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Q-Learning-based LTE-U and WiFi Coexistence Algorithm for Wireless Healthcare Systems

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***Abstract*— Due to the lack of resources in the low spectrum, LTE-U (LTE in unlicensed spectrum) technology has been proposed to extend LTE to unlicensed spectrum. LTE-U undertakes the task of medical streaming data traffic for licensed spectrum, which can greatly improve the system capacity. However, the introduction of LTE-U technology into wireless healthcare systems also brings coexistence with the current WiFi-based systems. In this paper, an LTE-U coexistence algorithm based on Q-learning is proposed in multi-channel scenarios, the algorithm is based on the idea of LTE-U and WiFi in turn, taking into account the fairness and performance which is vital for medical devices with either LTE-U or WiFi capabilities to work together, to optimize the duty cycle. The simulation results show that the proposed coexistence algorithm based on Q-learning can improve the system throughput while ensuring fairness.**

***Keywords*— LTE-U, WiFi, Q-Learning, Reinforcement learning, Coexistence algorithm**

I. INTRODUCTION

With the development of mobile Internet, intelligent devices and mobile applications grow rapidly, people can carry out all kinds of communication connections anytime, anywhere. Faced with such a huge amount of equipment access and business growth, industry and academia are trying to achieve the full use of unlicensed spectrum. They proposed the concept of deploying LTE in unlicensed spectrum [2], known as LTE-U technology. The LTE-U technology extend LTE to the unlicensed spectrum, that is, using the LTE standard protocol to communicate on the unlicensed spectrum, and aggregate licensed spectrum and unlicensed spectrum through the CA technology, the licensed part of the data transmission to the unlicensed spectrum [1].

Introducing LTE into a free, common, unlicensed spectrum will inevitably compete and coexist with other unlicensed communication technologies in the same spectrum. Traditional communication technologies represented by WiFi use unlicensed spectrum for data transmission. In order to realize spectrum sharing, access channels can only be accessed through a competitive way. The LTE design used in the licensed spectrum, the spectrum has absolute control, through the base station on the wireless resource centralized scheduling, so as to obtain higher spectral efficiency. Obviously, if only used the unlicensed spectrum as a new spectrum of LTE, the transmission of LTE-U will cause serious interference to WiFi due to WiFi channel detection and backoff mechanism. Therefore, for the time slot and the scheduling system is completely different from the two systems, need additional design reasonable and fair coexistence in order to ensure that both in the unlicensed spectrum good transmission.

At present, the academia have proposed a lot of LTE-U coexistence algorithms. In [2], an LTE-U MAC protocol based on LBT is proposed. The algorithm requires that the LTE-U device be detected at the end of the WiFi transmission frame. In [4], an LBT adaptive algorithm is proposed, which requires LTE-U to be aware of the channel at the edge of the subframe, and to select a new free channel for use. In [5], a fair LBT algorithm is proposed, which combines the total throughput of the system and the fairness factor between LTE-U and WiFi, by allocating the appropriate idle period for WiFi to ensure its transmission. The LTE-U Forum proposed a Carrier sensing and adaptive duty cycle based transmission algorithm (CAST) [6]. Abinader *et al.* [7] proposed a basic framework of the cooperative coexistence algorithm, which describes the general flow of collaborative coexistence algorithms. In [8], a coexistence algorithm for allocating idle slots by LTE according to a predetermined duty cycle is proposed. In addition, several papers (e.g., [13-19]) have studied related wireless and networking issues.

In healthcare, Implementable Medical Devices (IMDs) have been widely used in the last few years. These devices are usually controlled by patients or remotely by a third party (doctors, nurses, etc.) and should be well secured to prevent any kind of threat that can be harmful to patients. For instance, an intruder can listen to an IMD’s radio transmission and can frequently learn private data with insignificant effort from the patient. Attackers can have access to the programming radio, directional receiving wires, and other listening gears of the medical devices. One such review done by Halperin *et al.* [21] has considered this attack of listening stealthily or eavesdropping, could steal patients’ information. Another attack that was reported where the intruder had the capability to create radio transmissions tended to the IMD, or to replay recorded operations (known as replay attack). A study performed by Rathore *et al.* [22] showed that with a programmable radio, one could control implantable defibrillator by replaying messages thereby incapacitating modified treatments or conveying a stun planned to initiate a deadly heart attack.

