Fuzzy Logic Power Control in Cognitive Radio

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Abstract — **Opportunistic radio spectrum access has the possibility to improve spectrum utilization needed for next generation mobile networks. The main challenge to opportunistic radio spectrum access lies in finding balance in conflicting goals of satisfying performance requirements while minimizing interference. In this paper we propose new strategy for fuzzy logic transmit power control which enables cognitive secondary user to achieve its required transmission rate and quality, while minimizing interference to the primary users and other concurrent secondary users.**

Keywords - cognitive radio; opportunistic radio spectrum access; transmit power control; fuzzy logic systems

I. INTRODUCTION

In recent years, demand for wireless communication services has grown far beyond earlier predictions. Furthermore, in order to satisfy future market demand for mobile and broadband services, we can envisage deployment of next generation mobile networks and services which will need rapid and more flexible access to radio spectrum. Due to policy of exclusive frequency assignment, radio spectrum has become congested and scarce resource. Nevertheless, related surveys have proved that most of the allocated spectrum is underutilized [1, 2]. To deal with increasing conflict of spectrum congestion and spectrum underutilization, cognitive radio technique has been proposed as a flexible method which allows secondary users to utilize already licensed bands opportunistically [3, 4]. Opportunistic radio spectrum access has the possibility to improve spectrum utilization and in perspective allowing next generation mobile networks access to the attractive radio spectrum bands.

The main challenge to opportunistic radio spectrum access lies in finding balance in conflicting goals of satisfying performance requirements for secondary user (SU) while minimizing interference to the active primary users (PU) and other secondary users. Secondary user should not degrade performance statistics of licensed primary users. In order to achieve these tasks, secondary user is required to recognize primary users, determine environment characteristics and quickly adapt its system parameters corresponding to the operating environment. Main abilities of cognitive radio (CR) with opportunistic radio spectrum access capabilities are spectrum sensing, dynamic frequency selection and adaptive transmit power control.

In recent years, studies on transmit power control (TPC) are progressing in order to investigate different TPC strategies for opportunistic radio spectrum access systems [5-9]. Presented TPC strategies differ depending on settings of primary goals for TPC, presumptions about available input data and on methodology used for transmit power control parameter determination. In [5], opportunistic TPC is presented which enables cognitive user to maximize its transmission rate i.e. power, while guaranteeing PU outage probability. The authors in [6] proposed fuzzy logic TPC scheme which dynamically adjust transmit power relating to SU interference observed at PU, distance between PU and SU and received power difference at the SU base station. In order to avoid interference at PU, exchange of sensing information between PU and SU is required. In [7], authors propose distributed cognitive network access scheme with the aim of providing best QoS with respect of combination of radio link and core network performance. Fuzzy logic decision has been used to choose the most suitable access opportunity even in multi-technology scenarios. A power control approach based on spectrum sensing side information in order to mitigate interference to the PU is presented in [8]. Cognitive radio transmit power is calculated in three step procedure using missing probability of energy detection dependence on distance between PU and SU. In [9], the authors investigate the optimal power control with and without interference temperature constraints based on observed Shannon capacity. The optimal power control in cognitive radio network is modeled as a concave minimization problem [10].

In this paper we propose alternative transmit power control strategy which enables cognitive secondary user to achieve its required transmission rate and quality, while minimizing interference to the primary users and other concurrent secondary users. Proposed TPC ensures that each SU in the network receives and transmits just enough energy to convey necessary information. Spectrum sensing data and regulatory requirements defines maximum acceptable SU transmit power. Depending on the quality of service, SU receiver sets required signal-to-interference-plus-noise ratio (SINR). Comparison of measured and required SINR at SU receiver determines transmit power control ratio and minimum required SU transmit power. SU transmit power is determined by balancing these two requirements of maximum acceptable SU transmit power to satisfy interference constraints and minimum required SU transmit power to satisfy determined level of service.

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Proposed TPC strategy is implemented using fuzzy logic system (FLS) [11, 12]. Fuzzy logic systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems and computer vision. Advantage of FLS is that it merge objective analytic and experience based subjective knowledge. FLS formalize control algorithms which can tolerate imprecision and uncertainty of input data like spectrum sensing data and SINR measurements in this case. Additionally, proposed TPC strategy can be implemented with low cost and easy to implement fuzzy logic controllers.

