Energy Efficient Inverse Power Control for a Cognitive Radio Link

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Abstract—**In this paper, a novel adaptive energy and spectrum efficient inverse power control method that is based on the truncated filtered-x LMS (FxLMS) algorithm is introduced. By truncated power control we mean power control where transmission is interrupted if the channel state deteriorates to bad enough. Inverse power control minimizes the interference that a cognitive radio (CR) creates to licensed users and allows more users to share the spectrum. To further reduce the transmission power and consequently the interference, truncation in power control is used. The performance of the system is improved and the amount of needed transmitted energy is smaller. Based on numerical analysis this new method offers energy efficient transmission, helps to minimize interference to the primary users, and allows even more users to share the same spectrum.**

Keywords-FxLMS algorithm; truncated power control; interference control;

I. INTRODUCTION

Spectral efficiency plays a key role as future wireless communication systems will accommodate more and more users and high performance services. Nowadays the spectrum is used inefficiently. Cognitive radio technologies have been proposed to improve the spectral efficiency [1], [2]. The aim of cognitive radio system is very practical and concentrates on the efficient use of natural resources, which include frequency, time, and transmitted energy.

Spectrum awareness is a key requirement for a CR to operate [3]. However, dynamic spectrum management and power control are equally important functions as spectrum sensing. It is important to know how detected spectrum holes can be efficiently exploited while assuring the minimal interference to the primary users (PU) as well as to the other cognitive networks that share the same spectrum. Transmission parameters have to be adapted based on the sensed spectrum and the channel estimation. Inside the net, interference can be controlled with orthogonality principles whereas interference to the other networks is mainly controlled by reducing the transmitter power to the minimum. Because of interference, the cognitive radios have to adjust their power levels according to their potential proximity to a primary receiver [4]. In [5] the task of power control is presented as “to permit transmission at full power limits when necessary, but constrain the transmitter power to a lower level to allow greater sharing of spectrum when higher power operation is not necessary”.

In active cognitive radio system, secondary users (SU) actively sense the surrounding radio environment and adapt their transmission based on the measurements. Spectrum sensing sensitivity can be used to calculate the potential proximity to the primary receiver and to estimate the power limit for secondary transmission. Given this power limit for transmission, can we use conventional adaptive power control methods to cope with multipath fading in a CR system? How can we efficiently use available spectral and energy resources and reduce interference to primary users and other secondary users sharing the same spectrum? What are the actual interference ranges of our own system? This paper addresses these questions, proposes a method for calculation of power limit and introduces a novel FxLMS algorithm based method to be used for power control over a cognitive link.

A very conventional approach for transmitter power control is to maintain desired signal strength at the receiver by inverting the channel power gain based on the channel estimates. Delay-sensitive applications require full inversion methods to be used in power control. However, in a cognitive radio network using active awareness principles, delays cannot be avoided because of periodical sensing. Such a network is not good for real-time communication. Thus, power control method does not need to assure delayless communication. A large part of the transmission power in continuous inverse control solutions is used to compensate the deepest fades in a fading channel. For energy or power efficiency, threshold policies have to be used. It has been recently proven in [6] that regardless of modulation and demodulation methods and taken general assumptions in wireless channel model into account, the optimal power control method is based on threshold policy. Power efficiency and throughput can be clearly improved when compared to continuous transmission schemes.

Link budget is an estimation technique for evaluating communication system performance [7]. The required bit error rate (BER) dictates the value of received signal-to-noise ratio (SNR) in order to meet that performance. In link budget calculations transmitter power, gains, and losses in the link are calculated with primary purpose of determination of actual operation point in the BER curve. However, conventional link budget calculations do not take effects of transmitter power control into account. We have shown in [8] that power control can improve or deteriorate the link budget depending on what kind of power control is used. Bit error rate depends both on the link budget and the distribution of the received signal.

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Therefore, the link budget can be worse with inverse power control than without it because the distribution is better.