There are few solutions which address authentication and authorization issues in wireless medical devices. Biometric based approaches use a unique physiological characteristics of the human body and provide authentication to the authorized users. Though these mechanisms may be secure and lightweight, most schemes fail to accommodate the changes of biometric with respect to time. Key management protocols, another way of authentication, were used to provide authentication to the authorized users using symmetric [21], public key [22] and physiological [23], [24], 25] signals for the generation of keys. However, key management protocols based on symmetric and public key concepts are less reliable and incur extra waiting time for the authentication. Also, once these keys are known, the adversary can take control of the entire system.

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In this paper, we study the coexistence of LTE-U and WiFi in the unlicensed spectrum, a LTE-U coexistence algorithm based on Q-learning is proposed. The algorithm model the coexistence scenarios by Q-learning, and get the optimal duty cycle of the system in multiple channels by learning iterations. The algorithm guarantees the fairness between the two systems, at the same time, improve the system throughput. In addition, this is vital in particular to the use of medical devices with either LTE-U or WiFi capabilities to work together, to optimize the duty cycle.

The rest of this paper is organized as follows. In Section II, the system model considered in this paper is described, at the same time, we design a LTE-U coexistence algorithm based on Q-learning in multi-channel. The performance evaluation has been conducted in Section III. Finally, section VI concludes the paper.

II. SYSMTEM MODEL AND ALGORITHM DESIGN

A. System Model

The system scenario is shown in Fig. 1. In the current scenario, the LTE-U system and the WiFi system form a heterogeneous network with a common spectrum. The network contains LTE-U nodes and WiFi nodes. The LTE-U nodes include LTE-U Small Cell (USC) and LTE-U Small Cell UE (SUE), and the WiFi node includes an AP and a WiFi device (WUE). Among them, in addition to the central deployment of LTE-U system and WiFi system between the mutual interference, the surrounding deployment of USC will also bring some interference effects.

In the heterogeneous network, U USCs are deployed, and the USC informs the SUE of the use of one or more unlicensed channels for transmission through the licensed spectrum. In the unlicensed spectrum, a total of M unlicensed channels are available, with one AP and W_m WUEs activity in each unlicensed channel. The LTE-U system is transmitted through the LTE air interface. There are N resource blocks (RBs) available for transmission in each transmission time slot (TTI), the number of which is related to the current unlicensed channel bandwidth.

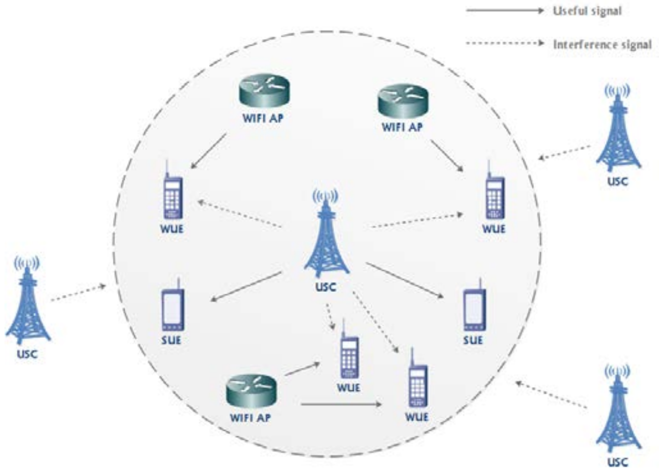

Fig. 1. LTE-U and WiFi coexistence network scenarios.