The advantage of proposed TPC strategy is in minimizing mutual interference and reduction of frequency reuse distance for PU and other SU. This leads to radio spectrum utilization improvement and increasing overall networks capacity with available radio spectrum. Additionally, reduction of SU transmitter power results in minimizing battery consumption of mobile terminals for next generation mobile networks and services.

The outline of the paper is as follows. Section 2 describes system model of primary licensed system and co-existence with opportunistic spectrum access secondary system in the same geographic area. In section 3 outline of the proposed TPC strategy is presented. The design of cognitive radio fuzzy logic TPC is elaborated in section 4. Simulation results and performance evaluation of proposed TPC strategy are presented in section 5. Conclusions are given in Section 6.

II. SYSTEM MODEL

In this paper we consider scenario in which a primary system is licensed service with a coherence time T_C and activity probability α following block static model. Primary transmitter is operating with average transmit power $\overline{P_{PU\_Tx}}$. Cognitive secondary system co-exists in the same area with primary system using opportunistic radio spectrum access and should not increase level of interference observed by primary system. We assume that primary system is not aware of the presence of cognitive secondary system and that there is no active communication or cooperative behavior between PU and SU.

Channel model for a pair of primary users and cognitive secondary users is shown in Fig. 1. We assume that the quasi-static Rayleigh fading is present, and the channel coefficients between communication users are considered to be independent Rayleigh distributed variables. The receive signal model can be presented as:

$$Y_{PU}(t) = h_{11}(t) \cdot X_{PU}(t) + h_{21}(t) \cdot X_{SU}(t) + Z_{PU}(t) \qquad (1)$$

$$Y_{SU}(t) = h_{22}(t) \cdot X_{SU}(t) + h_{12}(t) \cdot X_{PU}(t) + Z_{SU}(t) \qquad (2)$$

where Y_{PU} and Y_{SU} denotes PU and SU received signal, X_{PU} and X_{SU} denotes PU and SU transmitted signal, t is time, h_{11} and h_{22} are random variables representing fading channel coefficients between primary and secondary transmitter and receiver, h_{12} and h_{21} are random variables representing interference fading channel coefficients. $Z_{PU}(t)$ and $Z_{SU}(t)$ are additive white Gaussian noise at PU and SU with variances σ_{PU}^2 and σ_{SU}^2. Observed SINR at the primary receiver $SINR_{PU\_A}$ can be represented as:

$$SINR_{PU\_A} = \frac{|h_{11}|_A^2 \cdot P_{PU\_A}}{\sum_{i=1}^{N} |h_{21}|_i^2 \cdot P_{SU\_i} + \sum_{\substack{j=1 \\ j \neq A}}^{K} |h_{11}|_j^2 \cdot P_{PU\_j} + \sigma_{PU\_A}^2} \qquad (3)$$

and SINR at the cognitive secondary receiver $SINR_{SU\_B}$ is calculated as:

$$SINR_{SU\_B} = \frac{|h_{22}|_B^2 \cdot P_{SU\_B}}{\sum_{\substack{i=1 \\ i \neq B}}^{N} |h_{22}|_i^2 \cdot P_{SU\_i} + \sum_{j=1}^{K} |h_{12}|_j^2 \cdot P_{PU\_j} + \sigma_{SU\_B}^2} \qquad (4)$$

where K and N represent number of co-channel primary and cognitive secondary users, $|h_{ij}|^2$ is power gain of fading channel coefficients, P_{PU_A}, P_{PU_j} are transmitted powers of co-channel primary users, and P_{SU_B}, P_{SU_i} are transmitted powers of co-channel cognitive secondary users. SINR at the cognitive secondary receiver is used for determination of minimum required transmit power of SU in order to minimize interference potential of cognitive secondary user.

