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Efficient and fair Wi-Fi and LTE-U coexistence via communications over content centric networking

Kuo Chi [a], Xiaojiang Du [b], Guisheng Yin [a,*], Jie Wu [b], Mohsen Guizani [c], Qilong Han [a], Yaling Yang [d]

[a] College of Computer Science and Technology, Harbin Engineering University, Harbin, Heilongjiang 150001, China
[b] Department of Computer and Information Sciences, Temple University, Philadelphia, PA 19122, USA
[c] Department of Computer Science and Engineering, Qatar University, Doha 2713, Qatar
[d] Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA 24059, USA

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ABSTRACT

With the increasingly huge mobile traffic, numerous mobile operators try to seek some ways to alleviate the situation, such as expanding the LTE (Long Term Evolution) system into unlicensed spectrums. However, LTE-U (LTE in unlicensed spectrums) may interfere with Wi-Fi system that originally communicates in unlicensed spectrums and lead to marked decline of both Wi-Fi and LTE-U service qualities. To enable the fair coexistence of Wi-Fi and LTE-U systems in unlicensed spectrums, a novel mechanism over CCN (Content Centric Networking) containing two modes of communication (direct and indirect) between LTE-U and Wi-Fi systems is proposed in this paper. Moreover, the fair coexistence of LTE-U and Wi-Fi systems in unlicensed spectrums can be regarded as a resource allocation problem and formulated as a constrained optimization problem whose goal is to maximize the amount of data transmitted by different systems in a communication cycle, two approaches are also proposed to solve the optimization problem by adjusting the transmission time of different systems. The performance of the proposed mechanism and approaches is evaluated by simulations via NS-3 and theoretical calculations, the results demonstrate that the proposed mechanism and approaches can effectively ensure the fair coexistence of LTE-U and Wi-Fi in unlicensed spectrums and improve the overall channel utilization of unlicensed spectrums.

1. Introduction

With the rapid development of mobile communication technology and widespread popularity of portable intelligent devices, the interpersonal communication has entered a new era of multimedia data transmission. There is no doubt that they greatly facilitate people's daily life and make the communication more convenient. Although the current mobile communication technology has developed to the fifth generation (5G), limited by cost, reliability of technology and other factors, LTE (Long Term Evolution) will remain the dominant technology for some time and will be further developed.

However, the worldwide popularity of portable intelligent devices has led to an explosion of mobile traffic, which can result in low communication quality of LTE [1–4]. At present, more and more researchers and mobile operators have focused on expanding the data transmission of LTE to ensure high quality of service (QoS) [5–8]. Due to LTE has been applied for years, the operating frequency spectrums will continue to become more crowded with the increasing mobile devices. Some original equipment manufacturers (such as Qualcomm, Huawei, Ericsson) and cellular mobile network operators (such as AT&T, T-Mobile, Verizon) propose to extend the LTE system from existing licensed spectrums to unlicensed spectrums [9–13].

However, unlicensed spectrums have been occupied by some other wireless systems, such as Wi-Fi system operating in 2.4 GHz and 5 GHz [14]. Different from LBT (Listen before Talk) mechanism (Before data transmission, it is necessary to detect whether the channel is idle or not, and only transmit data when the channel is idle) in CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) protocol applied in Wi-Fi system, Carrier Sense Adaptive Transmission (CSAT) allows LTE to access the channel without considering potential ongoing transmissions. If LTE try to compulsively occupy unlicensed spectrums for communication, the interests of Wi-Fi's users will be damaged. The collisions between different systems will also reduce the utilization of these unlicensed spectrums and lead to an internecine

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* Corresponding author.
E-mail addresses: hrbeu.ygs@outlook.com, yinguisheng@hrbeu.edu.cn (G. Yin).

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result. In consequence, a new challenge of ensuring the communication quality of LTE and Wi-Fi systems in the same unlicensed spectrum has appeared. Due to the collision avoidance of Wi-Fi system relies on contention-based access and carrier-sensing, they make Wi-Fi difficult to compete with LTE system using schedule-based in the same channel and lead to Wi-Fi transmission at a disadvantage without taking some actions [15]. Therefore, how to realize the fair coexistence of the two systems in unlicensed spectrums by taking some efficient measures has become an urgent problem.

CCN (Content Centric Networking), as a hot proposal of ICN (Information Centric Networking), is expected largely to replace the traditional host-centric networks [16,17]. In CCN architecture, instead of accessing the data from a specific location, users can request and retrieve the data they need from any networked devices that is storing it. Based on our precious work [18], we propose a novel mechanism over CCN in this paper to enable LTE-U and Wi-Fi systems fair coexistence in unlicensed spectrums via communication between Wi-Fi's AP (Access Point) and LTE's eNodeB (evolved Node B). In the beginning, LTE's UE (User Equipment) broadcast spectrum sharing request to nearby APs, and they can join in the coexistence network provided by the AP that returns the response. Then, two modes of communication, direct or indirect, can be adopted according to the distance between Wi-Fi's AP and LTE's eNodeB. In addition, we take the fair coexistence between LTE-U and Wi-Fi systems as a resource allocation problem and formulate a constraint optimization problem with the goal of maximizing the amount of data transmitted by different systems in a communication cycle, which can be solved by two approaches presented in this paper.

The main contributions of this paper are described as follows:

- A mechanism over CCN is proposed in this paper, it makes LTE's UE conveniently and speedily join in a coexistence network by requesting unlicensed spectrum sharing from any Wi-Fi's AP that is willing to share spectrums.
- The proposed mechanism makes fair coexistence possible that LTE-U system can communicate with Wi-Fi system by direct or indirect communication. Direct communication is suitable for short distance between Wi-Fi's AP and LTE's eNodeB, and indirect communication is suitable for long distance.
- A constrained optimization problem is formulated to enable the fair coexistence between Wi-Fi and LTE-U, with the goal of maximizing the amount of transmitted data by adjusting the transmission time of different connections when the minimum amount of transmitted data of each network can be guaranteed in a communication cycle.
- Two approaches are also presented to solve the above constrained optimization problem and the calculative process can be carried out on the AP of Wi-Fi system.
- Some experiments and simulations are conducted and the results can demonstrate the feasibility and validity of the proposed mechanism and approaches.

