DWT Based Optimal Power Allocation Schemes For Scalable Video Transmission in OFDM Based Cognitive Radio Systems

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Abstract*—In this paper, we propose and investigate the performance of optimal power loading algorithms towards scalable video transmission over an Orthogonal Frequency Division Multiplexing (OFDM) based Cognitive radio (CR) system. The proposed power allocation scheme minimizes the overall video distortion while restricting secondary user interference. For this purpose, we employ the two level Daubechies wavelet D2 to encode the video as a layered scalable stream comprising of one Base layer and several enhancement layers. The coded video layers are assigned to the secondary OFDM subcarriers of the CR user. A convex optimization framework is developed for video distortion as a function of the subcarrier power allocation. We employ this framework and derive a closed form expression towards the optimal power allocation for video quality maximization. We also propose a low complexity scheme for near optimal video transmission. The performances of the proposed optimal schemes are compared in terms of the Peak Signal to Noise Ratio (PSNR) of the received video stream in the OFDM CR wireless system. Presented numerical results demonstrate that the proposed optimal scheme results in a significantly enhanced PSNR of video transmission compared to the competing scalable and non-scalable schemes.

I. Introduction

Recent times have witnessed an unprecedented growth in the number of personal wireless devices, which has led to an increasing demand and the resulting scarcity of the wireless radio spectrum. On a paradoxical note, measurements have demonstrated that a significant portion of the total wireless spectrum is vacant at any given instant of time [1] as has been reported by the spectrum policy task force appointed by the Federal Communications Commissions (FCC). Thus, the spectrum scarcity in current radio communication scenarios is arising out of inefficient static frequency management policies. This has led researchers to propose and develop novel technology solutions for dynamic allocation and management of the available radio spectrum. In this context, Cognitive radio (CR) is a novel concept that enables efficient use of the available spectrum by permitting a limited set of non-licensed users to exploit vacant underutilized licensed frequency bands. Hence, CR defines two classes of users, the first of which are the primary users who are the licensed users possessing a guaranteed and proprietary access to the spectral band under consideration. The other set comprises of secondary users, also termed as cognitive users, who are opportunistic unlicensed users. The task of the CR base station is to dynamically sense the channel continuously so as to determine the vacant bands of the spectrum, also termed as the spectrum holes. The CR users can then be allowed to utilize these vacant bands for communication by adapting their power levels such that the interference introduced to the primary users is restricted to a certain preset threshold. This CR approach to spectrum access is therefore based on robust schemes for power adaptation over the available CR bands.

Orthogonal Frequency Division Multiplexing (OFDM) employs closely spaced narrowband orthogonal subcarriers for data transmission, thus avoiding the problem of inter symbol interference associated with wideband frequency selective channels. Further, the time-frequency nature of resource allocation in OFDM and OFDMA systems gives it additional flexibility towards dynamic radio resource allocation for multiple users with a low interference between adjacent subcarriers. These factors make OFDM an appropriate modulation scheme for CR systems [2]. Further, it also simplifies the spectral mask shaping as per the PU's spectral activity. In [2], [3], the authors have demonstrated a model for mutual interference between PU and the OFDM based CR users. The magnitude of interference introduced at the primary user by a CR user subcarrier depends on the power allocated to the subcarrier and its spectral distance from the primary user band.