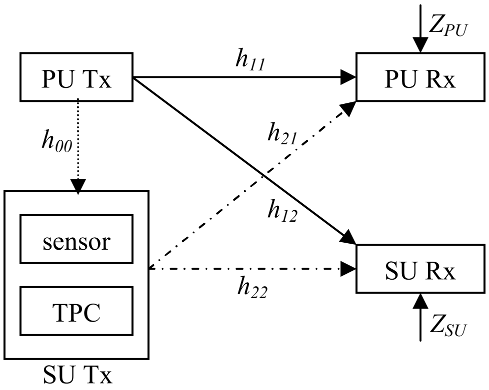

Figure 1. Channel model for scenario of co-existing pair of PU and SU

III. POWER CONTROL STRATEGY

In order to fully exploit potential of opportunistic spectrum access, interference control is a crucial issue. It is essential to keep the transmission power of the cognitive SU at a minimum level while ensuring adequate signal quality at the receiving end. Proposed power control strategy is based on balancing SU transmit power level between minimum required and maximum acceptable. Minimum required transmit power is obtained by adjusting it to satisfy targeted SINR at the SU receiver. Maximum acceptable transmit power is established considering permissible interference at the primary user's receiver. It is determined by spectrum sensing data and predefined regulatory constraints. As a result, proposed TPC strategy tries to maintain required SINR at the cognitive SU receiver, while not causing excessive interference to the licensed primary users.

Initial power of cognitive SU transmitter is calculated using path loss estimation determined by measurement of common pilot channel in open-loop power control cycle. Common pilot channel is broadcast signal with known transmitted power. Initial power is calculated as:

$$P_{Tx\_SU\_i} = P_{Tx\_CPC} - P_{Rx\_CPC} - L_{add} + SINR_{Req} + N_{SU} + \sum_i I_i \quad (5)$$

where $P_{Tx\_SU\_i}$ is initial SU transmit power, P_{Tx_CPC} is predetermined transmitted power of common pilot channel, P_{Rx_CPC} is measured power of common pilot channel at SU receiver, L_{add} are additional gain, loss and tolerances, $SINR_{Req}$ is required SINR, and $N_{SU} + \sum_i I_i$ is measured noise plus interference at SU. Initial power of cognitive SU transmitter is used for initial communication between SU transmitter and receiver of next generation mobile network. It is starting point for process of adaptive adjusting of transmitter power which is done by iterative self adapting power control strategy described bellow.

Instant transmit power of the secondary user P_{Tx_SU} is determined by balancing maximum acceptable transmit power $P_{Tx\_SU\_MAX}$ and minimum required transmit power $P_{Tx\_SU\_Req}$ as follows:

$$P_{Tx\_SU} = \left\{ \begin{matrix} P_{Tx\_SU\_Req} & if\ P_{Tx\_SU\_MAX} \geq P_{Tx\_SU\_Req} \\ 0 & if\ P_{Tx\_SU\_MAX} < P_{Tx\_SU\_Req} \end{matrix} \right\}. \quad (6)$$

Maximum acceptable transmit power $P_{Tx\_SU\_MAX}$ represent maximum allowed power of the cognitive SU in order to satisfy interference constraints determined by spectrum sensing of the primary user at the secondary user location $P_{Tx\_SU\_sens}$ and requirements imposed by regulatory regime $P_{Tx\_SU\_rr}$. Maximum acceptable transmit power is determined as:

$$P_{Tx\_SU\_MAX} = \min\{P_{Tx\_SU\_sens}, P_{Tx\_SU\_rr}\}. \quad (7)$$

Determination of transmit power interference constraint $P_{Tx\_SU\_sens}$ used for calculation of maximum acceptable transmit power is illustrated in Fig. 2. Based on the sensing power P_{Rx_sens} measured at the secondary user transmitter we can determine transmit power interference constraint $P_{Tx\_SU\_sens}$ according to the following three cases:

CASE 1: Sensing power is bellow PU threshold level ($P_{Rx\_sens} < P_{PU\_th}$).

When licensed primary user is undetectable, cognitive secondary user transmitter can transmit with its peak power. If SU sensing controller is determining primary link with low power level, cognitive SU has to reduce its maximum transmit power in order to avoid harmful interference to the PU receiver at unknown location. Transmit power interference constraint is proportional to the additional path loss beyond threshold level as illustrated in Fig. 2.

