Quantum Games Based Communication Protocols

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Abstract: Medium access control (MAC) and efficient spectrum allocation function particularly, are real challenges that wireless communications are facing nowadays and Dynamic Spectrum Access (DSA), enhanced with quantum computation techniques, is the most promising alternative. In such a context, we capitalize quantum games and quantum decisions strengths to design protocols that make classic communications more efficient. That is, we focus on protocols running on quantum devices whose input and output signals are classic. In this work we propose a quantum media access control (QMAC) that allows dynamic and fair spectrum allocation. Particularly, we point to two of the main DSA functions, which are Spectrum Sharing and Spectrum Allocation.

Keywords: Quantum games, minority, spectrum allocation, cognitive radio, spectrum sharing.

1. INTRODUCTION

One of the most significant current discussions in wireless communications is the rapid growth in the number of users that have some kind of mobile communication device and the difficulties that this entails. In that context, Cognitive radio (CR) is an arising paradigm which comes to extend the frontiers of wireless communications by improving the utilization of the radio frequency spectrum. The basic idea of CR is that unlicensed users can opportunistically exploit spectrum holes temporarily unused by licensed users. The cognitive agents, that can be thought as the decision making module of the CR devices, must execute an autonomous decision algorithm based on environmental information they gather. Such a task is one of the most challenging tasks of CR communications, because information and opportunities change dynamically. In order to address that, we model the situation as a multi-armed bandit problem [1] and propose quantum computation techniques to solve it more efficiently than any classic method. Moreover, while in conventional wireless systems users actions are regulated by base stations, it is necessary for cognitive radio to operate in a decentralized manner [2]. In such a case, a competitive scenario among cognitive users is established, making it suitable for game theory treatment. We have studied recently MAC protocols functions, [3, 4, 5], from a quantum game theory perspective showing that quantum techniques are one of the best manners to design wireless communications protocols for current classics and for quantum future communication systems. In this work, we focus on two quantum CR-MAC protocol important functions which are spectrum sharing and spectrum allocation. The spectrum sharing protocol is based on the interference quantum properties to manage the channel access priorities. The proposal of spectrum allocation based on quantum minority game has been introduced previously [5] and is revisited here.

2. THE QUANTUM MEDIA ACCESS PROTOCOL

Dynamic spectrum access implies users opportunistic access to the unoccupied licensed bands without interfere with them. Because of that, MAC protocols design implies more consideration for cognitive radio than that needed for conventional networks. Moreover, DSA includes spectrum sensing, spectrum access, spectrum allocation, spectrum sharing and spectrum mobility beside conventional control procedure [6]. The medium access control (MAC) protocol proposed is relevant both for classic and quantum communications. It takes into account two of the mentioned functions, which are spectrum sharing and spectrum allocation. In order to make migration easier, it takes advantage of quantum parallelism and quantum entanglement strengths taking into account the current standards. A cellular structure wireless network is analyzed in this work. Each cell (named Basic Service Set, BSS) is controlled by a Base Station (BS), figure **1**. That is, the CR belonging to each cell must follow a spectrum allocation process stated by the corresponding BS. At the same time, Base Stations negotiate with Primary Users the spectrum sharing under the rules of the Quantum Spectrum sharing function.