The rest of this paper is organized as follows: In Section 2, some current research works on coexistence of LTE and Wi-Fi systems in unlicensed spectrums are described. Then, the mechanism over CCN of enabling LTE-U and Wi-Fi to directly or indirectly communicate is proposed in Section 3. In Section 4, we present a constrained optimization problem to enable LTE-U and Wi-Fi fair coexistence, and propose two approaches to solve this optimization problem. In Section 5, the proposed mechanism and approaches are validated via some experiments and simulations. Finally, we conclude this paper and forecast the future work in Section 6.

2. Related work

Due to the current licensed spectrums are difficult to meet the needs of bandwidth. Industry and academia have all concentrated on the unlicensed spectrums that can relieve the congestion by data assignment [19–23]. Nonetheless, the competition between Wi-Fi and LTE systems is inevitable to arise in the unlicensed spectrums. To relieve the LTE communication pressure in licensed spectrums, Verizon worked with some equipment manufactories to develop LTE-U technology based on Release 12 published by 3GPP (3rd Generation Partnership Project). LTE-U can take licensed spectrums as the main carrier and use CSAT to seek unlicensed spectrums to transmit data together by carrier aggregation. Since LBT mechanism is not adopted, LTE-U has more advantages in unlicensed spectrums occupancy compared to Wi-Fi. Therefore, LTE-U has raised concerns among Wi-Fi providers due to it may interfere with Wi-Fi transmission and lead to a decline in service quality of Wi-Fi.

To decrease the possibility of conflicts between LTE and Wi-Fi systems in unlicensed spectrums, some recent studies focused on maintaining the performance of Wi-Fi system in the LTE and Wi-Fi coexistence network by adjusting associate settings of LTE system. Zhang, et al. proposed a new MAC protocol based on LBT to ensure LTE coexist with Wi-Fi system friendly [24]. Cano, et al. considered the channel access probability of LTE network in the CAST mechanism which can ensure the fairness between Wi-Fi and LTE [25]. Abinader, et al. proposed a novel approach by performing duty cycle for LTE-U without interrupting the communication of Wi-Fi networks [26]. Nihitil, et al. found the interference from LTE might affect Wi-Fi transmission that could lead to a remarkable decrease of Wi-Fi throughput, then they proposed a muting scheme of LTE which can ensure LTE and Wi-Fi access to a same medium [27]. Bairagi, et al. formulated an optimization problem with the goal of maximizing the sum-rate of LTE-U users to ensure LTE-U coexist with Wi-Fi, and proposed a cooperative Nash bargaining game to solve the coexistence between LTE-U and Wi-Fi systems and presented a one-sided matching game to solve the resource allocation problem in LTE-U [28]. Rastegardoost et al. developed a model that LTE-U estimated and used the white space of Wi-Fi transmission to transmit data on unlicensed spectrums [29]. These studies can ensure the coexistence for Wi-Fi and LTE systems while guaranteeing the transmission quality of Wi-Fi networks but without considering the service quality of LTE-U.

Besides, several research works concentrated on the coordination mechanisms that the fair coexistence can be implemented and the performance of these two systems can keep high quality. Chen, et al. proposed a contention-free period to LTE users based on a novel hyper access point and it also allowed a contention period to original Wi-Fi users [30]. Li, et al. leveraged stochastic geometry to measure the main performances of neighboring LTE and Wi-Fi networks in unlicensed spectrums [31]. Kwan, et al. designed LBT mechanisms for LTE LAA to ensure it could operate at least as fairly as Wi-Fi in unlicensed spectrums [32]. Ko, et al. proposed a fair LBT algorithm for co-existing of WLAN and LTE-U in unlicensed spectrums [33]. Maglogiannis, et al. combined Q-learning technology and previously proposed mLTE-U scheme to provide the fair coexistence between LTE and Wi-Fi in unlicensed spectrum by automatically selecting the opportune combinations of variable transmission opportunity and muting period [34]. Ali et al. proposed a new mechanism ReLBT (Reinforcement Learning-enabled LBT) to make LTE and Wi-Fi coexistence by using a channel collision probability to optimize the channel access parameters [35]. In Addition, many other studies have also done some significant works about this issue [36–41]. These studies allowed LTE and Wi-Fi to coexist in unlicensed

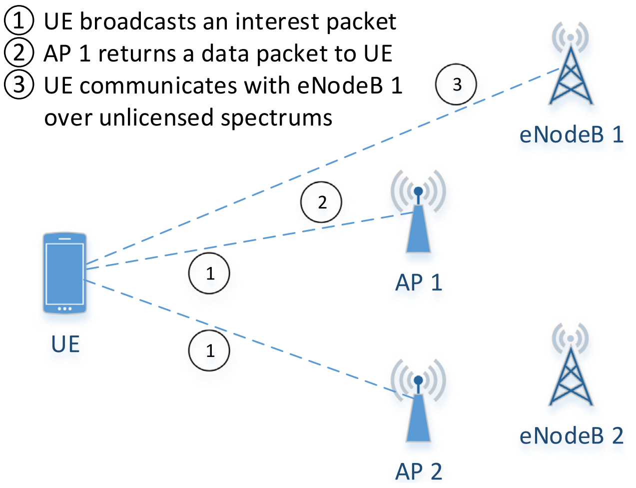

Fig. 1. The process of spectrum sharing request over CCN.

spectrums and guaranteed their respective transmission quality to some extent. However, none of them permit LTE-U and Wi-Fi systems to communicate with each other momentarily in order that adjust their transmission time accordingly in unlicensed spectrums.

In order to adapt to the continuous development of wireless communication technologies, we suggest a novel mechanism over CCN without altering relevant protocols. Moreover, we take the fair coexistence in unlicensed spectrums as a resource allocation problem on the application layer and propose approaches to solve it.

3. The mechanism over CCN to make the communication between Wi-Fi and LTE-U systems

The proposed mechanism over CCN includes two phases. In the first phase, An LTE's UE broadcasts spectrum sharing request to nearby Wi-Fi's APs and joins in the coexistence network provided by any AP that returns the response. Then in the second phase, Wi-Fi system can directly or indirectly communicate to LTE-U system in the coexistence network. The specific description is as follows.