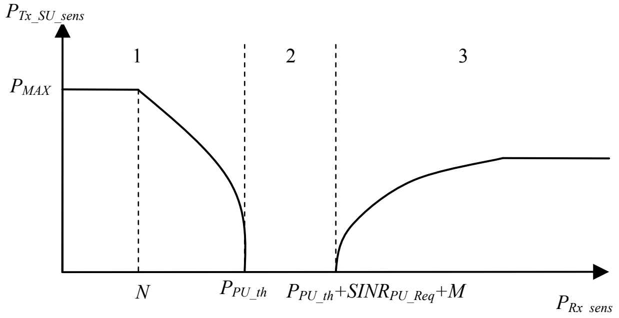

Figure 2. Determination of transmit power interference constraint

CASE 2: Sensing power is above PU threshold level in the PU working area ($P_{PU\_th} \leq P_{Rx\_sens} < P_{PU\_th} + SINR_{PU\_Req} + M$) where $SINR_{PU\_Req}$ is required SINR for PU and M is additional fading and multiple interference margin.

In this case transmitter of the cognitive secondary user is situated near the edge of the PU coverage zone, therefore all transmissions should be avoided in order no to cause additional interference to the primary user receiver in the same area. Preferably, secondary user should delay transmissions for later of transfer its transmissions to different channel using channel mitigation techniques for opportunistic radio spectrum access.

CASE 3: Sensing power is well above PU threshold level ($P_{PU\_th} + SINR_{PU\_Req} + M \leq P_{Rx\_sens}$).

Since SU sensing controller is determining primary link with relatively high power, cognitive SU is situated near to the PU transmitter. In this case cognitive SU can transmit with lower power level without causing measurable disturbing interference to the PU receiver. This case is appropriate for short range communications between SU transmitter and receiver distant from PU receiver. Transmit power interference constraint of cognitive SU should be adjusted in such way that required SINR for the PU receiver is guaranteed.

Minimum required transmit power $P_{Tx\_SU\_Req}$ determines cognitive SU transmit power just enough to satisfy required SINR at SU receiver. Comparison of measured SINR at SU receiver with required SINR determines SU transmit power control ratio for transmit power adjustment. The new minimum required transmit power is obtained by multiplying present minimum required transmit power with transmit power control ratio R_{TPC} obtained from the output of the fuzzy logic system as follows:

$$P_{Tx\_SU\_Req}(t+1) = P_{Tx\_SU\_Req}(t) \cdot R_{TPC}\,. \qquad (8)$$

Possible implementation of proposed adaptive transmit power control strategy using fuzzy logic is described in next section.

IV. FUZZY LOGIC TPC DESIGN

Fuzzy logic transmit power controller for opportunistic radio spectrum access contains fuzzy logic processor, performance evaluator and regulatory database as shown in Fig. 3. Regulatory database contains regulatory rules defining maximum permissible radiated power or power spectral density of cognitive SU transmitter in geographic area of interest. Spectrum sensing data collected at cognitive SU determines level of spectrum activity and potential influence of cognitive SU to the primary network. These two elements define maximum acceptable transmit power of cognitive SU as described in section 3. Performance evaluator compares measured SINR at SU receiver with required SINR. Based on SINR difference fuzzy logic processor determines transmit power adjustment for estimating minimum required transmit power of cognitive SU.