The amount of transmitted energy needed to achieve prescribed requirements is used as a metric for energy efficiency. Energy efficiency is an important metric for potentially mobile cognitive radios where energy is taken from battery and is therefore limited. Transmitter power level defines the interference level a CR creates to PUs. We use the interference range as a metric to compare different power control methods. Interference range is a range within which the interference level is more than the victim receiver can tolerate. This defines both how close to primary user we can operate and how well we can share the same spectrum with other secondary users. In addition, capacity under interference or energy constraint is one performance metric. Capacity can be improved either by using more bandwidth or with spectrally more efficient modulation method. The motivation for truncation in CR environment is that it

- Reduces energy consumption, battery lasts longer
- Reduces interference to the primary users
- Improves capacity both under interference range and energy consumption constraint
- Allows more secondary users to share same spectrum
- Relaxes sensing requirements; since the interference range is smaller, there is no need to sense as weak signals as with full inversion power control

This paper is organized as follows. Section II gives some background, and Section III introduces the method for power limit calculation and model used in simulations. Truncated inverse power control method is presented in Section IV. Numerical performance analysis with link budget and interference range calculations is provided in Section V. Section VI draws the conclusion.

II. BACKGROUND AND BASIC CONCEPTS

Interference temperature concept has been proposed as a basis for power control adjustment for SUs. The interference temperature limit T_L characterizes the maximum amount of tolerable interference for a given frequency band in a particular location where the receiver can operate satisfactorily [9]. CR terminals operating in licensed frequency bands have to measure the current interference temperature and adjust their transmission in a way that they avoid raising the interference temperature over the limit. Power control rules that takes T_L into account are proposed in [2] and [9]. The fundamental problem with that approach is that cognitive radios cannot be aware of the precise locations of primary receivers and they cannot measure the effects of their transmissions on all possible receivers. In addition, regulation authorities have not provided actual numbers for T_L.

References [4] and [10] proposed measurements of primary signal to be used as a basis for adjusting own secondary transmitter signal power to a level that allows interference-free communication to the PUs. Either signal from the PU transmitter [4] or so called beacon signal from receiver, [10] can be used to estimate the attenuation between the SU transmitter and PU receiver. The problem with latter approach is that it cannot be used without modification to primary receivers. In addition, typically fast fading channel is not reciprocal, i.e., fading to opposite directions correlate poorly. Thus, measurements cannot give accurate information to the power control adjustment. In order to get the CR system working with wide variety of primary systems, we will take the same approach than [4]. The primary transmitter signal is detected with highly sensitive spectrum sensor and the decision about spectrum use with required power level is made based on that. When data transmission is on, transmitter power should be adjusted adaptively taking the changing channel conditions into account.

A practical closed loop inverse control method is fixed step adjustment power control (FSAPC), known also as conventional closed loop power control (CLPC) [11]. When this method is used, transmission power is adjusted up- or downwards by a fixed amount (typically 1 dB/ms) depending on whether the received power has been over or below a threshold value. The FSAPC method is simple but not fast enough to compensate deep fades in the channel. In the literature adaptive step size and also predictive power control methods are used to improve the performance of the conventional FSAPC algorithm [12]–[14].

The FxLMS algorithm is developed from the LMS algorithm by inserting the model of the controlled system between the input data signal and the adaptive algorithm that updates the coefficients of adaptive filter [15]. This makes the algorithm stable and suitable for active control applications. The FxLMS algorithm is perhaps the most commonly used adaptive algorithm in active noise cancelling applications. The structure and operation of the algorithm are ideally suited to the architectures of standard digital signal processing (DSP) chips and it behaves robustly in the presence of modeling errors and numerical effects caused by finite-precision calculations [15]. In addition, the algorithm is very well suited to adaptive inverse control solutions [15]. FxLMS algorithm can be efficiently used for power control [14]. It is a variable step algorithm that adjusts the step size in a nearly optimal way. In this paper, we investigate and propose a truncated FxLMS algorithm based power control algorithm to cope with fading in a CR environment.

Instead of interference temperature concept, 1 dB coexistence criterion is used in calculations to provide actual interference ranges with different receiver sensitivities. In [17], the fundamental criterion for coexistence in terms of acceptable interference in the victim receiver is defined as the interference level that causes 1 dB degradation in receiver sensitivity. This means that the interference power has to be 6 dB below receiver thermal noise. The interference range for secondary transmission can be defined as a range in which coexistence criterion stated above is not met.