3.1. Spectrum sharing request over CCN

When an LTE's UE has difficulty receiving sufficient data from nearby eNodeBs over licensed spectrums, it needs transmit data in unlicensed spectrums. However, to ensure fairness, the UE needs to be approved by a Wi-Fi system that is willing to share spectrums with LTE-U. Therefore, we design a spectrum sharing request over CCN for LTE-U in the first phase of the proposed mechanism.

Based on CCN architecture, the UE broadcasts an interest packet to all nearby Wi-Fi's APs to request unlicensed spectrums sharing in the beginning. After receiving the interest packet, APs check whether they have idle time or channels that can be provided to LTE-U for transmission. Any AP that is willing to share spectrum if they have idle time or channels will return a data packet by the same route. Then, the UE can communicate with the eNodeB in the unlicensed spectrum provided by the Wi-Fi's AP that returns the data packet, and the coexistence network of Wi-Fi and LTE-U is formed. The whole process is shown in Fig. 1.

Table 1
Symbols and definitions.

Symbol	Definitions
T	Total number of timeslots in a communication cycle
T_i^w	The number of timeslots of Wi-Fi connection i in a communication cycle
T_j^l	The number of timeslots of LTE-U connection j in a communication cycle
$n1$	The number of Wi-Fi connections
$n2$	The number of LTE-U connections
s_i^w	Throughput of Wi-Fi connection i during timeslots T_i^w
s_j^l	Throughput of LTE-U connection j during timeslots T_j^l
D_i^w	Data transmitted in a communication cycle of Wi-Fi connection i
D_j^l	Data transmitted in a communication cycle of LTE-U connection$j$
$\overline{D}_i^w$	Minimum transmitted data of Wi-Fi connection i in a communication cycle
$\overline{D}_j^l$	Minimum transmitted data of LTE-U connection j in a communication cycle
ε_1, ε_2	Preset ratios of the transmitted data between Wi-Fi system and LTE-U system in a communication cycle as the fairness parameters, $\varepsilon_1 \leq \varepsilon_2$

3.2. A symbolic description of the coexistence problem

After an LTE-U system joins in a coexistence network, there are two different systems in the coexistence network. A Wi-Fi system may contain several APs, and an AP may also connect to many stations. Similarly, an LTE-U system may contain several eNodeBs, and an eNodeB may connect to some UE. For convenience, we set only one AP in the Wi-Fi system and only one eNodeB in the LTE-U system. Moreover, the AP can connect to some stations, a connection between the AP and a station can be regarded as a Wi-Fi connection, and suppose there are $n1$ connections in the Wi-Fi system. Similar setting for LTE-U system, and suppose there are $n2$ connections in the LTE-U system.

During the process of communication, a timeslot is the minimum transmission time unit for each connection, and T is the number of timeslots in a communication cycle. For Wi-Fi connection i $(i = 1, \ldots, n1)$, s_i^w denotes its throughput, T_i^w denotes the number of timeslots that it transmits in a communication cycle, D_i^w is the transmitted data of it in T_i^w and it can be calculated by $s_i^w \times T_i^w$. Similar definitions apply to LTE-U connection j $(j = 1, \ldots, n2)$. In addition, ε_1 and ε_2 are the preset ratio of the data transmitted in a communication cycle between LTE-U system and Wi-Fi system to ensure the two systems fairly coexist. Table 1 shows the symbols and their definitions that will be used in this paper.

In view of the distance between Wi-Fi's AP and LTE's eNodeB, the proposed mechanism contains two modes: direct communication and indirect communication. When the distance between Wi-Fi's AP and LTE's eNodeB does not exceed the wireless transmission range of Wi-Fi's AP, Wi-Fi's AP can directly communicate to LTE's eNodeB by wireless communication. When the distance exceeds the range, a repeater is needed to ensure the communication between them, such as APs provided by LTE operators. They can communicate to Wi-Fi's AP by wireless transmission and communicate with LTE's eNodeB by wire transmission no matter how far apart they are.

3.3. Direct communication between Wi-Fi and LTE-U systems

Given that the AP of Wi-Fi system provided by a Wi-Fi provider, the eNodeB of LTE-U system provided by an LTE operator (Wi-Fi provider and LTE operator are different). Although the

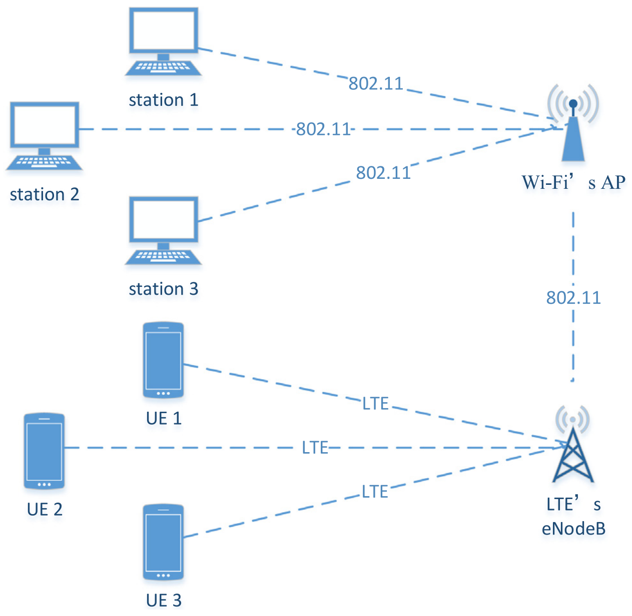

Fig. 2. The direct communication mode between Wi-Fi' AP and LTE's eNodeB.

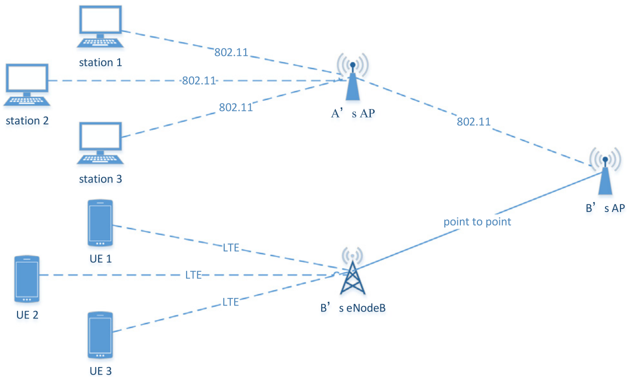

Fig. 3. The indirect communication mode between Wi-Fi' AP and LTE's eNodeB.