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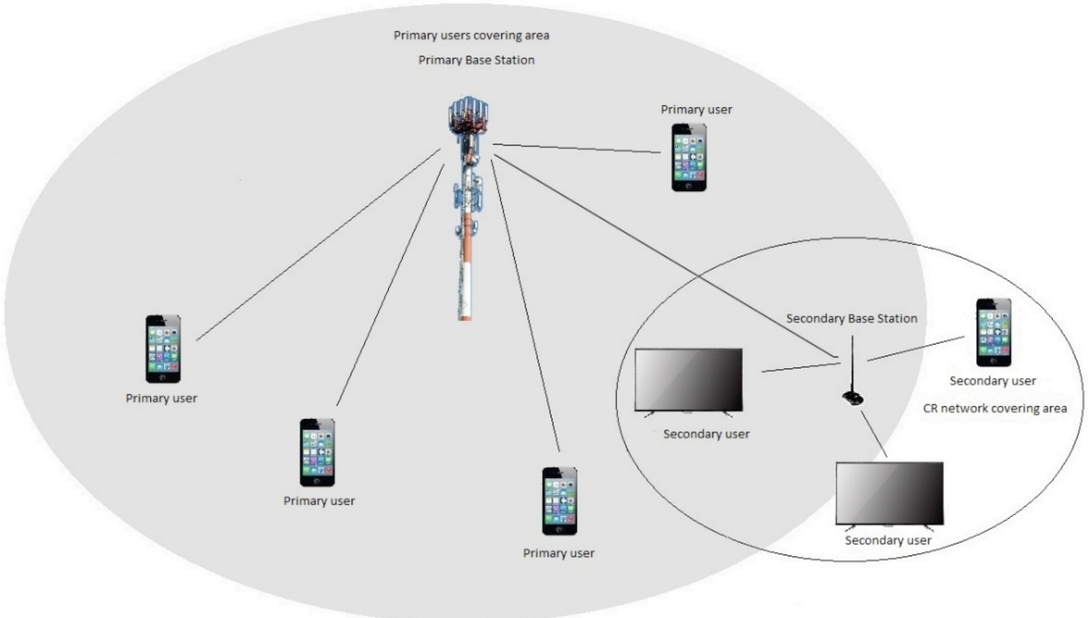

Figure 1: Cellular Cognitive Radio scheme.

3. SPECTRUM SHARING

The quantum spectrum sharing protocol proposed in this work plays the role of managing the spectrum access to Primary and Secondary users, by assigning qubit 1 or 0 to every BS that determines if they can or cannot access respectively. The state $|,00\ldots1.$, for instance, means that only BS^1 is enabled and the rest are not. On the other hand, state $|,00...101.$ means BS^1 and BS^2 are enabled. Although if more than one BS are allowed to share the spectrum, the control process we look upon is to allow that only one BS have access at the same time, which contributes to security, and CR network Quality of Service (QoS). Moreover, state $|00...00\rangle$, the lower energy and more probable state is reserved to the Primary user because it has priority over any CR user. In order to give some access priority order to the different base stations, an entangled state W is generated among them. The quantum circuit used for the case of three BSs case is depicted in figure **2**.

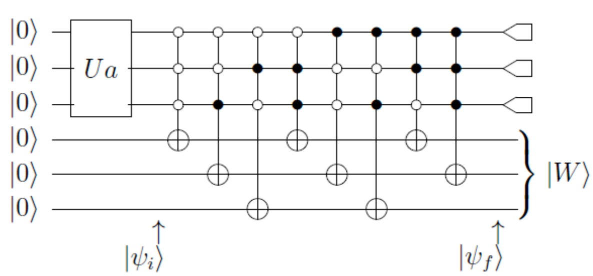

Figure 2: Circuit to obtain a quantum W-state: If a measure is made on one of the three upper qubits, $|W\rangle$ collapses to one of the three particular basis states $|001\rangle, |010\rangle or |100\rangle$.

From the circuit, the system state before applying the CNOT's array is:

$$|\psi_i\rangle = \left(\sum_{k=0}^{7} \alpha_k |k\rangle\right) \otimes |0\rangle^{\otimes 3}, \quad U_a|000\rangle = \sum_{k=0}^{7} \alpha_k |k\rangle \tag{1}$$

Then, the output after applying the CNOT's array is:

$$|\psi_f\rangle = (\alpha_0|000\rangle + \alpha_3|011\rangle + \alpha_6|110\rangle)|001\rangle + (\alpha_1|001\rangle\alpha_4|100\rangle + +\alpha_7|111\rangle)|010\rangle + (\alpha_2|010\rangle + \alpha_5|011\rangle)|100\rangle \tag{2}$$

