of divisors of N_D (N_{Per}) are difference.

$$i = (N_{CBPS}/N_{Per})(k \bmod N_{Per}) + floor(k/ N_{Per}) \tag{3}$$

$$j = s * floor(i/s) + (i+N_{CBPS} - floor(N_{Per}*i/ N_{CBPS})) \bmod s \tag{4}$$

where, *mod* is the function of modulo, *floor*(·) denotes the largest integer not exceeding the parameter, *i* and *k* is numbers from 0 to N_{CBPS}-1, and *s* is larger value either $N_{CBPC}/2$ or 1.

N_{Per} in IEEE 802.11af is specified with 16 which is a divisor of 48. In Ecma-392, N_{Per} is selected by MAC in [8] with either 14 or 7. When the retransmission is requested by receiver, the transmitter selects the different value of N_{Per} from previous frame. This makes receiver obtain channel diversity gain by combining the two received frames in which the coded bits are transmitted in different subcarriers.

E. *Mapping*

The interleaved bits are subsequently converted into constellation symbol according to BPSK (802.11af only), QPSK, 16QAM, or 64QAM modulation types. The combinations of different modulation schemes and code rates are defined by ten modes in [8] and eight modes in 5MHz CBW and single antenna operation of [6]. Table Ⅱ represents three modes, 1~3, used in software simulation and mode 4 of maximum throughput.

F. *Pilot Insertion*

One OFDM symbol in both standards has four pilots for estimation of residual frequency offset and phase offset. The 802.11af allocates the pilots on fixed subcarrier index for all symbols. Otherwise, Ecma-392 defines the pilot insertion pattern allocating the pilots to different subcarriers for 13 OFDM symbols. This intends to additionally enable the adaptive channel estimation by gathering the pilots in several OFDM symbols according to the channel environments.

III. PHYSICAL LAYER SIMULATION RESULTS

Ecma-392 and IEEE 802.11af will be deployed in various environments such as home, offices, industrial buildings, and parks. So, we will provide the performance results of both standards according to RMS delay spread of 50 ns, 100 ns, and 200 ns. Otherwise, the simulations for comparing the performance of two standards under specific conditions are performed in 100ns circumstance. The Jakes' model is adopted for modeling the Rayleigh fading channel with a mean corresponding to an exponentially decaying average power delay profile [9]. The independently random channel per each frame is considered for software simulation.

The performance takes the form of PER vs. average SNR of subcarriers. The perfect synchronization and channel estimation are considered, and soft decision Viterbi decoding with weighted metric of channel state information is used. The outer decoder for RS code in Ecma-392 is based on the Berlekamp-Massey (BM) algorithm [10]. In some simulations, the encoder and decoder for RS code is not utilized to compare two standards under the same channel coding condition.

Fig. 2 shows the simulation results without bit interleaver in transmitter and bit de-interleaver in receiver. In OFDM system, the coded bits to be allocated on subcarriers which are under a deep fading are easily in error due to noise enhancement. If there is no bit interleaver and the successive bits corrupted due to fading channel are used in computing the metrics of Viterbi decoder, the errors cannot be corrected once the number of them became more than constraint length. Furthermore, the smaller subcarrier spacing is, the worse PER performance is because the number of subcarriers under a deep fading increases in the same or similar CBW. Therefore, the PER performance of Ecma-392 is worse than IEEE 802.11af's in all three modes of Fig. 2.

Fig. 3 presents the simulation results using the bit interleaver. As would be expected, the PER performances of all modes is enhanced due to channel diversity gain by interleaver than the one of Fig. 2. It has been observed that the Ecma-392 outperforms 802.11af unlike trends in Fig. 2. This is expected due to less number of errors within constraint length. After performing the de-interleaver process, the coded bits affecting poor channel are distributed within a whole code word in an OFDM symbol. In addition, if the number of subcarriers is increased, the dependency among bits within a constraint length can be decreased according to the condition of coherent bandwidth and CBW because the coded bits per a subcarrier are widely distributed. Therefore, Ecma-392 having more subcarriers has better coding performance than 802.11af. To verify the effect by interleaver parameter of IEEE 802.11af, N_{Per} in Eq. (3) and (4), we have considered the values of 8 and 12 but the results in mode 1 are the same as the value of 16.