AP and the eNodeB provided from different providers, we believe they can transmit the data to each other with the improvement of compatibility technology between different systems.

When LTE's eNodeB is located in the transmission range of Wi-Fi's AP, (in general, LTE system has broader coverage than Wi-Fi system.) the direct communication between Wi-Fi's AP and LTE's eNodeB can be adopted (see Fig. 2). The Wi-Fi's AP connects to several stations simultaneously, and it may transmit the data to these stations in any communication cycle. Similarly, the LTE's eNodeB connects to some UE, and it may also need to transmit to them in any communication cycle. They can communicate normally if they are not sharing the same channel, but they need communicate in turn in a communication cycle once they are sharing the same channel. Therefore, we propose a direct communication mode to make Wi-Fi's AP communicate with LTE's eNodeB about the assignment of transmission time in a communication cycle.

The thresholds ε_1 and ε_2 are preset as the fairness parameters to control the data transmitted in a communication cycle of the two system to ensure fairness coexistence between the two systems. The whole process of direct communication between Wi-Fi's AP and LTE's eNodeB can be explained as: If the ratio of data transmitted in a communication cycle between Wi-Fi system (including all the Wi-Fi connections) and LTE-U system (including all the LTE-U connections) is not in the range $[\varepsilon_1, \varepsilon_2]$, the AP will send a wireless data packet to LTE's eNodeB which contains the assignment of transmission time in next communication cycle for each connection. LTE's eNodeB will return an ack packet after receiving the data packet so that Wi-Fi's AP can know the communication between them is successful. Then, each connection will transmit its data according to the transmission time setting of the data packet in the next communication cycle. Thus, it can enable the ratio of the transmitted data between the two systems to maintain in the range of fairness thresholds.

3.4. Indirect communication between Wi-Fi and LTE-U systems

The direct communication between LTE-U and Wi-Fi systems can save some time and construction cost. However, the transmission range of wireless communication is limited, the data cannot reach the destination when the distance between Wi-Fi's AP and LTE's eNodeB exceeds the range. Therefore, the indirect communication between LTE's eNodeB and Wi-Fi's AP needs to be adopted to ensure the smooth communication when the distance is long.

In this condition, another AP which provided by LTE operator (many LTE operators also provide paid Wi-Fi services in areas of high passenger volume, such as subway stations, shopping malls, campuses, but their signals are weak in many places and difficult to use for continuous data transmission) will be introduced as a repeater between Wi-Fi's AP and LTE's eNodeB (see Fig. 3). Since it is easy to build a wire transmission between two devices provided by the same provider, and the wire transmission between LTE's AP and LTE's eNodeB theoretically ensures that the transmission distance can be infinite. Hence, we propose an indirect communication mode to make Wi-Fi's AP communicate with LTE's eNodeB between two communication cycles. The network settings and the communication in a communication cycle of the two systems are similar to the direct communication mode between them, the only difference is Wi-Fi's AP communicates with LTE's eNodeB via LTE's AP.

The whole process of indirect communication between Wi-Fi's AP and LTE's eNodeB can be explained as: If the ratio of transmitted data in a communication cycle between the two systems is not in the range of $[\varepsilon_1, \varepsilon_2]$, Wi-Fi's AP will send a wireless data packet to LTE's AP which contains the assignment of transmission time in next communication cycle for each connection, and the packet is forwarded to LTE's eNodeB in the form of wire transmission. Then, LTE's eNodeB will return an ack packet via LTE's AP again after receiving the packet. In the next communication cycle, each connection will transmit its data according to the transmission time setting of the packet. Similar to the direct communication mode, the indirect communication between Wi-Fi's AP and LTE's eNodeB via LTE's AP can also enable the ratio of the transmitted data between the two systems to maintain in the range of fairness thresholds $[\varepsilon_1, \varepsilon_2]$.

4. The optimization problem to ensure the fairness between Wi-Fi and LTE-U

4.1. The optimization problem description

The above only mentions the mechanism which can enable Wi-Fi and LTE-U coexistence by communication between Wi-Fi's AP and LTE's eNodeB. However, the key of the communication is to assign the transmission time for each connection in the next communication cycle. In other words, the coexistence of Wi-Fi and LTE-U in unlicensed spectrums can be regarded as a resource allocation problem of transmission time. Moreover, how to maximum the amount of data transmitted in a communication cycle of all the shared connections is the main objective of data transmission.

In order to describe the above problem, we formulate a constrained optimization problem P:

$$\text{Max} \sum_{i=1}^{n1} D_i^w + \sum_{j=1}^{n2} D_j^l \tag{1}$$

$$\text{s.t. } \varepsilon_1 \le \frac{\sum_{i=1}^{n1} D_i^w}{\sum_{j=1}^{n2} D_j^l} \le \varepsilon_2 \tag{2}$$

$$\sum_{i=1}^{n1} t_i^w + \sum_{j=1}^{n2} t_j^l \le T, t_i^w, t_j^l = 1, 2, \dots, T \tag{3}$$

$$D_i^w \ge \overline{D}_i^w, \qquad i = 1, \dots, n1 \tag{4}$$

$$D_j^l \ge \overline{D}_j^l, \qquad j = 1, \dots, n2 \tag{5}$$

$$D_i^w = s_i^w \times t_i^w, \quad i = 1, \dots, n1 \tag{6}$$

$$D_j^l = s_j^l \times t_j^l, \qquad j = 1, \dots, n2 \tag{7}$$

In optimization function P, Eq. (1) as the objective function is to maximize the amount of transmitted data in a communication cycle of all the connections. Constraint condition Eq. (2) can be regarded as the fairness condition that the ratio of the data transmitted in a communication cycle between all the Wi-Fi and LTE-U connections is limited to the range of $[\varepsilon_1, \varepsilon_2]$. Constraint condition Eq. (3) is used to ensure the total of timeslots number for each connection less than or equal to the number of timeslots in a communication cycle. Eqs. (4) and (5) are used to ensure the participation of each Wi-Fi or LTE-U connection by presetting the minimum transmitted data in a communication cycle. Eqs. (6) and (7) show the transmitted data equal to the product of the throughput and the transmitted time for each connection.