III. SYSTEM MODEL

A. Basic scenario

Interference range can also be seen as a sensing range for a cognitive radio device. To be more exact, sensing range r_s should be as much as the transmission range of primary transmitter r_{pu} plus interference range of secondary transmitter r_{int} to avoid interfering with primary user in the case the primary receiver is located in the edge of the transmission range. So the spectrum sensor should be highly sensitive. The scenario is shown in Fig. 1. Transmission range of the cognitive radio is r_{cr}.

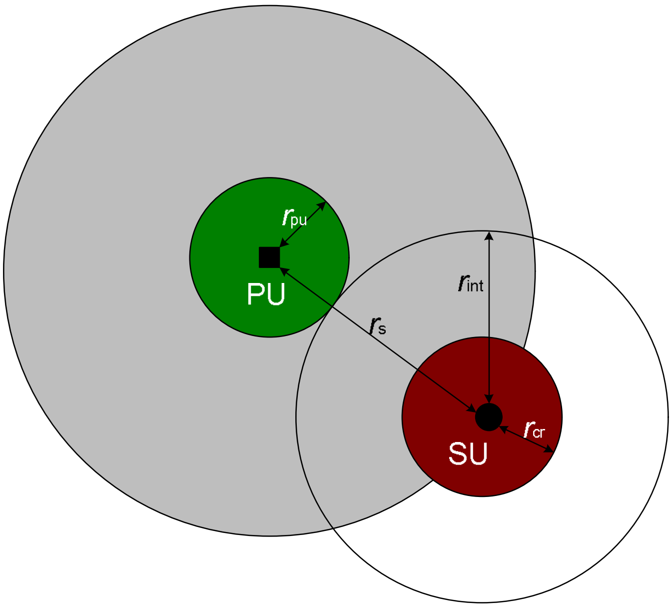

Figure 1. Sensing , interference, and transmission ranges.

So what is the rule for transmission power limit calculation? While it could be very helpful to know the location of PU receivers and the power loss gain of channel between them and secondary transmitters, neither of this information may be available in real systems. If the locations of primary receivers are available, e.g., in some database, this information should of course be used. But assuming fully active CR system we don't get information from primary users during operation. However, we could know something about primary users when we manufacture our cognitive radios. The receiver decoding sensitivity of the PU and the noise figure are the key issues to know. Knowing the decoding sensitivity of PU receiver and the spectrum sensing sensitivity of the cognitive radio we can calculate how much further a CR can detect the primary transmission than a primary receiver. Using worst case budgeting, i.e., assuming only the free space path loss between CR transmitter and PU receiver and large fading in a secondary link, and using 1 dB coexistence criterion, we can calculate how much power we can transmit and what could be the transmission range of the CR system.

Receiver sensitivity defines the minimum radio frequency (RF) signal power level required at the input of a receiver for a certain BER performance. This is a decoding sensitivity of receiver. It is defined as

$$S = N + N_F + \gamma_r \text{ [dB]}, \tag{1}$$

Where $N = kTB$ is the noise floor level in a band of interest, $k = 1.38 \cdot 10^{-23} J/K$ is the Bolzmann's constant, T is the temperature in degrees Kelvin and B is the bandwidth. The symbol N_F is the noise figure and γ_r represents required received SNR value. The decoding sensitivity and the spectrum sensing sensitivity are different things. While decoding sensitivity tells how much power is needed to decode the signal correctly, the sensing sensitivity defines the power level that can be detected. If the PU decoding sensitivity and noise figure are not known, they should be assumed to be as good as possible.

Rule above is for a single sensing device. More reliable sensing results can be achieved with collaboration and then worst case budgeting is not needed. The locally sensed spectrum information of nodes could be sent to the conscious node (CNode) that plays a role of spectrum coordination in the network [18] through a common control channel, combined, and then broadcasted to the CR terminals in the network. In the link level, spectrum has to be estimated periodically to obtain current spectrum use pattern. The system may also employ passive awareness principles and receive spectrum use information from e.g., servers, databases, or beacon signals. Based on the channel and spectrum estimates and the control channel information, operating frequency is selected and suitable power level adjusted to meet the prescribed requirements.