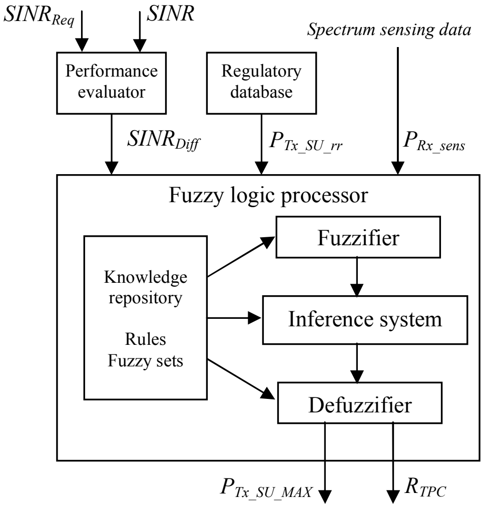

Figure 3. Architecture of fuzzy logic transmit power controller

Fuzzy logic processor is in general non-linear mapping parallel processor of input data vector into output data scalar or vector. Fuzzy logic processor contains four main components: fuzzifier, inference system engine, knowledge repository and deffuzzifier as shown in Fig. 3. Input variables are crisp values which are transformed in appropriate fuzzy sets degree of membership via membership function. Implication method is performed by the set of rules which have general form: if X is X_1 and Y is Y_1 THEN Z is Z_1. Knowledge repository contains inference rules used for connecting input and output space of linguistic variables and fuzzy sets of input and output variables. Aggregation and deffuzification of results is done by the weighted average of all rule outputs obtained by inference system. A detailed overview of the fuzzy logic systems is out of the scope of this paper and can be find in the literature [11, 12].

Fuzzy logic transmit power controller supply three input variables to fuzzy logic processor: SINR difference ($SINR_{Diff}$) from performance evaluator, maximum permissible radiated power $P_{Tx\_SU\_rr}$ from regulatory database and spectrum sensing data P_{Rx_sens} from SU Tx sensor. Output variables are: maximum acceptable transmit power $P_{Tx\_SU\_MAX}$ and transmit power control ratio R_{TPC}. For membership function for input and output variables a trapezoidal function $g(x; x_0, x_1, a_0, a_1)$ is chosen given by:

$$g(x) = \begin{cases} \dfrac{x - x_0}{a_0} + 1 & \text{for} \quad x_0 - a_0 < x \le x_0 \\ 1 & \text{for} \quad x_0 < x \le x_1 \\ \dfrac{x_1 - x}{a_1} + 1 & \text{for} \quad x_1 < x \le x_1 + a_1 \end{cases} \qquad (9)$$

where x_0 (x_1) is left (right) edge of the trapezoidal function and a_0 (a_1) is left (right) width of the trapezoidal function.

V. PERFORMANCE EVALUATION

In this section we give some numerical results of proposed fuzzy logic transmit power control strategy. We have randomly generated 30 SU transmitter and receiver pairs and simulated 3000 samples of Rayleigh faded received signal for each pair. To evaluate transmit power control strategy maximum power of PU transmitter is set to 40 dBm and maximum power of SU transmitter is set to 33 dBm. PU is implemented without transmit power control function. Transmit power control ratio R_{TPC} is obtained as crisp dB value from difference of observed and required SINR at SU receiver. Fig. 4 shows Sugeno type fuzzy inference diagram for determining transmit power control ratio.

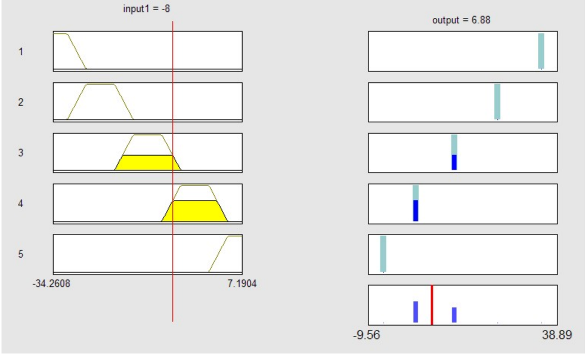

Figure 4. Fuzzy inference diagram of R_{TPC}

The maximum acceptable transmit power of secondary user is determined using regulatory constraint set to 30 dBm and simulated PU spectrum sensing data. Spectrum sensing data of primary user transmitter is simulated with 3000 randomly distributed Rayleigh faded signal samples for three characteristic cases of spectrum sensing data as described in section 3. Fig. 5 shows results of adaptive regulation of SU transmit power using proposed cognitive radio fuzzy logic controller. First diagram shows calculated SINR difference at SU receiver which is input parameter for determination of transmit power control ratio parameter. SU transmit power is adjusted in order to achieve required SINR at SU receiver and satisfy interference constraints defined by maximum acceptable transmit power as shown in second diagram. It can be seen that instant power of the SU transmitter is significantly bellow maximum power of SU transmitter used in literature for capacity optimal power adaptation [5, 9]. Finally, resulting SINR measured at SU receiver is presented in third diagram. Fuzzy logic transmit power controller maintains constant SU receiver SINR with ±1 dB deviation comparing to required SINR.