$SINR_{i,n}$ is the SINR of the USC i in the resource block n. The formula is shown in (1):

$$SINR_{i,n} = \frac{P_{i,n} G_{i,n}}{\sum_{j=1, j \neq i}^{S} P_{j,n} G_{j,n} + \sigma^2} \tag{1}$$

where $P_{i,n}$ and $P_{j,n}$ represent the transmit power of the USC i and USC j in the RB n, $G_{i,n}$ is the link gain between the USC i and its serving users in the resource block n, and $G_{j,n}$ is the link gain between the USC j and its serving users in the resource block n, σ^2 is the noise power. LTE-U conforms to the physical layer standard protocol of LTE, implements adaptive coding modulation through CQI of SINR mapping, and the higher CQI means higher transmission rate [11].

WiFi system through the use of competing access channel, in DCF protocol mode, WUE throughput can be expressed as:

$$T_{wi-fi} = R \times t_r \tag{2}$$

where t_r is the statistical value obtained by simulating the flow of the WUE access channel. The physical layer rate of the WUE is mapped by the formula (2) according to the SINR of the WUE.

B. Algorithm Design

In this paper, we use Q-learning to solve the coexistence of LTE-U and WiFi problem, mainly considering the Q-learning has a model-independent feature, cannot get the environment transfer function and reward the expected conditions to obtain the system optimal policy, in line with the actual situation of the LTE-U network.

In Q-learning based scenario, the USC learning for each unlicensed channel. The agents, states, actions, reward function of Independent Q-learning based algorithm is defined as follows:

Agents: USC $u \in \{1,2,...,U\}$ is used as an agent, where an unlicensed channel is used as the allocation unit for the duty cycle, and the set of unlicensed channels in each USC is $m \in \{1,2,...,M\}$.

States: The state set is expressed as:

$$\overrightarrow{s_u} = \left\{ T_u^m, \overline{F_u} \right\} \tag{3}$$

where T_u^m is the total throughput obtained by the system in the unlicensed channel m, and $\overline{F_{th}}$ is the average of the fairness coefficients calculated by the system on each of the unlicensed channels m. The fairness factor is used to calculate the fairness between the parameters, which is in the range of [0,1]. The closer to 1 represents the better the fairness, and the formula is as follows:

$$F = \frac{\left(\sum x_i\right)^2}{N\left(\sum x_i^2\right)} \tag{4}$$

where x_i is the calculation factor and N is the number of factors. In this paper, x_i is the normalized LTE-U system and WiFi system throughput value. This way, the agent u is divided into four states according to the pre-set throughput thresholds T_{th}^m and $\overline{F_{th}}$, and the state set is I, which means low profitability low fairness, high throughput low fairness, low throughput high fairness and high throughput and high fairness.

$$s_i^m = \begin{cases} 1, & T_u^m \le T_{th}^m \,\&\, \overline{F_u} \le \overline{F_{th}} \\ 2, & T_u^m > T_{th}^m \,\&\, \overline{F_u} \le \overline{F_{th}} \\ 3, & T_u^m \le T_{th}^m \,\&\, \overline{F_u} > \overline{F_{th}} \\ 4, & T_u^m > T_{th}^m \,\&\, \overline{F_u} > \overline{F_{th}} \end{cases} \tag{5}$$

Actions: The duty cycle set $a_j^m \in \{a_1^m, a_2^m, \ldots, a_k^m\}$, which represents the set of optional actions for the agent u on the unlicensed channel m.

Reward：

$$r_u^m = \begin{cases} 0, & if\ \overline{F_u} < F_{\min}\ or\ T_u^m < T_{\min} \\ \dfrac{T_u^m}{T_{\min}} \times e^{-\left|1-\overline{F_u}\right|}, & others \end{cases} \tag{6}$$

Among them, $F_{\min}$ is the minimum requirement of system fairness coefficient, $T_{\min}$ is the minimum requirement of system throughput. The reward function takes into account the overall network throughput performance and network fairness factors, making the system throughput as large as the minimum threshold of throughput while the fairness factor is close to 1. Under this reward function, USC's policy chooses to iterate in the direction of high-throughput high fairness.