B. Power control model

The system model used in power control simulations is presented as follows. The data are assumed to be known in the receiver, and thus the system is data-aided (DA). The data are transmitted through the channel and the instantaneous transmit power $P[k]$ is allocated based on the channel gain estimate $\hat{h}[k]$ sent by the receiver. The received complex baseband signal has the form

$$r[k] = x[k]\sqrt{P[k]}\,h[k] + n[k] \tag{2}$$

where the complex fading gain of the channel is $h[k] = \alpha[k]e^{j\theta[k]}$ and $n[k]$ is additive white Gaussian noise (AWGN) at time k. The amplitude of the fading gain is $\alpha[k]$ and $\theta[k]$ is the phase shift. Direct least-squares (LS) estimation of $h[k]$ is made online. The transmission data $x[k]$ are BPSK modulated with a rate of 10 kilobits per second.

Signal-to-noise ratio definitions: The average transmitted and the average received energy are usually normalized by the receiver noise spectral density N_0 leading to the average transmitted SNR per symbol [8]

$$\bar{\gamma}_{tx} = \bar{E}_{tx} / N_0 \tag{3}$$

and the average received SNR per symbol [8]

$$\bar{\gamma}_{rx} = \bar{E}_{rx} / N_0 . \tag{4}$$

Transmitted energy is a basic system resource. In a mobile system it is taken from the battery of the transmitter and is therefore limited. Transmitted SNR should be used as a performance metric in order to obtain fair comparisons between different adaptive transmission systems.

Channel modeling: Our multipath channel is modeled by summing up equal amplitude sinusoids with different Doppler shifts. This gives us a flat Doppler power spectrum that corresponds to urban and indoor environments [19]. The time-variant channel gain can be written as

$$h[k] = \sum_{i=1}^{M} a e^{j(2\pi f_i k + \phi_i)} \tag{5}$$

where M is the number of multipath components, a is the amplitude of every component, f_i is the Doppler shift of the ith component, ϕ_i is the random uniformly distributed phase shift of the ith component in range $[0, 2\pi[$ and k is time.

IV. TRUNCATED POWER CONTROL

Truncated channel inversion (TCI) compensates fading above a cutoff while meeting power constraint [20]. Transmission is interrupted and transmission power is zero when the channel gain deteriorates under certain cutoff value. Data are transmitted only when channel gain is above the threshold. The received SNR is kept in the level

$$\sigma_0 = 1/\left[1/\gamma\right]_{\gamma_0}, \tag{6}$$

where

$$\left[1/\gamma\right]_{\gamma_0} = \int_{\gamma_0}^{\infty} \frac{1}{\gamma} p(\gamma) d\gamma, \tag{7}$$

and cutoff value γ_0 is chosen by numerical root finding to maximize capacity per unit bandwidth [21]

$$\frac{C_{\text{tci}}}{B} = \log_2\left(1 + \frac{\bar{\gamma}}{E_1(\gamma_0/\bar{\gamma})}\right) e^{-\gamma_0/\bar{\gamma}} \text{ [bits/s/Hz].} \tag{8}$$

Symbol γ represents instantaneous received SNR value and $\bar{\gamma}$ is the average of it. $E_1(x)$ is the first order exponential integral. FxLMS power control structure can be modified to meet same constraint. Modified structure that approximates TCI is presented in Figure 2.

The algorithm can be presented with the equations

$$\varepsilon_k = |x_k| - \left| x_k c_{k-1} K_k / \sqrt{\sigma_0 \cdot N_0} h_k + n_k \right|, \tag{9}$$

$$c_k = c_{k-1} + \mu K_k \sqrt{\sigma_0 \cdot N_0} \varepsilon_k |x_k h_k|. \tag{10}$$

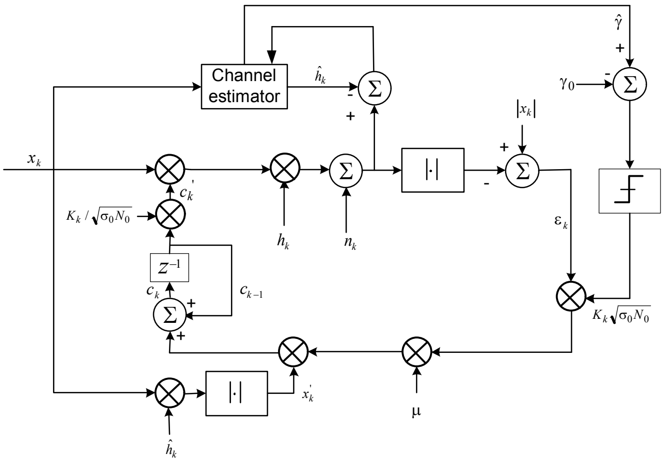

Figure 2. Truncated FxLMS power control.