As can be deduced from eq. 3, the function circuit permits to control the access probability of the different BSs operating on the system state to change α_i values.

$$p_1 = |a|^2 = |\alpha_0|^2 + |\alpha_3|^2 + |\alpha_6|^2$$
$$p_2 = |b|^2 = |\alpha_1|^2 + |\alpha_4|^2 + |\alpha_7|^2 \tag{3}$$
$$p_3 = |c|^2 = |\alpha_2|^2 + |\alpha_5|^2$$

The BS enabling to access to the licensed Spectrum do not imply that the CRs are able to transmit. Moreover, the users in the cell of the shared BS must compete under a spectrum allocation detailed in the next section.

4. SPECTRUM ALLOCATION

The spectrum allocation function is responsible for fairly allocating available spectrum bands to users in a

CR network. Whenever a spectrum band is allocated, the information about the allocated spectrum band will be announced to other users. Either a cooperative or a non-cooperative manner can be used for spectrum allocation.

4.1. System Model

The system analyzed in this work considers N channels and N users that must be assigned to one of those channels. The system state of some user *j* in Dirac notation, $j \in 0,1,...,N-1$ is denoted $\left|c_j\right\rangle$, with $c_j \in 0,1,...,N-1$. Moreover, the state prepared by the BS for the entire system $|\psi\rangle = |c_0\rangle \otimes |c_1\rangle \otimes ... \otimes |c_{N-1}\rangle$. Thus, it must be understood that user 0 is assigned to channel c_0, user 1 is assigned to channel c_1, and so on.

Suppose there are N users accessing the spectrum assumed to be divided into N channels. Because none of the users has information about other users, there is a high probability that more than one of them will take part in a collision. When that occurs, all those involved cannot transmit, resulting in a situation that must be avoided or, at least, minimized by means of appropriate spectrum allocation protocols. This kind of problems is difficult to solve classically as the number of players increases, that is, they are included in the group referred to as NP problems [7]. Accordingly, they cannot be solved in polynomial time, which generally results in inefficient solutions.

We are facing a type of decision problem consisting of agents with similar objectives that compete for a limited number of resources. Therefore, the spectrum allocation problem may be modeled as a multiple-options minority game [5, 8].

The cellular network considers that each cell has a single cognitive BS and a group of CR users in its coverage range. The BSs are transceivers in charge of connecting the devices to other devices in the cell. To achieve this, they collect the CR user reports, and prepare to allocate the radio channels. It is assumed that the devices cooperatively sense the spectrum and record information about the spectrum holes, which will eventually be provided to the base stations. Cooperative sensing has been previously analyzed by other authors [9].

In the following, we focus on a quantum algorithm capable of managing the spectrum allocation based on probability amplitude amplification. More specifically, we present two cases of interest: the first one aims to avoid all users being assigned to the same channel, and the second one aims to enhance the probability of quantum states that assign different channels to users. The proposed quantum medium allocation evolves by following three basic steps:

1. The cognitive quantum BS assigns a set of qubits to the cognitive users in the cell range and prepares entangled state $|\psi_e\rangle$.

$$|\psi_e\rangle = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \omega_N^{k.p} |kk\,...\,k\rangle, \tag{4}$$

where $\omega_N = e^{2\pi i/N}$ and *p* is a tunable parameter that modifies the amplitude phase. Depending on *p*, it is possible to select BS preferences to avoid the least favorable case, $p=1$, or, on the other hand, to enhance the optimum one, $p = \frac{N(N-1)}{2}$.

Every node locally applies a one-shot strategy U to the initial state, which makes the system collapse to a new state.

$$|\psi_f\rangle = U^N |\psi_e\rangle, \tag{5}$$

The nodes of each cell measure the final state ψ_f to obtain the assigned channel.

