JOINT RATE AND POWER CONTROL USING DISTRIBUTED ALGORITHMS IN COGNITIVE RADIO NETWORKS

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ABSTRACT

Radio frequency spectrum is limited and highly contested, hence cognitive radio networks' perceived ability to improve spectrum utilisation has gained much attention. Joint rate and power control is a method that can be used by unlicensed secondary users to share spectrum with licensed primary users as long as it provides QoS guarantees to both secondary and moreover to primary users. In this paper, we propose a distributed joint rate and power control algorithm for infrastructure-less cognitive radio networks in which each user adjusts their transmit power and rate of transmission by considering the QoS of both primary and secondary users. We propose a fully distributed iterative algorithm in which the aggregate transmission power for cognitive radios is calculated assuming a maximum initial data rate. If the calculated power is more than the maximum allowed power level, the data rate is reduced and power is recalculated iteratively. Simulation results show that by using the proposed approach a higher number of users can be supported while the QoS constraints for both primary and the secondary users are maintained.

1. INTRODUCTION

The need for the spectrum resource increases with the increase in numbers of users and innovative bandwidth hungry services and hence efficient use of spectrum has become even more crucial. On the other hand spectrum underutilisation in a range of bands [1] is a major problem for the modern wireless communication systems. A study of Ofcom on radio frequency spectrum [2] indicates that, over space and time, not all the spectrum allocated to a user is used. The underutilisation of the spectrum lead to the concept of spectral holes where the spectrum is (in space or time) unoccupied and Cognitive Radio (CR) does the job of filling up the spectral holes [3].

CR's should satisfy simultaneously the Quality of Service (QoS) constraints for secondary transmissions (CR users) as well as preventing any adverse effect on the QoS of licensed users (Primary users). Regarding QoS requirements of the licensed users, regulatory policy reform has led to a situation where in some frequency bands the use of underlay access by CR may be permitted, provided the Maximum Interference Level (MIL) [1] at the licensed receiver remains below a certain threshold. Similarly QoS requirements of CR users can be translated in terms of the received Signal to Interference and Noise Ratio (SINR) at the CR receiver.

Power control plays an important role in maintaining link quality, avoiding interference to other users and to save power. It is also very important in CR networks since CRs re-use the licensed spectrum and must be prevented from interfering with licensed communications. The power control strategies can be implemented either centralised or in a distributed fashion. The centralised power control mechanism uses a central entity (e.g. base station) to control power of all users, which significantly increases signalling overhead and overall system complexity [4]. On the other hand, Distributed Power Control (DPC) algorithms are widely accepted due to their lower complexity and lower signalling overhead. The standard DPC algorithm proposed by Foschini and Miljanic [5] and its variants [6] attracted lot of attention in cellular networks due to their excellent fix point convergence.

In cognitive radio networks, the power control problem is more challenging: transmission power allocation of a CR must consider the total interference at the receiver of the licensed users. Hence, classical DPC algorithms cannot be directly applied. In order to satisfy the QoS of the licensed users, an additional process can be used by the CR's using DPC, which informs the CR about the level of interference caused to the licensed users. For example, in [7] a genie aided DPC algorithm was proposed, were the genie placed near the licensed user, it could inform the CR's in cases the interference caused to the licensed user increases above the maximum allowed MIL. A fully autonomous DPC technique for CR networks is proposed in [8]. Each CR user determines its own transmission power on considering interference to the licensed users also taken into account. Here the total interference constraint at the licensed user caused by all CR users is divided equally among all CR users and therefore there is no need of any additional process as described in [7].

In [9], an admission control algorithm is proposed, which blocks the users when the network load is high. The admission control technique will cause the CR users not to access the network at full rate, instead they can be allowed to join at a reduced rate. A joint power and channel allocation algorithm is proposed in [10], where Lagrange multipliers are used to determine tackle the capacity issue and then to be able to maximise the sum capacity. Joint power and rate control using non-cooperative game theory is proposed in [11].

In all the approaches, the rate of data transmission is kept as a constant. But, in future wireless networks, users also have different requirements of the data rates and hence joint control of data rate and power is essential. In this paper, we formulate a joint rate and power control problem while keeping the strict QoS constraint. Inspired by the DPC algorithms presented in [8], we modify the problem for the case when users are transmitting at different data rates and propose a framework for joint rate and power control. In the proposed approach, CR data rates are varied according to the channel conditions and the interference level. The rate is reduced as the channel degrades and hence less power is needed for transmission, thereby reducing interference to other users. Simulation results prove that more users can be supported with lower individual data rate, even in a degraded channel thereby increasing the fairness between users.