In summary, the Q-learning based algorithm is as follows:

1) *t=0, for the agent u, initialize its Q-value 0 of the state and action in the unlicensed channel m.*
2) *Computes the initial state s_t of the agent u in unlicensed channel m.*
3) *Calculate the probability values of agent u in the unlicensed channel m with the different action a_j^m in the state s_t according to the formula (10) and the formula (11), perform the action with the maximum probability in current state, if there are multiple identical probabilities, then randomly selected one;*
4) *Perform action a_j, get the corresponding environmental reward value γ_t, then enter the next state s_{t+1};*
5) *Update the corresponding action Q value of the agent u;*
6) *t ← t+1，jump to step 1 in the learning phase.*
7) *Unlicensed channel m is learning is completed, m ← m+1, jump to the beginning of the cycle.*

For the Q-learning based coexistence algorithm, Boltzmann [12] algorithm is used as the action policy of the agent selection. The Boltzmann algorithm is a common algorithm for balancing the accumulation of experience and exploring. The algorithm calculates the probability of different actions according to formula (10), and then select the action according to the probability,

$$\Pr\left(a \mid s\right) = \frac{e^{\frac{Q(s,a)}{T}}}{\sum_{a' \in A} e^{\frac{Q(s,a')}{T}}} \tag{10}$$

where $\Pr\left(a \mid s\right)$ is the probability that the agent will select action a in the state s, and T is the temperature value. We reduce the T value by equation (10), to reduce the number of explorations of the optimal policy of the agent,

$$T = \frac{T_0}{\log_2(1+N)} \tag{11}$$

where T_0 is the initial temperature value, and N the times that the action is selected for the agent.

III. PERFORMANCE EVALUATION

A. *Simulation Parameter Settings*

The system simulation uses the snapshot mode, that is, the user location is random and no moving model, through the number of points to take the average way to statistics. In the simulation of a total of three unlicensed channels, each unlicensed channel is deployed an AP, and by setting a different WUE, simulation of idle, general, busy three WiFi transmission strength. USC allows the use of multiple unlicensed channels at the same time, and informs the UE to complete the communication process on the corresponding channel through the licensed spectrum.

The simulation scene parameters are set as shown in TABLE I. The simulation parameters for the LTE-U and WiFi systems are shown in TABLE II.

B. *Simulation Results And Analysis*

In the simulation process, the algorithms that compare with the proposed algorithm include Traditional algorithm, Average algorithm, LBT algorithm, and CSAT algorithm.

In the comparison algorithm, the USC of the Traditional algorithm chooses the channel with the least interference to transmit without any coexistence measures. The Averaging algorithm requires the USC to take the available channels in a polling manner during the transmission time, so that the SUEs are balanced in different channels. The LBT algorithm achieves coexistence through idle channel selection and carrier sense avoidance. The CSAT algorithm first selects the most idle channel in the currently available channel, and dynamically adjusts the percentage of the LTE-U in the slot of the unlicensed channel by listening to the WiFi data transmission to achieve coexistence.

TABLE I. SIMULATION PARAMETER.

Simulation scene	SDL	**Number of channels**	3
USC transmit power	23dBm	**AP transmit power**	7dBm
SUE number	6	**WUE number**	2/6/10
SUE packet size	50	**WUE packet size**	20
Spectrum	5.8GHz	**Noise power density**	174dBm/Hz
Packet arrives model	Poisson	**Simulation time**	10s
PL model	36.7log10(d[m])+22.7+26log10(frq[GHz])		

TABLE II. WIFI AND LTE-U SYSTEM PARAMETER.

WIFI		**LTE-U**	
MAC protocol	DCF	**Bandwidth**	20MHz
Time slot	20us	**Scheduling method**	Polling
CW	32-256	**Discount factor β**	0.04
SIFS	10us	**Learning factor α**	0.5
DIFS	50us	**T_0**	0.15

The abscissa of the simulation below, Traditional represents the Traditional algorithm, Average represents the Average algorithm, Qlearning represents the Q-learning based algorithm.