The algorithm updates the real coefficient c_k of a one-tap filter, μ is the adaptation step size and N_0 is the noise spectral density. The optimal step size for multipath fading channel is given by [14]

$$\mu_{\text{opt}} = \frac{1}{(|x_k|^2 |\hat{h}_k|^2) + c_{\text{term}}}, \tag{11}$$

where c_{term} is a small number that prevents the adaptation step size to grow to infinity when the estimated received power is very small. The parameter K_k in equations is a factor that defines when the transmission is interrupted,

$$K_k = \begin{cases} 1, & \text{when } \hat{\gamma} \geq \gamma_0 \\ 0, & \hat{\gamma} < \gamma_0 \end{cases}. \tag{12}$$

Channel state estimate that is compared to cutoff value is

$$\hat{\gamma} = \bar{E}_{tx} \cdot (|\hat{h}_k|^2 / N_0), \tag{13}$$

where $\bar{E}_{tx}$ is the average transmitted energy. The transmitted energy is approximately $E_{tx} \approx \bar{E}_{tx}$ $(\sigma_0 / \hat{\gamma})$ for $\hat{\gamma} \geq \gamma_0$ and zero otherwise.

If the data rate is kept constant during transmission above threshold and the aim is to keep overall data rate in the same level R than in continuous transmission scheme, it has to be normalized with inverse of probability of outage P_{out}. Thus, the data rate will be

$$R_t = R/(1 - P_{\text{out}}). \tag{14}$$

Outage is the cutoff time when transmission is off, i.e., channel gain is below the threshold. Additional outage time in CR system comes from the fact that transmission has to be off during spectrum sensing to obtain reliable results about spectrum use. In addition, some time is needed also for spectrum allocation between users and also for time needed to reconfigure the transmitter after frequency shift.

V. RESULTS

A. Energy efficiency

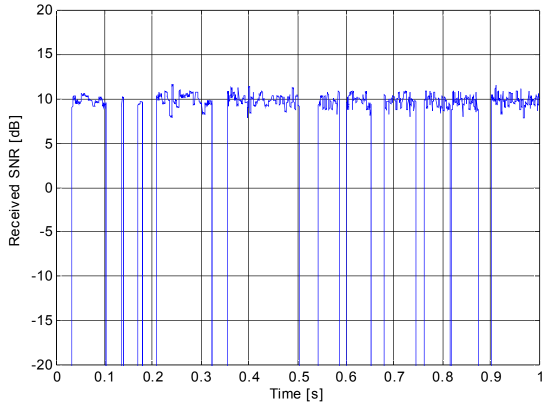

Figure 3. The received SNR with truncated FxLMS power control, average transmitted SNR = 20 dB.

Figure 3. shows the received SNR in a flat fading multipath channel with M = 12 when average transmitted SNR is set to 20 dB. In this system Doppler shift f_d is chosen to be 10 Hz which corresponds to a slowly fading channel. Basically it tells how rapidly receiver is moving. 10 Hz corresponds to the walking speed 1.5 m/s when carrier frequency is 2 GHz. The target received SNR σ_0 is 9.9 dB and the probability of outage 27%. Delays caused by truncation are random.

To compare full inversion FxLMS method, FSAPC method, and variable step adjustment power control (VSAPC) [12] methods to truncated scheme we made simulations with same channel. Approximately same amount of energy is needed with every full inversion methods. As can be seen in Figure 4. the needed transmitted SNR to achieve received target SNR is clearly smaller with truncation. However, when the target SNR is increased, the lines get closer. When the difference is almost 9 dB with 6 dB target SNR, it is almost 3 dB smaller with 12 dB target. The reason for that is that more transmitted energy is allocated to deeper fades. This can be seen also from outage percentage. Probability of outage for three cases presented are 0.47/6 dB, 0.31/9 dB and 0.21/12 dB. Truncated scheme is clearly much more energy efficient. However, to achieve the same average throughput, data rate during the transmission has to be higher and this reduces the actual SNR difference.