Further, video transmission in such CR scenarios is challenging due to the stringent interference constraints imposed on the secondary users. In [4], the authors propose a end to end system to minimize the average video distortion under certain bounded video packet delay constraint. An algorithm is proposed in [5] to transmit an image, audio and video over a cognitive radio in a prioritized manner, taking into account the processing time and bandwidth utilization. A fountain code based technique for distributed multimedia transmission over a cognitive radio network is studied in [6], wherein distribution of the multimedia content over the unused spectrum is achieved using the fountain codes. A two-phase channel and power allocation policy is explored in [7]. Here, the base station is first allocated power with the aim of maximizing the total coverage followed by allocation of channels to the active subscribers based on a maximal bipartite matching algorithm to maximize the throughput. However such schemes are ad hoc in nature and do not consider optimal interference threshold based power allocation for interweave OFDM cognitive radio systems. Recently, we have proposed a novel procedure for optimal video power allocation in OFDMA systems [8]. This scheme has wide appeal for efficient video transmission in several wireless scenarios. Hence, in this paper, we present optimal video transmission schemes for the CR downlink scenario where a CR base station transmits video streams to the CR receivers in the frequency bands currently unoccupied by the primary users. A scalable video stream is obtained by employing the 2D Discrete Wavelet transform (DWT) to decompose the video into a hierarchical layered stream comprising of a base layer and several enhancement layers. The proposed algorithm subsequently performs an intelligent assignment of these disparate video layers to the the different OFDM subcarriers followed by a optimal power adaptation of the subcarriers of the CR user. Towards this end, we propose an optimal video transmission paradigm based on optimal video layer assignment to the CR user subcarriers followed by subcarrier power allocation. Our optimal power loading scheme is based on a closed form power allocation solution and utilizes the OFDM interference model described in [3]. The presented simulation results demonstrate the superior performance of our proposed schemes which employ intelligent video layer subcarrier mapping followed by the optimal subcarrier power allocation compared to other sub-optimal schemes.

The organization of the paper is as follows. Section II gives a brief overview of the structure of the scalable coded video stream for wireless transmission. Section III presents the key results for video distortion over erratic fading wireless channels, the framework for video distortion minimization and the optimal power allocation (OPA) scheme for wireless OFDM CR video transmission. In section IV we present the near-optimal low complexity proportional power allocation (PPA) scheme for video transmission. Simulation results are presented and discussed in section V while section VI concludes the paper.

II. Video Transmission Scheme

We employ an interweave based OFDM CR model [2], in which the primary users occupy the L frequency bands of bandwidth $B_1, B_2, ..., B_L$ Hz. These bands are determined by the CR user through an appropriate *spectrum sensing* procedure. The unoccupied spectral holes sensed by the CR base station for possible transmission are interspersed among the L PU bands as shown in the Fig.1. The bandwidth available for the CR transmission is divided into a subbands of bandwidth Δf per subcarrier for OFDM based transmission. Thus, as described above, the fine frequency resolution of the OFDM/ OFDMA modulation format yields a tremendous flexibility in shaping the spectral mask for CR transmission based on the available bandwidth. We consider video data transmission by the CR base station to the CR users. A typical DPCM encoded digital video stream consists of Intra coded I frames and predictively encoded P frames. Such a motion prediction compensation based video coding scheme is ideally suited for video compression, especially for communication over bandlimited wireless channels. The motion prediction for the P frames can be obtained through the Exhaustive Block Matching Algorithm described in (EBMA)[9]. The collection of I frame and the associated P frames, which encode the predictive differences between the successive video frames are termed as a group of picture (GOP) and are transmitted over the channel. Further, video data can be naturally organized into hierarchical layers for differential priority allocation and error protection. For this purpose, we employ the standard Daubechies-2 wavelet based discrete wavelet transform described in [10] to spatially decompose the video stream into the base layer corresponding to the spatial low frequency components and enhancement layers corresponding to the spatial high frequency refinements. Thus a natural decomposition of the video into hierarchical layers of ordered significance is obtained for transmission through the wireless medium. Each of these video layers can then be multiplexed over the allocated OFDM subcarriers. Hence, in this context it is key to develop optimal video layer-OFDM subcarrier mapping strategies to maximize end user video quality.