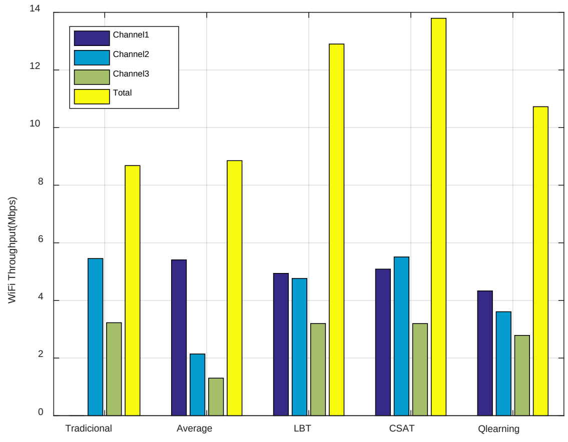

Fig. 3. WiFi throughput comparison.

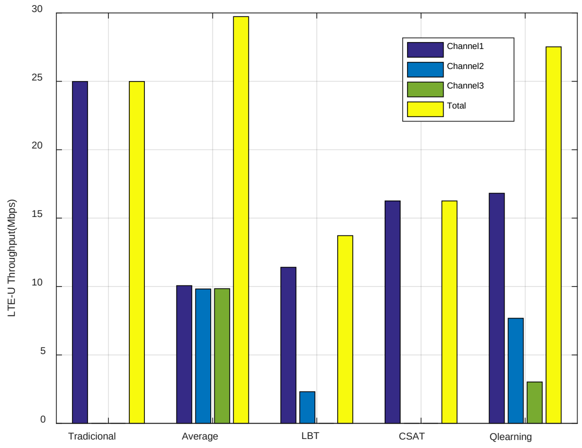

Fig. 4. LTE-U throughput comparison.

As can be seen from Fig. 3 and Fig. 4, For the Traditional algorithm and the Average algorithm, the performance of WiFi and LTE-U is extremely unbalanced, therefore the Traditional algorithm and the Average algorithm do not suitable for the actual scene.

From the perspective of WiFi, the LBT algorithm and the CSAT algorithm get a high throughput, which shows that both two algorithms realize the protection of WiFi system performance and facilitate the deployment of LTE-U. However, it can be seen from Fig. 4 that this protection greatly sacrifices the performance of LTE-U, and then the overall utilization of Fig. 2 system, the two coexistence algorithms for low utilization of the spectrum, comprehensive performance slightly worsen. For the Q-learning based algorithm mentioned in this paper, we can see that the distribution of WiFi and LTE-U throughput on different channels is highly correlated with the busy degree of the channel, that is, the throughput of LTE-U is relatively large in the idle channel, while in the more busy channels get less throughput. It can also be seen from Fig. 4 that the average throughput of WiFi users in each channel is relatively balanced, that is, the fairness between users is higher.

Fig. 5 and Fig. 6 are WiFi user average retransmission rate and delay statistics. It can be seen that the two sets of simulation data are similar in performance. Among them, the Traditional algorithm in the Channel 1 due to be completely occupied by LTE-U channel, resulting in its retransmission rate and delay are infinite. The Q-learning based algorithm has achieved better performance in both respects, and the data values in the respective channels are more balanced, reflecting the presentation of the fairness of the previous algorithm.

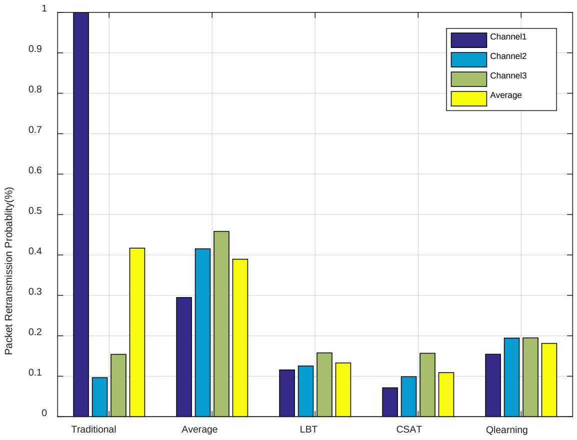

Fig. 5. WiFi packet retransmission rate comparison.