The rest of the paper is organised as follows. The system model used is explained in section 2. The proposed joint rate and DPC algorithm is explained in detail in section 3. The simulation environment is described and the results are analysed in section 4. Finally, the conclusion and summary are provided in section 5.

2. SYSTEM MODEL

We consider a CR adhoc network with N independent CR transmitter and receiver pairs as shown in the Fig. 1. The primary network is considered as a TV network with a range of transmission R, transmission power P_{TV} and randomly distributed TV receivers. The centre of the CR network is considered to be at a distance D from the worst case location of TV receiver. A path loss based channel model is assumed with a path loss exponent for TV and the CR users as α_1 and α_2 respectively. Since the TV transmitter is a tall TV antenna and the CR users are at ground level, CR users transmit power will attenuate faster than the TV signal and hence α_1 is less than α_2.

3. JOINT RATE AND DISTRIBUTED POWER CONTROL ALGORITHMS

The CR should satisfy the QoS of both the licensed users and the CR users. The QoS of the licensed user is measured in terms of the MIL at the worst case location of licensed user. The aggregate interference at licensed user caused by the CR network should not exceed the MIL of the licensed user, which is normally specified by the regulatory body.

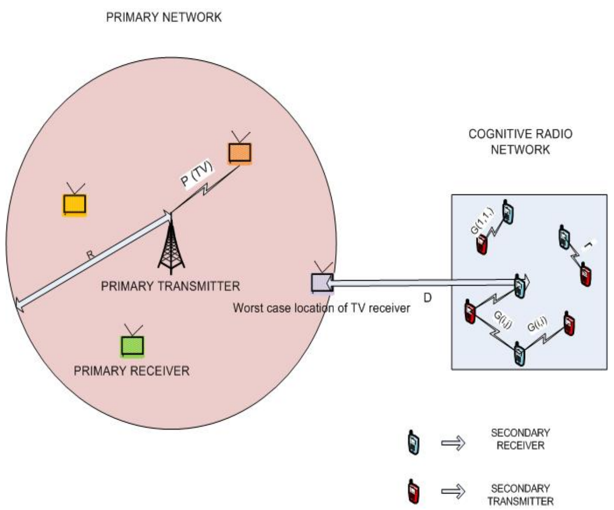

Fig. 1. System Model

Let P_i be the transmission power of the i^{th} CR user, $G_{TV,i}$ be the link gain from i^{th} CR user to the TV receiver and ξ_{TV}^{thr} is the MIL of licensed users. The condition for satisfying QoS of the TV receiver can be given by the equation (1),

$$\xi_{tv} = \sum_{i=1}^{N} G_{TV,i} P_i \leq \xi_{TV}^{thr} \quad (1)$$

QoS of the CR's can be measured in terms of received SINR and for a reliable communication the received SINR should be greater than the lowest threshold value γ_{SU}^{thr}. Let the link gain from the j[th] CR transmitter to the i[th] CR receiver be $G_{i,j}$, from licensed TV user to the i[th] CR user be $G_{i,TV}$ and the receiver noise power be N_0. Hence the QoS requirements for the i[th] CR user is expressed as follows,

$$\gamma_{SUi} = \frac{B}{R_i} \frac{G_{i,i} P_i}{\sum_{j=1,j\neq i}^{N} G_{i,j} P_j + G_{i,TV} P_{TV} + N_0} \geq \gamma_{SU}^{th} \quad (2)$$

Where, γ_{SUi} is the received SINR at the i[th] CR receiver, B is the channel bandwidth and R_i is the transmission rate of the i[th] CR user. From equation (2), the transmission power of i[th] user can be written in an iterative form as in equation (3).

$$P_i(t+1) = \frac{\gamma_{SU}^{th}}{G_{i,i}} \frac{R_i}{B} \left(\sum_{j=1,j\neq i}^{N} G_{i,j} P_j(t) + G_{i,TV} P_{TV} + N_o \right)$$

$$= \frac{\gamma_{SU}^{th}}{\gamma_{SUi}(t)} P_i(t), t = 0,1 \ldots \quad (3)$$

where $\gamma_{SU_i}(t)$ and P_i (t) are the received SINR and the transmission power of the t[th] iteration.