Consider a decomposition of the video stream into M spatial layers with one base and $M-1$ enhancement layers, where each lower layer is of progressively higher significance with respect to its impact on the overall video quality. It is clear that the base layer which has the most significant impact on video reconstruction can be transmitted at higher power levels and subsequent enhancement layers at progressively lower power levels to obtain the best video reconstruction at the receiver. Further, since the interference induced to the primary user is a limiting factor, which in turn depends on the spectral distance of the subcarrier from the primary user, a suitable joint subcarrier allocation to the video layers coupled with power allocation is challenging. In this context we propose a novel video subcarrier power allocation procedure towards the objective of minimizing the overall video distortion in the next section.

III. Optimal Power Allocation Scheme(OPA)

A. Video Distortion Modeling

For a given video sequence $\mathcal{V}(x, y, t)$, the video distortion $D_l(\mathcal{V})$ corresponding to the errors in the layer $l \in 1, 2, ..., N$ can be modeled as $D_l(\mathcal{V}) = \mathrm{E}\left\{\left\|\psi^{-1}(\Delta S_l)\right\|^2\right\}$, where the video transform domain basis ψ corresponds to the DB-2 wavelet employed for the spatial layering of the video stream and ΔS_l is the error in the spatial layer S_l. The mean distortion $D(\mathcal{V})$ for the video stream can then be expressed as,

$$D(\mathcal{V}) = \sum_{l=1}^{N} D_l(\mathcal{V})\, \phi_e(P_l). \tag{1}$$

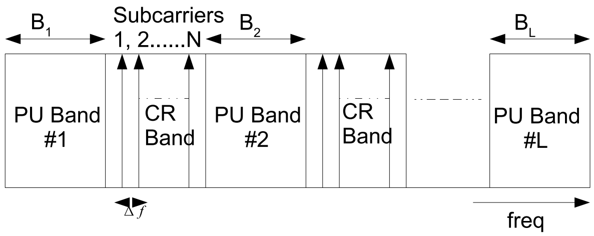

Fig. 1. Schematic of primary and secondary user spectral bands

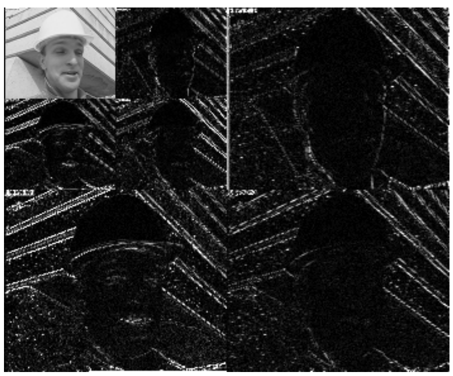

Fig. 2. Two Level Duabechies-2 Wavelet Video Layering

The probability of bit error $\phi_e(P_l)$ for Binary Phase Shift Keying (BPSK) modulated data over an Additive White Gaussian Noise (AWGN) channel is given by [11] as,

$$\phi_e(P_l) = Q\left(\sqrt{\frac{P_l}{\sigma_v^2}}\right), \tag{2}$$

where $Q(\cdot)$ denotes the Gaussian error function. Considering a Rayleigh flat-fading wireless channel across each of the OFDM CR user subcarriers, the average probability of bit-error, averaged over the distribution of the fading gain of the Rayleigh fading wireless channel is given as,

$$\phi_e(P_l) = \int_0^\infty Q\left(\sqrt{\frac{a^2 P_l}{\sigma_v^2}}\right) f_A(a)\, da, \tag{3}$$

where a denotes the envelope of the Rayleigh flat-fading coefficient, the probability density function (PDF) governing which is given as $f_A(a) = 2a\, e^{-a^2}$. Hence, the net expression for the average bit-error in (3) can be simplified as,

$$\phi_e(P_l) = \int_0^\infty Q\left(\sqrt{\frac{a^2 P_l}{\sigma_v^2}}\right) 2a\, e^{-a^2} da = \frac{\sigma_v^2}{P_l}.$$