4.2. The approaches to solve the optimization problem

The result of the above optimization problem will be the content of data packet in the direct communication or indirect communication from Wi-Fi's AP to LTE's eNodeB. Because of the improved hardware and computing power of equipment, the calculative process of optimization function P can be carried out on the AP of Wi-Fi system.

If the transmitted time is not limited to an integral multiple of a timeslot, the optimization problem P is a linear constrained optimization problem. the Lagrangian multiplier method can be used to solve it. The function is:

$$\begin{aligned}&\left(T_i^w, T_j^l, \lambda, \mu, \nu_i, \xi_j\right)\\ &= \left(-\sum_{i=1}^{n1} s_i^w T_i^w - \sum_{j=1}^{n2} s_j^l T_j^l\right) + \lambda\left(\sum_{i=1}^{n1} s_i^w T_i^w - \varepsilon \sum_{j=1}^{n2} s_j^l T_j^l\right)\\ &+ \mu\left(\sum_{i=1}^{n1} T_i^w + \sum_{j=1}^{n2} T_j^l - T\right) + \nu_i\left(\overline{D}_i^w - s_i^w T_i^w\right) + \xi_j\left(\overline{D}_j^l - s_j^l T_j^l\right)\end{aligned} \tag{8}$$

According to the KKT (Karush–Kuhn–Tucker) conditions of Eq. (8), the maximum value of the objective function Eq. (1) can be obtained as follow:

$$\max\left(\sum_{i=1}^{n1} D_i^w + \sum_{j=1}^{n2} D_j^l\right) = \frac{(1+\varepsilon)\sum_{i=1}^{n1} s_i^w \sum_{j=1}^{n2} s_j^l T}{n2\sum_{i=1}^{n1} s_i^w + \varepsilon n1 \sum_{j=1}^{n2} s_j^l} \tag{9}$$

However, the problem P may be a NP-complete problem if the timeslot is deemed to the minimum time unit of the transmitted time for a connection. We have two approaches that can be used to solve the problem P in this case. Approach 1 is based on the exhaustive algorithm, it needs to enumerate all the connection combinations that can meet all the constraint conditions, then the combinations with the largest amount of transmitted data can be selected from them and that is the optimal solution. The global optimization can be obtained by using this approach. However, the time complexity of Approach 1 is $O(T^{n1+n2})$, its implementation will be very difficult with the increasing number of shared connections.

Approach 2 is based on dynamic programming. At first, the initial connection combination can be defined according to the minimum transmitted data of each connection, and the current ratio ε of the transmitted data between the two systems can be calculated. Then, the remaining timeslots of a communication cycle are assigned one by one to the connection which has the largest throughput on the premise of meeting the current ratio ε which is always located in the range of $[\varepsilon_1, \varepsilon_2]$. Repeat the process until the number of remaining timeslots turns into 0. This approach is described in detail as follow:

Algorithm 1: The approach based on dynamic programming

```
Input: $s_i^w,\ s_j^l,\ \overline{D}_i^w,\ \overline{D}_j^l,\ T,\ i = 1,\dots,n1,\ j = 1,\dots,n2$;
Output: $T_i^w,\ T_j^l,\ \varepsilon$;
for each $i = 1{:}n1,\ j = 1,\dots,n2$ do
    $\overline{T}_i^w = \lceil \overline{D}_i^w / s_i^w \rceil;\ \overline{T}_j^l = \lceil \overline{D}_j^l / s_j^l \rceil$;
end for
initialize $\varepsilon = \sum_{i=1}^{n1} s_i^w \overline{T}_i^w / \sum_{j=1}^{n2} s_j^l \overline{T}_j^l;\ T_R = T - \sum_{i=1}^{n1} \overline{T}_i^w - \sum_{j=1}^{n2} \overline{T}_j^l$;
while $T_R \ne 0$ do
    if $T_R > 0$ and $\varepsilon < \varepsilon_1$ do
        for each $i = 1{:}n1$ do
            $\varepsilon^w(i) = (\sum_{i=1}^{n1} s_i^w \overline{T}_i^w + s_i^w) / \sum_{j=1}^{n2} s_j^l \overline{T}_j^l$;
        end for
        $k = \arg\max(\varepsilon^w(i), \varepsilon^w(i) \le \varepsilon_2)$;
        $T_k^w{=}T_k^w + 1;\ T_R = T_R - 1;\ \varepsilon = \varepsilon^w(k)$;
        continue
    end if
    if $T_R > 0$ and $\varepsilon > \varepsilon_2$ do
        for each $j = 1,\dots,n2$ do
            $\varepsilon^l(j) = \sum_{i=1}^{n1} s_i^w \overline{T}_i^w / (\sum_{j=1}^{n2} s_j^l \overline{T}_j^l + s_j^l)$;
        end for
        $k = \arg\max(\varepsilon^l(j), \varepsilon^l(j) \ge \varepsilon_1)$
        $T_k^l{=}T_k^l + 1;\ T_R = T_R - 1;\ \varepsilon = \varepsilon^l(k)$;
        continue
    end if
    if $T_R > 0$ and $\varepsilon_1 \le \varepsilon \le \varepsilon_2$ do
        for each $i = 1{:}n1,\ j = 1,\dots,n2$ do
            $\varepsilon^w(i) = (\sum_{i=1}^{n1} s_i^w \overline{T}_i^w + s_i^w) / \sum_{j=1}^{n2} s_j^l \overline{T}_j^l$;
            $\varepsilon^l(j) = \sum_{i=1}^{n1} s_i^w \overline{T}_i^w / (\sum_{j=1}^{n2} s_j^l \overline{T}_j^l + s_j^l)$;
        end for
        $k = \arg\max(\varepsilon(i), \varepsilon(j), \varepsilon_1 \le \varepsilon(i), \varepsilon(j) \le \varepsilon_2)$;
        $T_k^{w/l}{=}T_k^{w/l} + 1;\ T_R = T_R - 1;\ \varepsilon = \varepsilon^{w/l}(k)$
        continue
    end if
end while
return $T_i^w,\ T_j^l,\ \varepsilon$;
```

Table 2
The settings of Wi-Fi and LTE connections in CN. 1.