Fig. 4 shows the PER performance in various RMS delay spreads. Both standards have a similar trend as the PER performance is getting better in higher RMS delay spread. In a small RMS delay spread, the channel frequency response is relatively flat within the OFDM signal bandwidth, so if there is a deep fade, all the subcarriers are significantly attenuated [11]. On the other hand, a few adjacent subcarriers are only affected by a deep fade in the case of a large delay spread. Therefore, relatively strong subcarriers can compensate for the attenuated subcarriers in channel decoding process after de-interleaver. Furthermore, there is no performance degradation due to inter symbol interference (ISI) and ICI by multipath because both standards have defined enough length of guard interval to endure the large delay paths in RMS delay spread of 200ns.

In Fig. 5, the PER performance versus channel bandwidth of 802.11af is shown in comparison with the result of Ecma-392 using RS-CC concatenated code. If the channel bandwidth is getting larger, it is expected that more diverse channel values are existed in it, so the PER performance can be improved due to channel diversity gain even though the FFT size is the same. The subcarrier spacing of IEEE 802.11af in 5 MHz, 10 MHz, and 20 MHz CBW are 78.125 kHz, 156.25 kHz, and 312.5 kHz, respectively. Because the coherent bandwidth with correlation of 90% becomes 200 kHz when RMS delay spread is 100ns [12], the fading channel characteristics for all subcarriers in 20 MHz CBW are almost independent for each other. Therefore, the larger CBW of IEEE 802.11af is, the better PER performance is. Furthermore, the 20MHz CBW of IEEE 802.11af has superior PER performance in mode 1 and mode 2 to Ecma-392 and has almost same performance in mode 3 at the 1% PER.

IV. CONCLUSIONS

There are many standardization activities to support new applications using TVWS since it has been open to the secondary service. In this paper, we introduced the two standards of Ecma-392 and IEEE 802.11af operating on TVWS, of which target applications are very similar as the extended WLAN service. The similarities and differences of PHY layer on both standards are presented and the software simulation results in terms of PER are shown in various channel conditions. The effects of the different numbers of FFT size, RMS delay spread, and CBW were discussed through the performance evaluation. Finally, it is observed that Ecma-392 has better performance than IEEE 802.11af in the case of single TV channel and the performance of 802.11af is improved in large CBW such as 20 MHz by channel diversity effect.

ACKNOWLEDGMENT *(HEADING 5)*

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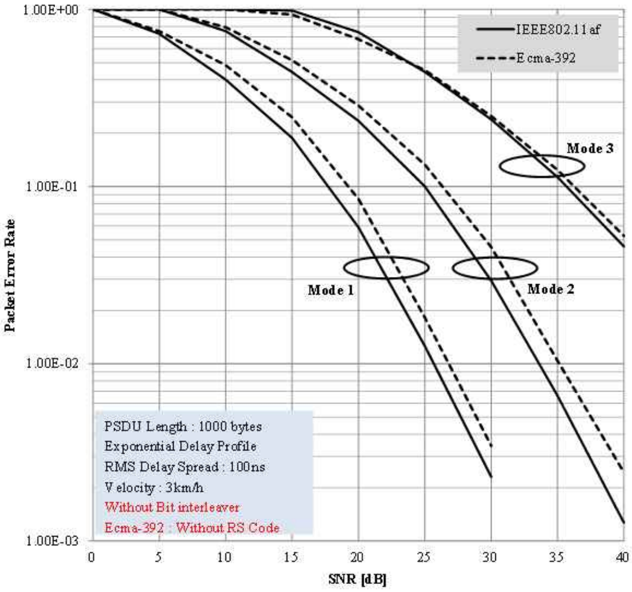

Figure 2. PER performances of IEEE802.11af and Ecma-392 standards without bit interleaver