4.2. Quantum Circuit Description

Figure **3** shows a possible circuit to generate the entangled state $|\psi_e\rangle$. The state of the system |*,00..0.* is modified by the action of gate *R* applied on the two upper qubits,

$$R = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix},$$

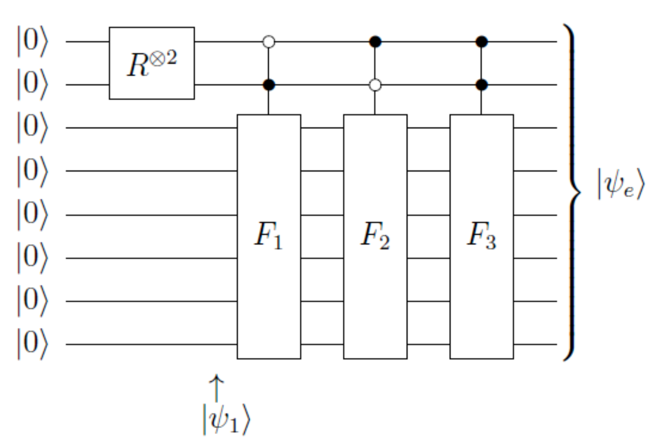

Figure 3: Circuit that generates the initial entangled state $|\psi_e\rangle$.

generating state $|\psi_1\rangle = \frac{|00000000\rangle}{2} - \frac{|01000000\rangle}{2} - \frac{|10000000\rangle}{2} + \frac{|11000000\rangle}{2}$. Then, the two upper qubits of $|\psi_1\rangle$ are the control lines of three Ctrl-F gates. A white circle in a control line indicates that the control qubit must be in state 0; meanwhile, a black circle implies that the control must be in state 1 in order to perform F_k (see Figure **4**). Note that the range of the system state is $N.\log_2 N$ and that $R^{\log_2(N)}$ must perform the rotation on the upper $\log_2(N)$ qubits in the general case. The extension of the circuit to N users is straightforward.

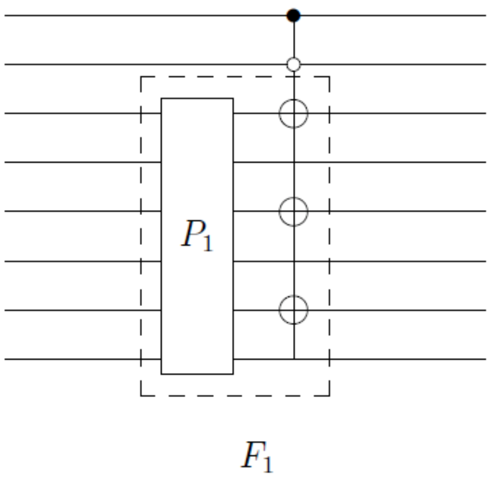

Figure 4: Ctrl-F_1 gate circuit, where $P_1 = \omega_N^{1p} \cdot I^{\otimes}$. Looking from top to bottom, the F_1 operation is performed on the last six lines only if the state of the first two upper lines is $|10\rangle$.

Finally, the action of gates F_k on state $|\psi_1\rangle$ yields:

$$|\psi_e\rangle = \frac{|00000000\rangle}{2} - \frac{|01010101\rangle}{2} - \frac{|10101010\rangle}{2} + \frac{|11111111\rangle}{2} \quad (6)$$

4.3. Strategy to Diminish Collision Risks

One of the main functions of cognitive radio is to provide a fair spectrum scheduling method among coexisting cognitive users. In this context, the purpose of the proposed method is to improve the classic methods ability to decrease the collision probability. When one user cannot transmit because of a collision, he must wait a lapse of time to re-manage the transmission request. System reliability and the network quality of service improve if collisions are avoided. As was described in Section 4.1, for the channel assignation procedure the base station prepares the entangled state of eq. 4 with all the users in the cell, setting $p=N(N-1)/2$. After that, the users are positioned to perform their strategies. The strategy U that applies each player is represented by an $N\times N$ unitary matrix whose elements are;

$$U_\omega = \frac{1}{\sqrt{N}} (e^{\frac{2\pi i}{N}})^{r.c}$$

where, $r, c = 0,1,...,N-1$ are the row and column indexes.