ID	Std.	MCS	Short GI	$\overline{D}$ (Mbit)	ε_1	ε_2
W1	802.11n	3	1	240	1.5	1.9
W2	802.11n	5	0	220		
W3	802.11n	7	1	230		
L1	–	–	–	400		
L2	–	–	–	250		

Table 3
The settings of Wi-Fi and LTE connections in CN. 2.

ID	Std.	MCS	Short GI	$\overline{D}$ (Mbit)	ε_1	ε_2
W1	802.11n	4	1	100	1.3	1.6
W2	802.11n	5	0	100		
W3	802.11n	6	1	230		
W4	802.11ac	7	–	180		
W5	802.11ac	7	–	200		
L1	–	–	–	100		
L2	–	–	–	150		
L3	–	–	–	120		

The time complexity of Approach 2 is $O(T(n1+n2))$. Obviously, it can save more time compared to Approach 1. However, it may plunge into local optimum because each step needs to ensure the ratio ε is limited to the defined range, the global optimization cannot be assured even if all the constraints can be satisfied.

From the above, Approach 1 is difficult to be applied in practice because of its high time complexity. However, it can serve as a benchmark to verify the results by Approach 2.

5. Performance evaluation

5.1. Setup

We conduct some experiments and simulations on the network simulator software NS-3 to evaluate the performance of proposed approaches. Three coexistence networks (CN. 1, CN. 2 and CN. 3) of Wi-Fi and LTE-U are built as the experimental subjects. CN. 1, CN. 2, and CN. 3 severally includes 3, 5, 7 Wi-Fi connections and 2, 3, 5 LTE-U connections. Table 2, Table 3, and Table 4 shows the basic settings of connections included in CN. 1, CN. 2, and CN. 3, respectively. (Wi-Fi connections can be customized by users with Modulation and Coding Scheme (MCS) value, communication channel width (All the Wi-Fi connections here are 40 MHz), short GI et al. and LTE connections are default setting because it is operated by the LTE operators. Other parameters, such as the pre-set minimum transmitted data and thresholds, are artificial.)

The process of simulation can be divided into three parts: In the first part, the timeslots in a communication cycle are assigned equally to all the connections so that the actual throughput of each connection can be obtained. Then, the solution of the optimization problem P can be calculated by Approach 1 and Approach 2, the assigned time for each connection is encapsulated in the data packet and sent from Wi-F's AP to LTE' eNodeB by direct or indirect communication. In the last part, each connection transmits data according to the assigned time in the data packet.

At first, we need to obtain the throughput of each connection on the basis of its setting by NS-3. Fig. 4 shows the throughput of Wi-Fi using IEEE Std. 802.11n and LTE connections in different settings and Fig. 5 shows the throughput of Wi-Fi using IEEE Std. 802.11ac and LTE connections.

5.2. Theoretical calculation results

In order to verify the proposed approaches in solving the optimization problem P, we conduct three experiments for each coexistence network: (1) timeslot = 1 s, T = 20; (2) timeslot = 1 s, T = 25; (3) timeslot = 1.5 s, T = 30. For each experiment, we

Table 4
The settings of Wi-Fi and LTE connections in CN. 3.

ID	Std.	MCS	Short GI	$\overline{D}$ (Mbit)	ε_1	ε_2
W1	802.11n	3	1	60	1.2	1.5
W2	802.11n	5	0	90		
W3	802.11n	6	0	100		
W4	802.11n	7	1	200		
W5	802.11ac	4	1	100		
W6	802.11ac	5	1	90		
W7	802.11ac	7	0	120		
L1	–	–	–	100		
L2	–	–	–	80		
L3	–	–	–	150		
L4	–	–	–	50		
L5	–	–	–	200		

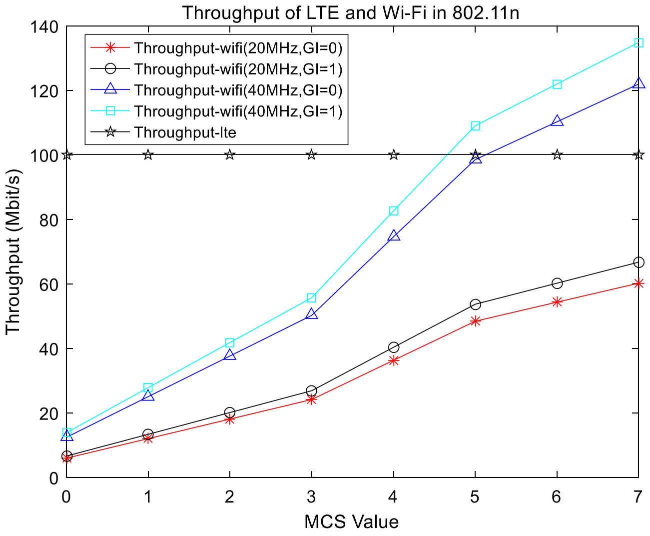

Fig. 4. The throughput of LTE and Wi-Fi in 802.11n.

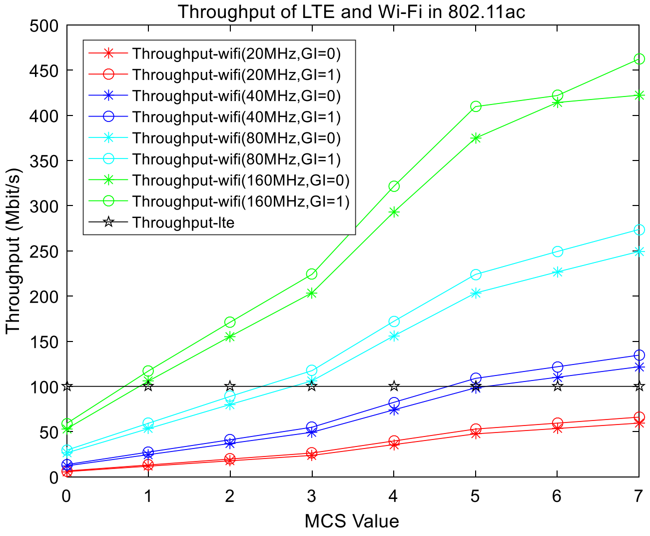

Fig. 5. The throughput of LTE and Wi-Fi in 802.11ac.