Substituting the above probability of bit-error expression in (1) gives us the final simplified expression of overall video distortion as a function of the layer-subcarrier power P_l as,

$$D(\mathcal{V}) = \sum_{l=1}^{N} D_l(\mathcal{V})\, \phi_e(P_l) = \sum_{l=1}^{N} D_l(\mathcal{V}) \left(\frac{\sigma_v^2}{p_l}\right) \tag{4}$$

B. CR Model for Video Transmission

An interweave OFDM CR downlink scenario is considered for video transmission. We denote the Rayleigh fading channel coefficient between the base-station and the CR receiver for the i^{th} subcarrier as h_i^{ss}. Further, the Rayleigh fading channel coefficient corresponding to the wireless channel between the CR user transmitter and the l^{th} PU receiver is denoted by h_l^{sp}, while that between the PU transmitter and the i^{th} CR receiver is denoted as h_l^{ps}. The interference introduced by the transmission of the i^{th} CR subcarrier to the l^{th} PU is given by the power spectral density (PSD) of the i^{th} subcarrier of the CR user, which is described as,

$$\phi_i(f) = P_i\, T_s \left(\frac{\sin \pi f T_s}{\pi f T_s}\right)^2, \tag{5}$$

where P_i is the total transmit power of the i^{th} OFDM subcarrier and T_s is the OFDM symbol duration. We denote the interference caused by the i^{th} subcarrier of the CR user to the l^{th} PU band as $I_i^l(d_{il}, P_i)$, which can be obtained by integrating the PSD of the i^{th} subcarrier across the l^{th} PU band as,

$$I_i^l(d_{il}, P_i) = P_i \underbrace{|h_l^{sp}|^2\ T_s \int_{d_{il}-B_l/2}^{d_{il}+B_l/2} \left(\frac{\sin \pi f T_s}{\pi f T_s}\right)^2 df}_{K_i^{(l)}}, \tag{6}$$

where d_{il} is the *spectral distance* between the i^{th} subcarrier of the CR user and the l^{th} PU band and B_l represents the bandwidth of the l^{th} PU band. Thus, the factor $K_i^{(l)}$ determines the impact of the interference of the i^{th} CR user on the l^{th} primary user.

C. Video Distortion Minimization Framework

The objective of the proposed framework is to minimize the overall video distortion modeled in (1) subject to the interference constraints imposed by the PU threshold. Therefore, the optimization problem [12] for minimizing the overall video distortion $D(\mathcal{V})$ for a video stream $\mathcal{V}$ can be modeled as,

$$\begin{aligned} \min.\ & D(\mathcal{V}) = \sum_{i=1}^{N} D_i(\mathcal{V}) \left(\frac{\sigma_v^2}{P_i}\right) \\ \text{s.t.}\ & \sum_{l=1}^{L}\sum_{i=1}^{N} I_i^l(d_{il}, P_i) \le I_{th} \\ & P_i \ge 0 \quad \forall 1 \le i \le N, \end{aligned} \tag{7}$$

where $D(\mathcal{V})$ denotes the overall video distortion, $D_i(\mathcal{V})$ denotes the distortion arising out of errors in reception of the i^{th} layer, N denotes the number of subcarriers allocated to the CR users, P_i represents the power allocated to the i^{th} subcarrier,

σ_v^2 denotes the variance of the AWGN, ${I_i}^l\left(d_{il}, P_i\right)$ is the interference introduced by the i^{th} subcarrier at power P_i at the l^{th} PU band with a spectral distance of d_{il}. The quantity I_{th} denotes the cumulative interference threshold level imposed by the PU policy enforcer. It can be readily seen that the above problem is convex in nature and hence can be solved efficiently employing convex optimization routines [12]. Using the KKT framework we can express the Lagrangian function $L(P_i, \lambda)$ of the above convex optimization problem as,