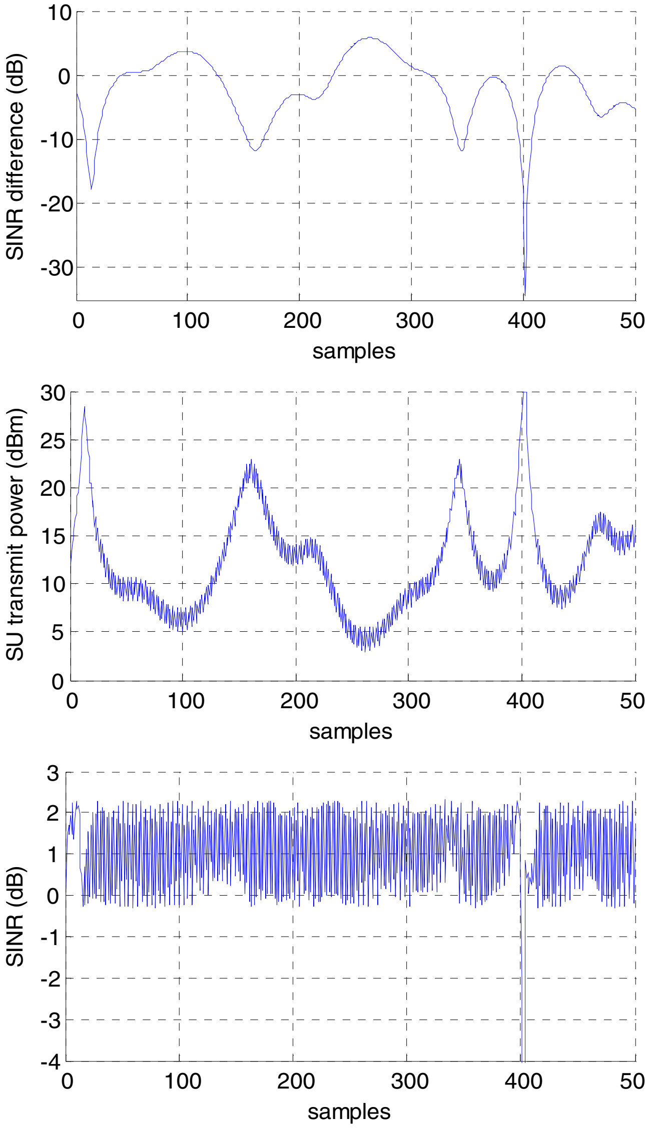

Figure 5. Fuzzy logic transmit power controller simulation results

Average SU transmit power in analyzed scenario is 12 dBm. Comparing this to average SU transmit power for capacity optimal power adaptation we can calculate co-channel frequency reuse distance for proposed TPC strategy. We can conclude that co-channel frequency reuse distance is reduced by 3.35 times in mobile environments using distance attenuation factor of 3.8. Therefore, interference potential of SU transmitter is reduced and same radio frequency channel can be used more frequently leading to improving spectrum utilization and increasing overall networks capacity with available radio spectrum. As a consequence of minimizing the SU transmitter power in proposed TPC strategy battery consumption of mobile terminals for next generation mobile networks and services is reduced.

VI. CONCLUSIONS

In this paper, we have presented alternative transmit power control strategy for cognitive secondary users applying opportunistic spectrum access. Transmit power control is realized using fuzzy logic system which enables simple and low cost implementation of TPC function. Presented TPC strategy allows cognitive secondary user to achieve its required transmission rate and quality, while minimizing interference to the primary users and other concurrent secondary users. Advantage of presented cognitive SU TPC scheme is that it is following altruistic approach which results in smaller interference potential and reduction of frequency reuse distance. This allows also other next generation mobile network users to benefit from available radio spectrum, leading to the improvement of overall spectrum utilization and maximizing overall PU and SU networks capacity.

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