The DPC algorithm defined in equation (3) calculates power of i[th] user by satisfying the SINR threshold of the i[th] user as a constraint. In order to maintain the power level of the CR users within the maximum allowed power value, a constraint was introduced in the DPC algorithm. This modified version of the algorithm is called as the Distributed Constraint Power Control (DCPC) algorithm [12] as in (4).

$$P_i(t+1) = \min \left\{ \frac{\gamma_{SU}^{th}}{\gamma_{SUi}(t)} P_i(t), P_{SU}^{max} \right\}, t = 0,1..$$

$$0 \leq P_i \leq P_{SU}^{max}, i\epsilon\{1,2,..,N\} \quad (5)$$

The DCPC algorithm helps in maintaining the power within the maximum allowed power value with limit given by equation (5). But there is no assurance that the minimum required SINR is achieved. Therefore, even if the maximum power is consumed, the user cannot achieve a reliable communication.

To overcome the drawbacks of the DCPC, Generalised Distributed Power Control (GDCPC) algorithm was introduced [13]. In GDCPC, if the desired SINR is not achieved, the transmission power is reduced to an arbitrary power value in the range of transmission, instead of transmitting in the maximum value. The GDCPC can be given by the equation (6),

$$P_i(t+1) = \left\{ \begin{array}{c} \frac{\gamma_{SU}^{th}}{\gamma_{SUi}(t)} P_i(t), \text{if } \frac{\gamma_{SU}^{th}}{\gamma_{SUi}(t)} P_i(t) \leq P_{SU}^{max} \\ \overline{P}, \text{if } \frac{\gamma_{SU}^{tr}}{\gamma_{SUi}(t)} P_i(t) > P_{SU}^{max} \end{array} \right\} \quad (6)$$

$$0 \leq \overline{P} \leq P_{SU}^{max}$$

Where $\overline{P}$ is an arbitrarily chosen value which is less than the maximum value (P_{SU}^{max}). The lower the value of $\overline{P}$, the less is the interference to the other CR users. If the value of $\overline{P}$ is equal to the maximum value, then GDCPC becomes DCPC algorithm.

For the CR networks, Autonomous Distributed Constraint Power Control (ADCPC) algorithm was proposed in [8], in which each power update process considers the QoS requirements of licence users as well.

$$G_{TV,i} P_i \leq \frac{\xi_{TV}^{th}}{N}, i\epsilon\{1,2, \ldots N\} \quad (7)$$

The interference to the licensed user because of the CR users is distributed among all the CR users. By this way QoS of the licensed user is guaranteed if the equation (7) is satisfied. Each CR user knows about the total number of users in the adhoc network with the help of routing protocol explained in [14]. In ADCPC, the maximum transmission power constraint is enforced to all the CR users. Therefore the maximum power value can be given by equation (8),

$$P_{SUi}^{max} = \min \left\{ P_{SU}^{max}, \frac{\xi_{TV}^{th}}{G_{TV,i} N} \right\} \quad (8)$$

From the maximum power value, the transmission power can be calculated using the modified equation as in (9).

$$P_i(t+1) = \min \left\{ \frac{\gamma_{SU}^{th}}{\gamma_{SUi}(t)} P_i(t), \min \left\{ P_{SU}^{max}, \frac{\xi_{TV}^{th}}{G_{TV,i} N} \right\} \right\} \quad (9)$$

Similarly in Autonomous Generalised Distributed Constraint Power Control (AGDCPC) algorithm, another maximum power constraint is enforced for each CR user to assure the QoS of licensed users. This is similar to the GDCPC algorithm discussed earlier, with a difference of considering the QoS of the licensed users.

$$P_i(t+1) = \begin{cases} \dfrac{\gamma_{SU}^{th}}{\gamma_{SUi}(t)} P_i(t), \text{if } \dfrac{\gamma_{SU}^{th}}{\gamma_{SUi}(t)} P_i(t) \le P_{SU}^{max} \\ \overline{P}_i, \text{if } \dfrac{\gamma_{SU}^{tr}}{\gamma_{SUi}(t)} P_i(t) > P_{SU}^{max} \end{cases} \quad (10)$$

The value of the arbitrary power is calculated by considering the licensed users as in (11). This ensures that the QoS of licensed user is satisfied.

$$\overline{P}_i = \min\left\{\overline{P}, \min\left\{P_{SU}^{max}, \frac{\xi_{TV}^{th}}{G_{TV,i}N}\right\}\right\} \quad (11)$$

In the proposed approach, joint rate and power control algorithm in which, initially, aggregate power is calculated for CR network by assuming that all users are transmitting at their maximum allowable data rate. If the calculated power is more than the maximum allowed power, then the rate (R_i) is reduced by half and the power is recalculated. The same procedure of rate reduction is carried on until the calculated power is below the maximum allowable power value. In this way, we are reducing the transmission rate in cases where the channel is worse and requires high transmission power for reliable communication. By keeping the rate low, we can maintain the link quality of the CR users also in bad channel conditions. If the channel is in an extremely bad state, the rate is reduced to zero and no data is transmitted. In this manner, we can assure that CR users are not interfering with the other CR users and more importantly not with the licensed users, thereby ensuring QoS of both the licensed and CR users.