$$\begin{aligned} &L(P_i, \lambda) \\ &= \sum_{i=1}^{N} D_i\left(\mathcal{V}\right)\left(\frac{\sigma_v^2}{P_i}\right) + \lambda\left(\sum_{l=1}^{L}\sum_{i=1}^{N} I_i^l\left(d_{il}, P_i\right) - I_{th}\right) \\ &= \sum_{i=1}^{N} D_i\left(\mathcal{V}\right)\left(\frac{\sigma_v^2}{P_i}\right) + \lambda\left(\sum_{i=1}^{N} I_i\left(d_i, P_i\right) - I_{th}\right), \end{aligned} \quad (8)$$

where λ is the Lagrange constraint and $I_i\left(d_i, P_i\right)$ is the total cumulative interference caused by the i^{th} subcarrier to the PU bands. Differentiating eq. (8) with respect to P_i we can simplify as,

$$\frac{\partial L}{\partial P_i} = -D_i\left(\mathcal{V}\right)\left(\frac{\sigma_v^2}{{P_i}^2}\right) + \lambda \underbrace{\frac{\partial I_i}{\partial P_i}}_{K_i}, \quad (9)$$

where $K_i = \sum_{l=1}^{L} K_i^{(l)}$, is the net interference factor for the i^{th} secondary user. Equating (9) to zero and solving for P_i, the optimal transmit power for the i^{th} subcarrier can be obtained as,

$${P_i}^* = \sqrt{\frac{D_i\left(\mathcal{V}\right)\sigma_v^2}{\lambda K_i}}.$$

Employing the total interference constraint $\sum_{i=1}^{N} I_i(d_i, {P_i}^*) = I_{th}$, the equation to compute the Lagrange multiplier λ is given as,

$$\sum_{i=1}^{N} \sqrt{\frac{D_i\left(\mathcal{V}\right)\sigma_v^2}{\lambda K_i}}\, K_i = I_{th}.$$

Hence the closed form expression for the Lagrange multiplier λ for the above optimization problem is given as,

$$\lambda = \left(\frac{1}{I_{th}}\sum_{i=1}^{N}\sqrt{D_i\left(\mathcal{V}\right)\sigma_v^2\, K_i}\right)^2. \quad (10)$$

Thus, the above closed form solution can be employed to compute the optimal power allocation that minimizes the overall video distortion, while keeping the interference caused to the primary users below an acceptable threshold level. The parameters $D_l\left(\mathcal{V}\right)$ are fixed for a video sequence $\mathcal{V}(x, y, t)$ and can be obtained through an offline computation. The values of these parameters for four standard video sequences *Foreman*, *Hall*, *Mobile*, *Coastguard* [13] are shown in Table I. The optimal power vector $P^* = [P_1^*\, P_2^* \ldots\ldots P_N^*]$ is obtained as the solution of the above problem. The base layer video sequence is then transmitted at the innermost CR subcarrier, farthest from the PU band, at the highest power level, thereby minimizing interference. The subsequent enhancement layers are transmitted at progressively lower power levels on subcarriers adjacent to the central subcarrier.

Video Sequence	Base Layer	Enhancement Layer 1	Enhancement Layer 2
Foreman	1280.26	346.36	48.28
Hall	885.63	189.26	32.64
Mobile	1365.25	442.56	69.25
Coastguard	1026.56	284.53	52.65

TABLE I
VIDEO DISTORTION COEFFICIENTS FOR STANDARD VIDEO SEQUENCES

IV. PPA BASED VIDEO POWER ALLOCATION

The scheme discussed in section III describes the OPA policy and yields the optimal power allocation that minimizes the overall video distortion, restricting the interference introduced to the primary users to lie below the acceptable threshold. This scheme is however computationally complex and may not be practically feasible in certain systems. Hence, to address this issue, we propose a near-optimal video distortion minimization scheme with significantly lower computational complexity.