Then, the final state is;

$$|\psi_f\rangle = U^{\otimes N}|\psi_e\rangle = \left(\frac{1}{\sqrt{N}}\right)^{N+1} \sum_{k=0}^{N-1} \omega_N^{k.p} |kk \ldots k\rangle,$$

$$|\psi_f\rangle = \left(\frac{1}{\sqrt{N}}\right)^{N+1} \sum_{k=0}^{N-1} \sum_{c_0=0}^{N-1} \cdots \sum_{c_{N-1}=0}^{N-1} \left(e^{\frac{2\pi i}{N}kp} e^{\frac{2\pi i}{N}kc_0} \cdots e^{\frac{2\pi i}{N}kc_{N-1}} |c_0 \cdots c_{N-1}\rangle\right).$$

Thus, the state coefficients can be expressed as:

$$\alpha_{c_0 \cdots c_{N-1}} = \left(\frac{1}{\sqrt{N}}\right)^{N+1} \sum_{k=0}^{N-1} e^{\frac{2\pi i}{N}k\overbrace{(p+c_0+\cdots+c_{N-1})}^{m}} \quad (7)$$

The fairness of the network implies that every user has a priori the same chances to transmit. In the language of games, the BS acts as the arbiter of the game because it assigns the qubits to the players and creates the entangled state. Later on, the players strategies modify the state amplitudes and hence their chances to win. The players receive a reward, which in this case is to succeed in transmitting.

Once spectrum holes are detected, the nodes must be assigned to one channel. Clearly, there are N! possibilities that every player will be assigned to different states, with N being the number of cognitive users. Therefore, provided that all the cognitive users are indistinct, the probability that all of them transmit at the same time is $P_c = \frac{N!}{N^N}$ in the classic world; for example, $P_c = 2.4 \times 10^{-3}$ if N = 8. Such a low success probability can only be increased by means of statistical methods involving exploration and/or a previous knowledge of the network [10], which is hardly possible if the network is continuously changing. In this framework, we propose the one-shot quantum game-based algorithm.

The m sum in the phase factor of eq. 7 is analyzed in order to properly select p. There by, a proper use of quantum interference makes it possible to improve the players chances. The case where $c_0 \neq c_1 \neq \cdots \neq c_{N-1}$ leadsto $= p + \frac{N(N-1)}{2}$. Thus, in order to guarantee the constructive interference, $p = \frac{N(N-1)}{2}$ and the phase factor is $e^{2\pi ik(N-1)}$. Finally, the probability of the most favorable case is $P_{best} = N \cdot \frac{N!}{N^N}$, which is N times larger than the classic one, $P_{best} = N \cdot P_c$. Clearly, the algorithm performance provides a more efficient use of the devices energy, extending the time of communication and battery life.

CONCLUSIONS AND FUTURE WORK

In this work we propose a Quantum Media Access Control (QMAC) protocol which allows a dynamic and fairly spectrum allocation to CR users. Particularly, we focus on two of the main DSA functions which are *Spectrum Sharing* and *Spectrum Allocation*. For Spectrum sharing we used an entangled circuit, which permits to discriminate between a Primary User to Secondary Users giving priority to the former and an opportunistic access to others. On the other hand, for Spectrum allocation case, the model aims to increase the no-collision probability over that of the classic approaches, which is essential in networks (such as cell phone networks) where quality of service is prioritized. Because of the characteristics of the one-shot algorithm, less time is wasted in the channel allocation process, which makes it possible to repeat the algorithm and further increase the success probability. An extra advantage is saving energy. This proposal is one step further on the design of a completely quantum MAC system.

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