4. SIMULATIONS

The simulation results shown in this section demonstrates the performance of the proposed approach. The various simulation parameters used for simulation are listed in Table 1.

PARAMETERS	VALUES
Number of Users	50
Transmission range of CR Users	500m
Maximum transmit power P_{SU}^{max}	100mW
Transmit power of TV station P_{TV}	100kW
TV Transmission Range	70km
Receiver noise power N_o	10^{-11}mW
QoS of licensed user: ξ_{TV}^{thr}	-100dBm
QoS of CR user: γ_{SU}^{thr}	3dB
Path loss exponent of TV user	3
Path loss exponent of CR users	4

Table 1: Simulation Parameters

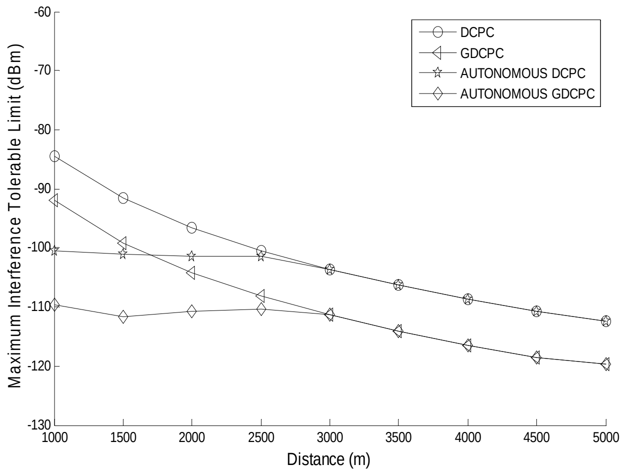

Fig. 2. MIL at Licensed users

The interference temperature level at the TV receiver is shown in Fig. 2. The distance of CR network from the worst case licensed user is varied from 1000m to 5000m and the MIL is calculated. It is clear from the Fig. 2 that the interference decreases as the distance increases and also ADCPC and AGDCPC never exceeds the MIL of the licensed user i.e. -100dBm. Since GDCPC and AGDCPC consume less power than DCPC and ADCPC, their MIL is lower than the DCPC and ADCPC.

The total number of supported users who can communicate reliably by satisfying both the QoS requirements is shown in Fig. 3. The transmission rate of CR users is kept as a constant and they transmit with maximum data rate. Due to the maximum power constraint in GDCPC and AGDCPC, the numbers of supported users are higher than the DCPC and ADCPC.

Using the proposed algorithm, all the users in the CR network (50 users) are supported with a less data rate. This is when there is no lower rate constraint to the users where some users may have very less data rate depending

Scenario	Mean Data Rate	Number of users	Throughput
No rate control (Transmission at maximum data rate)	1Mbps	8	8Mbps
Rate control with lower rate constraint of 700Kbps	0.782Mbps	12	9.384Mbps
Rate control with lower rate constraint of 500Kbps	0.635Mbps	16	10.16Mbps
Rate control with lower rate constraint of 300Kbps	0.511Mbps	22	11.242Mbps
Rate control with lower rate constraint of 200Kbps	0.407Mbps	28	11.396Mbps
Rate control with lower rate constraint of 100Kbps	0.336Mbps	34	11.424Mbps
Rate control without lower rate constraint	0.250Mbps	50	12.5Mbps