The interference introduced to a PU band by a CR subcarrier is inversely proportional to its spectral distance from the corresponding band, i.e. the interference caused by a CR subcarrier to the PU band decreases with increasing spectral distance. Therefore to reduce the interference caused to a PU, we allocate lower power to the subcarriers that are closer to that PU band and more power to the subcarriers that are away from it. Mathematically, the power allocated is inversely proportional to the factor $\sum_{l=1}^{L} K_i^{(l)}$ and gives rise to a step like power profile within the CR user band [2]. This scheme of power allocation is termed as Proportional Power Allocation(PPA) and can be expressed analytically as,

$$\sum_{i=1}^{N}\sum_{l=1}^{L} K_i^{(l)}\, P_i = I_{th}. \quad (11)$$

Since the power allocated to the i^{th} user is inversely proportional to the parameter $\sum_{l=1}^{L} K_i^{(l)}$, the final power allocation for PPA subject to the above interference constraint can be readily derived as,

$$P_i^B = \frac{I_{th}}{N\sum_{l=1}^{L} K_i^{(l)}}. \quad (12)$$

Thus, the PPA results in an allocation that allots the highest power to the central sub carrier farthest from the adjacent PU bands, and progressively lower powers to the subcarriers closer to the PU bands. As discussed in section II, the video stream transmitted by the CR user is decomposed into several layers in the order of their significance (base layer followed by enhancement layers). Hence, the PPA based video transmission appropriately transmits the video base layer streams on the central CR OFDM subcarriers and enhancement layers on the adjacent subcarriers, thus minimizing video distortion, while restricting interference. Thus, the video layering based scalable video transmission is naturally suited to such scenarios where the available OFDM subcarriers are of graded reliability owing to the loaded transmission power. This preserves the hierarchical significance of each layer in the composite video stream towards minimizing the overall video distortion and obtaining the best video reconstruction at the receiver. Results are presented in the next section to demonstrate the performance of the proposed optimal interweave CR video transmission schemes.

V. Simulation Results

We employ the standard video sequences available at [13] in our simulation setup for wireless video transmission. We simulated our CR system for $L = 2$ primary users, and an interweaved CR band in between the two licensed PU bands with $N = 3$ OFDM subcarriers. Corresponding to the number of available OFDM subcarriers, we employ a two level wavelet decomposition to obtain three video layers, essentially comprising of one base and two enhancement layers, with each layer transmitted on a different subcarrier. We consider symbol duration T_s to be 4 μs and subcarrier spacing Δf and primary bandwidths B_1, B_2 to be 0.3125 MHz, 1MHz, 1MHz respectively. The noise power is $\sigma_v^2 = -26$ dB. The channel gain h_l^{sp} is assumed to be Rayleigh fading with an average power gain of 10 dB. We compute the optimal power allocation vector $P^* = [P_1^*, P_2^*, P_3^*]$ for the optimization problem in (7) employing the CVX convex problem solver and verify its performance with that of the closed form power allocation in (10). We average the received video quality over 10^5 simulation iterations.

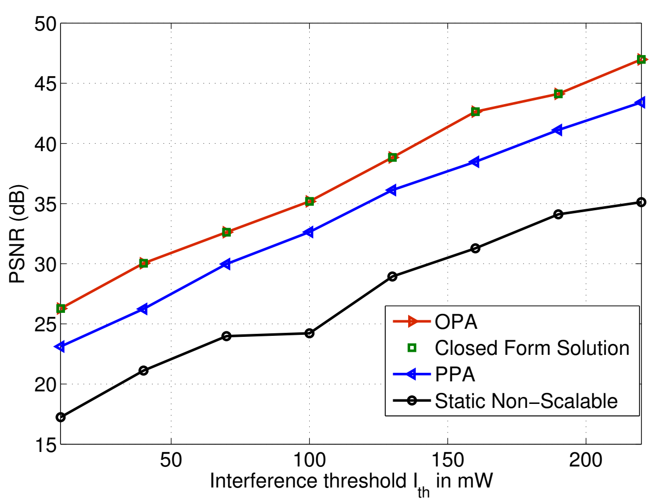

Fig. 3. PSNR of decoded *Foreman* video Sequence versus the interference threshold I_{th}

In Fig.3 we plot the PSNR of the decoded *Foreman* video sequence against the interference threshold acceptable to the primary user for the proposed optimal scheme OPA and near-optimal scheme PPA. We also compare the performance of these schemes with that of the sub-optimal static non-scalable

Fig. 4. Decoded *Foreman* video frame corresponding to OPA.