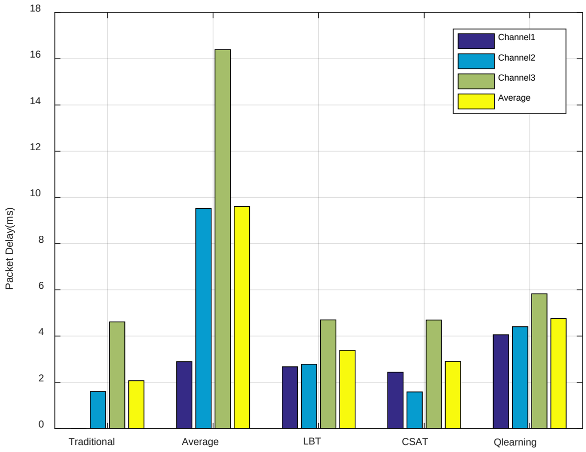

Fig. 6. WiFi packet delay comparison

From the above simulation results, we can see that the Q-learning based coexistence algorithm proposed in this paper can improve the reasonable occupancy ratio in different channels, reduces the retreat caused by collisions in the channel, saving a lot of channel time, channel utilization has been improved. At the same time, the proposed algorithm takes the fairness factor into the reward function of Q-learning, which makes the algorithm converge on the high fairness index and ensure the performance of the WiFi system. Whether it is compared with the Traditional algorithm and the Average algorithm, or compared to the current mainstream LBT algorithm and CSAT algorithm, Q-learning based algorithm in the system throughput, fairness coefficient, transmission retransmission rate and transmission delay and other indicators are balanced, comprehensive performance better.

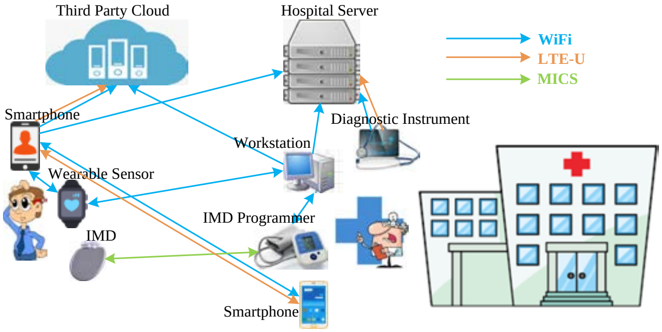

Fig. 7. A deployment example of modern healthcare system

As shown in Fig. 7, WiFi has already been widely used in existing healthcare systems. For example, the servers, workstations and medical equipment in a hospital and the patients' smartphones, wearable sensors and implantable medical devices (IMDs) form a mesh network via WiFi. On the other hand, smartphones and tablets have become the most popular devices among medical personnel and patients [20] with the development of mobile health (mHealth). The deployment of LTE-U provides a low-cost, seamless and more reliable connections, which is a good complement to WiFi, especially in a crowded environment (e.g., a hospital) where dozens or even hundreds of wireless devices may reside in a small area. To this end, our scheme aims to accelerate the deployment of LTE-U in originally WiFi-dominant wireless medical networks by solving the coexistence issues.

IV. CONCLUSION

In this paper, a LTE-U coexistence algorithm based on Q-learning is proposed, which is based on the scene of LTE-U. The system-level simulation platform of LTE-U and WiFi heterogeneous network is set up, and the co-existence mechanism algorithm is simulated accordingly. Through the comparison and analysis of the simulation results, we can see that the proposed algorithm can improve the performance of the system while maintaining a fair transmission of LTE-U and WiFi. The proposed scheme can improve the performance of wireless medical devices and systems.

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