Table 2. Average data rates and throughput of CR users

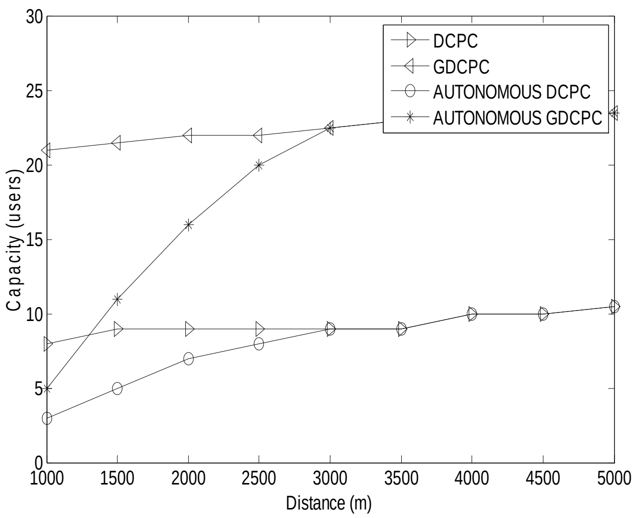

Fig. 3. Comparison of supported users for the DPC algorithms

upon the channel condition. Therefore, the average data rate is low when compared to the maximum data rate (1Mbps).

When a lower rate constraint of 100Kbps is fixed to all the users, the number of supported users reduces. According to the lower rate constraint limit, each user should have a minimum rate of 100Kbps after satisfying the QoS constraints of both the licensed and the CR users. The user will be allowed to transmit only on satisfying the constraint. Therefore, each user is provided with a minimum assured data rate of 100Kbps. This denotes a fair data rate allocated to all the supported users.

Various lower data rate constraints are used and the corresponding average data rate, number of supported users and the system throughput were obtained as in Table 2. When the users transmit at a maximum data rate, then only minimum number of users can be supported. This is the case when no rate control is employed and all the users transmit at maximum data rate. AGDCPC algorithm is used for the calculation of number of supported users, since it considers both licensed and the CR users for the power calculation.

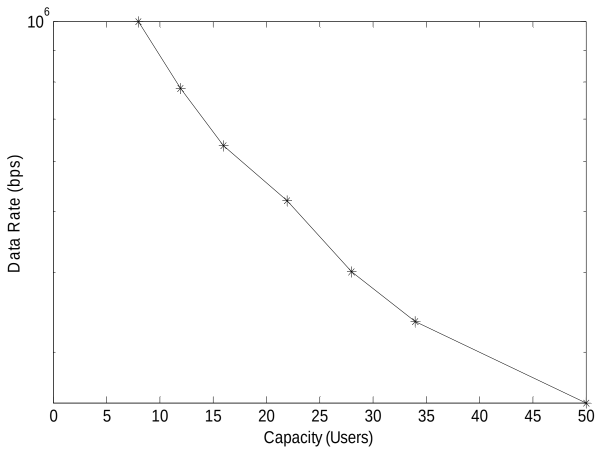

Fig. 4. Comparison of supported users with data rate

Fig.4. compares the mean data rate of the system with the number of supported users using the proposed approach. The number of users in the system is less, when the users transmit at a large data rate and more number of users can be supported in the system on satisfying the QoS if the mean data rate is reduced. The throughput of the system also increases with the number of supported users using the proposed technique as shown in Fig.5.

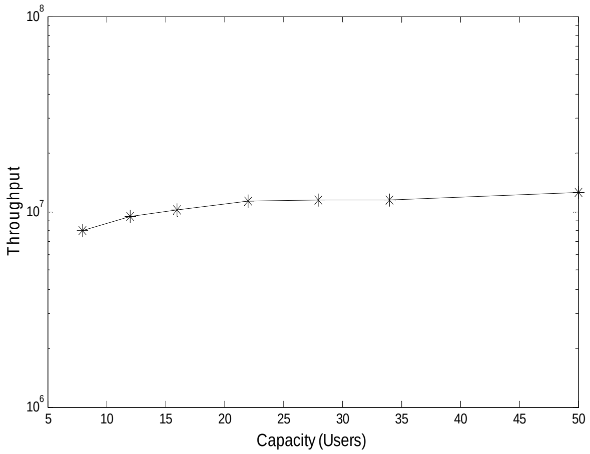

Fig.5. Comparison of supported users with system throughput

5. CONCLUSION

In this paper, a joint rate and power control algorithm was discussed which adjusts the transmission rate of CR users and controls their transmission power while maintaining the QoS of both the licensed and CR users. Various DPC algorithms were compared in simulations, using a range of performance measures such as number of supported users at a given QoS. Therefore the proposed scheme ensures that the QoS of both the licensed and the CR users are maintained simultaneously. It is clear from the results that by varying the transmission rate of the CR users more users can be supported, thereby increasing the spectral efficiency of the system. In our intended future work, issues related to providing fairness to each user and providing dedicated services with different data rates to each CR user according to the type of users will be addressed.

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