Table 5
The solution solved by the approaches in the first experiment.

Network		Solution	ε	Total data
CN.1	Approach 1	$t_1^w = 5,\ t_2^w = 3,$ $t_3^w = 5,$ $t_1^l = 4,\ t_2^l = 3$	1.7429	1922.5 Mbit
	Approach 2	$t_1^w = 5,\ t_2^w = 3,$ $t_3^w = 5,$ $t_1^l = 4,\ t_2^l = 3$	1.7429	1922.5 Mbit
CN.2	Approach 1	$t_1^w = 2,\ t_2^w = 2,$ $t_3^w = 3,$ $t_4^w = 2,\ t_5^w = 3,$ $t_1^l + t_2^l + t_3^l = 8,$ $(t_1^l \geq 1, t_2^l \geq 2, t_3^l \geq 2)$	1.4734	2142.2 Mbit
	Approach 2	$t_1^w = 2,\ t_2^w = 2,$ $t_3^w = 3,$ $t_4^w = 2,\ t_5^w = 2,$ $t_1^l + t_2^l + t_3^l = 9,$ $(t_1^l \geq 1, t_2^l \geq 2, t_3^l \geq 2)$	1.3386	2107.4 Mbit
CN.3	Approach 1	$t_1^w = 2,\ t_2^w = 1,$ $t_3^w = 1,\ t_4^w = 4,$ $t_5^w = 2,\ t_6^w = 1,$ $t_7^w = 1,$ $t_1^l + t_2^l + t_3^l + t_4^l + t_5^l = 8,$ $(t_1^l \geq 1,\ t_2^l \geq 1, t_3^l \geq 2, t_4^l \geq 1, t_5^l \geq 2)$	1.4333	2045.7 Mbit
	Approach 2	$t_1^w = 2,\ t_2^w = 1,$ $t_3^w = 1,\ t_4^w = 3,$ $t_5^w = 3,\ t_6^w = 1,$ $t_7^w = 1,$ $t_1^l + t_2^l + t_3^l + t_4^l + t_5^l = 8,$ $(t_1^l \geq 1,\ t_2^l \geq 1, t_3^l \geq 2, t_4^l \geq 1, t_5^l \geq 2)$	1.4884	1993.2 Mbit

Table 6
The solution solved by the approaches in the 2nd experiment.

Network		Solution	ε	Total data
CN.1	Approach 1	$t_1^w = 5,\ t_2^w = 3,$ $t_3^w = 8,$ $t_1^l + t_2^l = 9,$ $(t_1^l \geq 4, t_2^l \geq 3)$	1.8047	2527.4 Mbit
	Approach 2	$t_1^w = 6,\ t_2^w = 4,$ $t_3^w = 6$ $t_1^l + t_2^l = 9,$ $(t_1^l \geq 4, t_2^l \geq 3)$	1.6705	2406.5 Mbit
CN.2	Approach 1	$t_1^w = 2,\ t_2^w = 2,$ $t_3^w = 3,$ $t_4^w = 2,\ t_5^w = 6,$ $t_1^l + t_2^l + t_3^l = 10,$ $(t_1^l \geq 1, t_2^l \geq 2, t_3^l \geq 2)$	1.5829	2747.1 Mbit
	Approach 2	$t_1^w = 2,\ t_2^w = 3,$ $t_3^w = 3,$ $t_4^w = 2,\ t_5^w = 4,$ $t_1^l + t_2^l + t_3^l = 11,$ $(t_1^l \geq 1, t_2^l \geq 2, t_3^l \geq 2)$	1.4296	2676 Mbit
CN.3	Approach 1	$t_1^w = 2,\ t_2^w = 1,$ $t_3^w = 1,\ t_4^w = 6,$ $t_5^w = 2,\ t_6^w = 1,$ $t_7^w = 1,$ $t_1^l + t_2^l + t_3^l + t_4^l + t_5^l = 11,$ $(t_1^l \geq 1,\ t_2^l \geq 1,$ $t_3^l \geq 2, t_4^l \geq 1, t_5^l \geq 2)$	1.2873	2615.8 Mbit
	Approach 2	$t_1^w = 2,\ t_2^w = 1,$ $t_3^w = 1,\ t_4^w = 5,$ $t_5^w = 3,\ t_6^w = 1,$ $t_7^w = 1,$ $t_1^l + t_2^l + t_3^l + t_4^l + t_5^l = 11,$ $(t_1^l \geq 1,\ t_2^l \geq 1,$ $t_3^l \geq 2, t_4^l \geq 1, t_5^l \geq 2)$	1.3274	2563.4 Mbit

can obtain the solution of problem P by Approach 1 and Approach 2, respectively.

1. *timeslot* = 1 s, *T* = 20;

According to the parameters and the settings of the two systems, we can obtain the assignment of the transmitted time for each LTE and Wi-Fi connection in the next communication cycle. Table 5 shows the solution solved by the two approaches for CN. 1, CN. 2 and CN. 3 in the first experiment. In CN. 1, Approach 2 can obtain the same solution as approach 1, and the optimal solution of the total amount of transmitted data is 1922.5 Mbit. In CN. 2 and CN. 3, Approach 2 cannot obtain the optimal solution, but its solution 2107.4 Mbit and 1993.2 Mbit of the total amount of transmitted data is very close to the optimal solution 2142.2 Mbit and 2045.7 Mbit.

2. *timeslot* = 1 s, *T* = 25;

Table 6 shows the solution solved by the two approaches for CN. 1, CN. 2 and CN. 3 in the second experiment. In CN. 1, the optimal solution of the total amount of transmitted data is 2527.4 Mbit, and the solution solved by Approach 2 is 2406.5 Mbit. In CN. 2 and CN. 3, Approach 2 can obtain the solution 2676 Mbit and 2563.4 Mbit of the total amount of transmitted data, and it is very close to the optimal solution 2747.1 Mbit and 2615.8 Mbit.