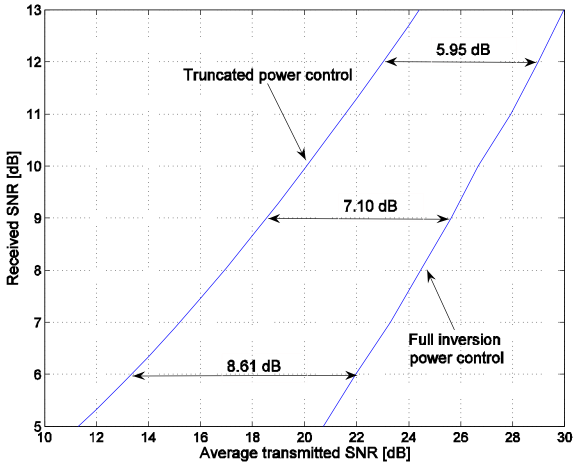

Figure 4. Transmitted SNR versus received SNR curves for truncated and full inversion power control.

To obtain results about interference range and more fair comparisons about transmitted SNR requirements that take data rate variation into account, we made link budget calculations that are offered in the next sections. Noise power in 10 kHz band is $N = kTB = 1.38 \cdot 10^{-23}\, J/K \cdot 290\, K \cdot 1 \cdot 10^{4} = 4.002 \cdot 10^{-17}$ W. In decibels it is 10 lg(kTB) = -164 dBW. Based on (14) and outage information we can compute data rate requirements and actual SNR differences between full and truncated inversion methods. Results are shown in Table 1.

TABLE 1. DATA RATES AND ACTUAL SNR DIFFERENCES BETWEEN FULL INVERSION AND TRUNCATED SCHEME

Received target SNR	R_t	Noise floor level N, $B = R_t$	Actual SNR difference
6 dB	18.87 kbps	-161.22 dB	8.61-(164-161.22)=5.83 dB
9 dB	14.49 kbps	-162.37 dB	5.47 dB
12 dB	12.66 kbps	-162.95 dB	4.90 dB

Because of higher data rate, the noise floor changes and this reduces the actual SNR difference between truncated and full inversion power control schemes. However, it remains remarkable.

B. Interference range

To obtain numerical results about the interference range variations, we made some calculations with a simple model. Node 1 and node 2 lie at the distance of d from each other. We assume that signal propagates in line-of-sight (LOS) environment characterized by the two-slope path loss model which describes well the attenuation in short distance, low antenna height environment [22], [23] such that average received signal power $\overline{P}_{rx}$ [W] is

$$\overline{P}_{rx} = \frac{K}{d^a (1 + d/g)^b} P_{tx}, \tag{15}$$

where K is a constant, a (usually two) is a basic path loss exponent for short distances, b (between two and six) is an additional path loss exponent, and P_{tx} [W] is the transmitted signal power. The parameter g [m] is the break point of path loss curve and is given by $g = 4h_{\text{tx}}h_{\text{rx}}/\lambda_c$ where h_{tx} [m] is the transmitter antenna height, h_{rx} [m] is the receiver antenna height, and λ_c [m] is the wavelength of the carrier. We use antenna heights $h_{\text{tx}} = h_{\text{rx}} = 2$ m, which are typical for mobile user [23]. When the carrier frequency f_c is 2 GHz, we obtain break point at 106.67 m

The parameter K in (15) depends on the used transmitter. The type of the antenna, use of beamforming etc. affects the constant value. When isotropical antenna is used, $K=1/(4\pi f_c/c)^2$. To find the maximal needed transmitted power we have to calculate the path loss with the distance $d = 200$ m, which we assume to be the maximal range for our cognitive link. With 2 GHz system the break point distance is 106.67 m. Let the path loss exponents to be $a = 2$ and $b = 4$. Then,

$$L_F = 10\log\left(\frac{d^a (1 + d/g)^b}{K}\right) = 102.8\,\text{dB}. \tag{16}$$