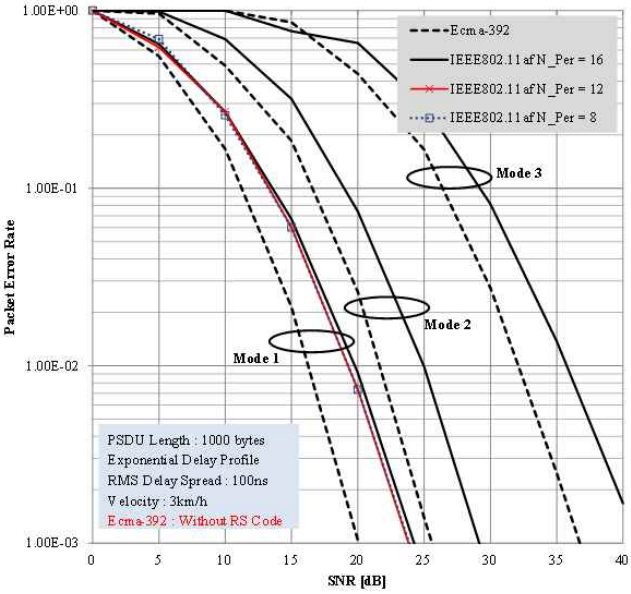

Figure 3. PER performances of IEEE802.11af and Ecma-392 standards with bit interleaver

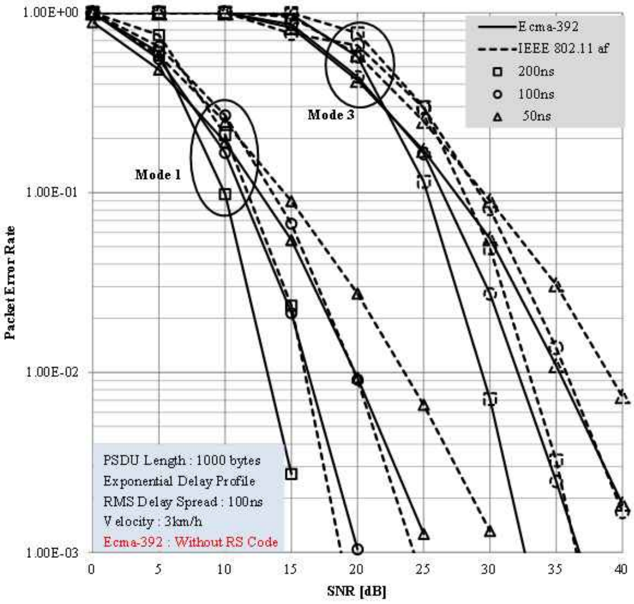

Figure 4. PER performances of IEEE802.11af and Ecma-392 standards in RMS delay spreads of 50, 100, and 200ns (Mode 1 and Mode 3)

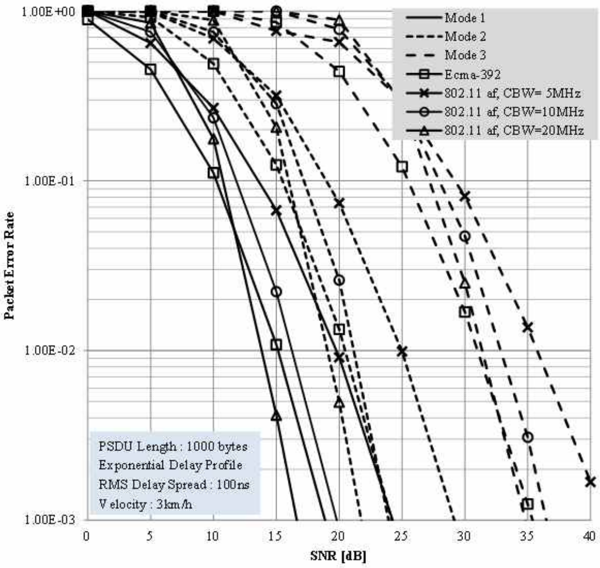

Figure 5. PER performances of IEEE802.11af using channel bandwidths of 5, 10, and 20MHz in comparison with Ecma-392 using RS-CC code