Fig. 5. Decoded *Foreman* video frame corresponding to PPA.

video transmission. From this figure, it can be readily observed that the proposed OPA scheme results in the highest PSNR of received video reconstruction, with PPA achieving a performance close to OPA with modest computational complexity. However, the performance of the static video codec which does not employ video layering is significantly worse compared to the investigated schemes. This clearly demonstrates the critical need for layering based optimal subcarrier power allocation schemes for OFDM based CR video transmission to minimize the overall video distortion, thus achieving high PSNR for video reconstruction corresponding to superior received video quality. Also, as the interference threshold in the PU band is increased, one is able to load more power onto the CR user subcarriers and thus the PSNR of the decoded sequences also increases progressively. It can also be observed that the theoretical closed form power allocation computed using the expression in (10) is in close agreement with the CVX solution. The frames from the decoded sequence are shown in

Fig. 6. Decoded *Foreman* video frame corresponding to suboptimal single layer video transmission.

Fig.4, Fig.5 and Fig.6 for the different competing schemes. These reconstructed video frames clearly demonstrate that the optimal scheme OPA has a significantly higher visual quality as compared to the other schemes. Quantitatively, OPA policy results in about $3\,\mathrm{dB}$ higher PSNR as compared to the PPA scheme with hierarchical video layering. However, OPA and PPA result in a PSNR improvement of about $8\,\mathrm{dB}$ and $5\,\mathrm{dB}$ respectively compared to the non-hierarchical flat video transmission scheme where the power allocation is done without video layering. PSNR results for the *Coastguard* video sequence are presented in Fig.7.

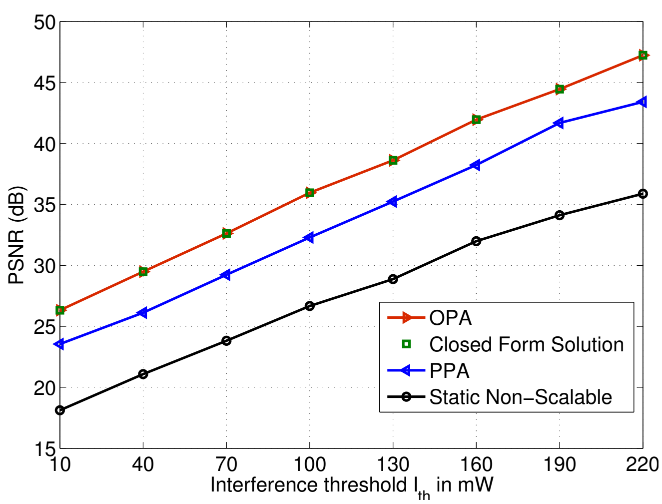

Fig. 7. PSNR of decoded *Coastguard* video Sequence versus the interference threshold I_{th}

VI. Conclusion

In this paper we have proposed a novel scheme for wireless video transmission over OFDM subcarriers in a cognitive radio environment and derived a closed form solution for optimal subcarrier power allocation based on a convex optimization formulation. We also developed a low complexity near-optimal scheme for video transmission and compared the performance of the proposed scheme with that of the suboptimal single layer video transmission through the PSNR of the decoded video sequence and reconstruction quality of the received frames. Simulation results have been given to establish that the OPA and PPA schemes perform significantly better than the suboptimal scheme resulting in an higher PSNR and better visual quality of the decoded frames. These results validate the significance of optimal scalable hierarchical video transmission toward overall received video quality optimization in OFDM CR networks.

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