When we assume noise figure of 5 dB [24] and take into account that desired SNR in the receiver is 9 dB to achieve BER of 10^{-5} we obtain that receiver sensitivity is (-134 + 5 + 9) dBm = -120 dBm. In Rayleigh fading channel, the probability of fade depth to be less than F is simply $p = \exp(-1/F)$. Thus, for 99% coverage, fade margin of 20 dB is needed. The maximal needed transmitter power with the fading margin of 20 dB and shadowing margin of 10 dB which provides 90% successful communications at the fringe of coverage with 8 dB standard deviation [25] is $P_{\text{tx}} = P_{\text{rx, desired}} + L_F = -150$ dBW + 20 dB + 10 dB + 102.8 dB = -17.2 dBW = 19 mW.

Note that shadowing does not exceed the fade margin for 90% of locations at the maximal range (200 m from transmitter). When the receiver is nearer the value of the total path loss is less. Thus, clearly more than 90 percent of locations will have acceptable coverage. With truncation and with target SNR of 9 dB, the needed transmitted SNR is 5.47 dB smaller. We can calculate that maximal needed transmitter power is then only 5.4 mW. With 1 dB coexistence criterion and assuming that the required SNR for link we are interfering is 9 dB the interfering signal has to be 15 dB below the receiver sensitivity not to interfere. For example, with -85 dBm receiver sensitivity, the signal has to be below -100 dBm at this receiver.

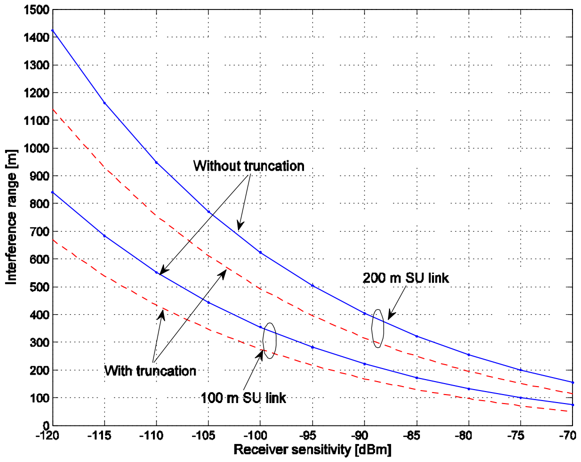

Figure 5. Interference range with different receiver sensitivities for 100 m and 200m SU links.

To see the interference range in the highly improbable worst case situation, when 30 dB fading exists in SU link that uses maximum distance of 100 or 200 meters, and no fading at all exists between SU transmitter and PU receiver, we made calculations with different receiver sensitivities. We assumed that signal propagates according to (14). Results are shown in Figure 5. With 200 m link and sensitivity of -70 dBm, the range is 155 m with full inversion and 115 m with truncation. Thus, the interference area that is a circle with radius of interference range is reduced to the 55 % of the original. When sensitivity is -95 dB, ranges are 396 m and 504 m with interference area ratio of 61.7 %. If the system we are interfering with is equally sensitive cognitive radio system with -120 dBm sensitivity, the ranges are 1424 m and 1141 m with interference area ratio of 64.2 %. Thus, the gain of using truncated power control scheme is that interference area is reduced almost to the half from original. If path loss exponents would be smaller, the difference would be even larger. With 100 m SU link, 12.88 dB less power is needed and consequently the interference ranges are smaller as can be seen in Fig. 5. The interference area ratios with shorter link are even better because the attenuation mainly happens before the break point in the path loss curve. Thus, truncation improves the performance of low power transmitter even more. In addition to the interference reduction to the primary users, truncation improves the spectrum efficiency by allowing more secondary users to access the spectrum at the same time.

Capacity. How much better capacity can we achieve with same energy consumption? Since the difference in transmitted SNR is 7.10 dB when BER target is 10^{-5}, we can raise the data rate with truncated scheme so that noise power becomes 7.10 dB higher. This happens with 51 kHz band which corresponds to (51 kbps · (1-0.31)) = 35.2 kbps average data rate. Thus, compared to full inversion scheme, we can achieve 3.5 times the throughput with the same energy consumption. If we are not allowed to raise our bandwidth, one option is to change the modulation to more efficient one. QPSK offers same BER performance than BPSK. If 16-QAM is selected, 3 dB larger SNR is needed to achieve same BER with double throughput.

This is less than the difference achieved with truncation. To achieve same throughput with full inversion, data rate during transmission should be 1.449 times higher. By changing the modulation we can double the data rate and still get clearly smaller interference range.

C. Coexistence scenario with 1 Mbps secondary link

Assuming 1 Mbps QPSK transmission in 500 kHz band, 5 dB N_F and 9 dB SNR to achieve required BER, the sensitivity of the receiver is S = -103 dBm. With 200 m link and 30 dB fading, transmitter power should be 29.8 dBm. If PU sensitivity is a realistic -90 dBm, interference ranges are approximately 845 m/670 m for full inversion/truncation. With 100 m link, transmission power should be 17 dBm and interference ranges are 490 m/383 m. Assuming PU link to be 200 m, spectrum sensor should sense signals 200 m farther than interference ranges mentioned above. With 30 dB fading, attenuations for cases mentioned are 170.2 dB/165.7 dB for 200 m link and 160.2 dB/157.0 dB for 100 m link.

When PU transmitter uses 40 dBm transmitted power, sensitivity of spectrum sensor should be -130.2 dBm/-125.7 dBm for 200 m link and -120.2 dBm/-117.0 dBm for 100 m link. Can we detect any of these signals when the noise floor is -117 dBm? Uncertainties in the noise and interference levels and the coherence time induce limits on how weak signals individual sensors can detect [26], [27]. The minimum power level is called SNR wall and cannot be overcome by increasing the sensing time. SNR wall with 1 dB noise uncertainty for energy detector is 3 dB below noise floor and can be further reduced by 20 dB by using feature detection. So the achievable sensing values are -120 dBm and -140 dBm for 500 kHz band. Only 100 m link with truncation can be used with energy detectors. All scenarios are achievable with feature detection. Assuming 10 dB gain for cooperative detection, also 200 m link with truncation can be used with simple energy detectors. Because the signal levels for detection with truncation are higher, faster sensing times and more efficient spectrum utilization can be achieved.

These calculations show that we can use highly sensitive cognitive radio system with relatively long transmission links inside the primary system even under worst case conditions. Interference can be controlled with transmitter power control together with reliable spectrum awareness method. However, if much higher data rate is needed, multi-carrier transmission over multiple spectral holes could be used. The other option is to cope multipath fading with diversity and use power control to mitigate the effects of path loss and shadowing. This would allow even better spectrum sharing and interference range reduction. Truncation offers much better energy efficiency also in shadowing channel [28].

VI. CONCLUSIONS

Cognitive radio should minimize interference it creates to licensed users. This can be done by using minimum amount of transmitter power. In an active cognitive radio system, spectrum sensing sensitivity together with worst case link budgeting tells how much transmission power is allowed to use in order to avoid interfering with primary receivers. In a cognitive radio network using active awareness principles, delays cannot be avoided because of periodical sensing. Such a network is not good for real-time communication. Thus, power control method does not need to assure delayless communication.

A large part of the transmission power in continuous inverse control solutions is used to compensate the deepest fades in a fading channel. Truncation in power control reduces the energy consumption and transmission power. Thus, interference to primary users is reduced and more secondary users are allowed to share the spectrum. Both energy and spectrum efficiency are improved. In addition, sensing requirements can be relaxed because of shorter interference range. This means faster sensing times and better spectrum utilization. Drawback is that no data are transmitted below threshold which causes random delays to transmission. However, we can achieve much better average throughput with same interference range when compared to conventional full inversion scheme.

Truncation is a good choice for transmission in a CR system. When channel becomes bad enough, the secondary transmitter should stop transmitting and continue again when situation is better. Another option is to change frequency. Further work is still needed to investigate how the multipath fading affects the operation of a cognitive radio and what are the best methods to mitigate these effects. For example, an interesting research topic could be to investigate the effects of diversity and beamforming to the transmitter power needs and to the interference range. Intuitively, the combination of directional antennas, good diversity method and truncated power control method could offer very efficient spectrum sharing solution. In addition, experiments with multiple secondary users causing aggregate interference could be done.

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