3. *timeslot* = 1.5 s, *T* = 30;

Table 7 shows the solution solved by the two approaches for CN. 1, CN. 2 and CN. 3 in the third experiment. In CN. 1, the optimal solution of the total amount of transmitted data solved by Approach 1 is 4698.5 Mbit, and the solution solved by Approach 2 is 4297.6 Mbit. In CN. 2 and CN. 3, although Approach 2 cannot obtain the optimal solution, its solution 4873 Mbit and 4782.9 Mbit of the total amount of transmitted data is very close to the optimal solution 5165.5 Mbit and 4831.1 Mbit.

Due to the number of connections in the experiments is small, the difference in time efficiency between the two approaches is not significant. However, with the increasing number of coexisting connections, the advantage in time efficiency of Approach 2 can be reflected because of its linear time complexity. In addition, as an exhaustive method, Approach 1 is difficult to be applied in reality.

5.3. Simulation results

At first, we test the effect of the distance between Wi-Fi's AP and LTE's eNodeB on the communication time of direct and indirect communication. The communication time always stays in 0.0148 s when the communication mode is direct communication and the distance is less than 20 m between the AP and the eNodeB. In addition, the communication time stays in 0.0202 s when the mode is indirect communication and the distance is less than 100 m.

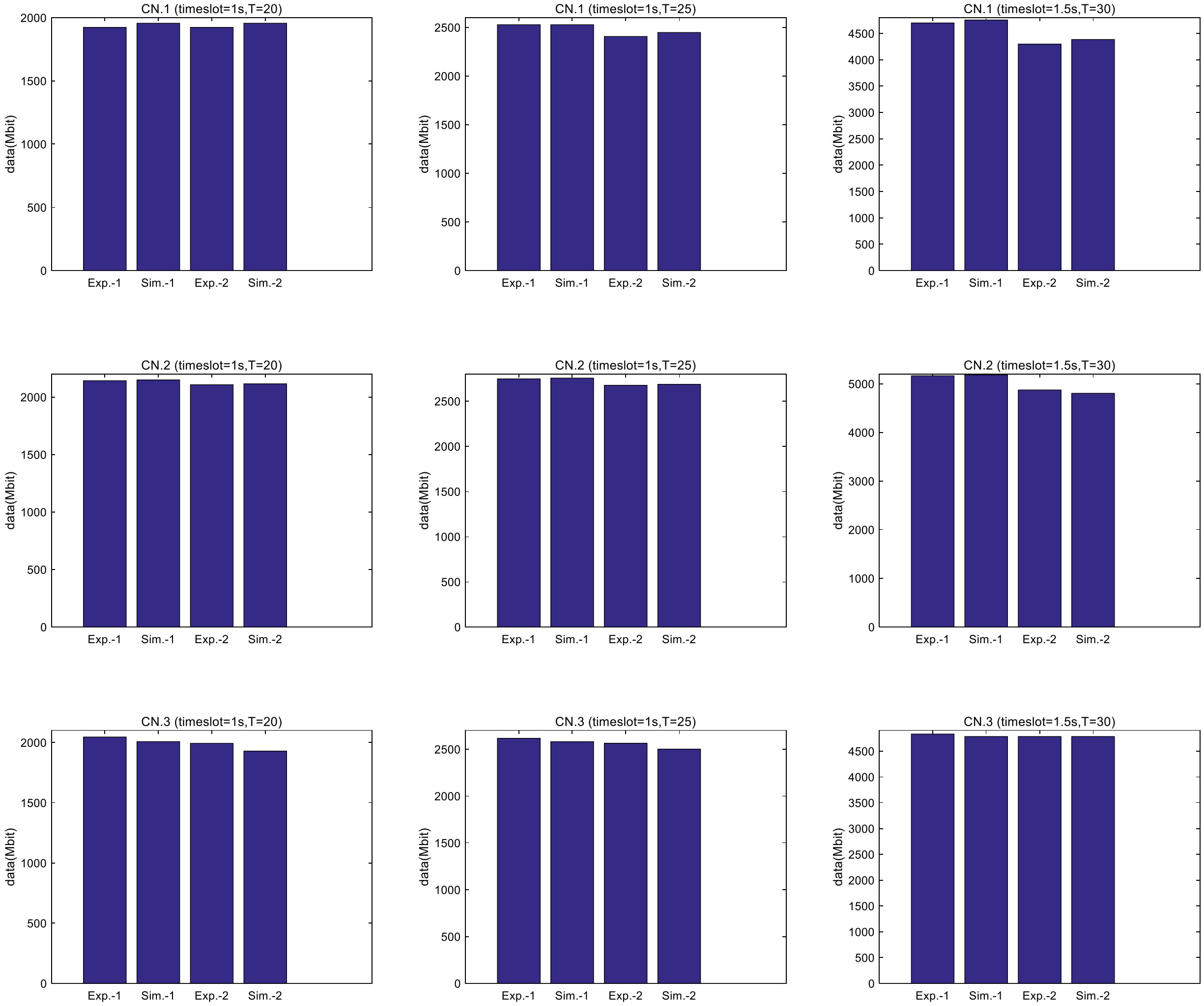

Fig. 6. The comparison among the experimental calculation results and simulation results by Approach 1 and Approach 2 in each experiment.

Then, we take the solutions solved by Approach 1 and Approach 2 in each experiment as inputs and simulate the Wi-Fi and LTE coexistence network on NS-3, the outputs are the simulation results. Fig. 6 shows the comparison of the four values (experimental calculation results by Approach 1 and Approach 2, and simulation results by Approach 1 and Approach 2) in each experiment. Although the theoretical calculation results and the simulation results are closed, the tiny difference still exist. There are two possible explanations of the difference between them: One is the throughput of each connection cannot be determined during initialization, and it may increase gradually to reach a stable value. The other one is that the possible interference between different connections can cause the simulation results lower than the theoretical calculation results.

6. Conclusions

In this paper, a novel mechanism over CCN is proposed to enable Wi-Fi and LTE-U fair coexistence in unlicensed spectrums. The mechanism contains two phases: In the first phase, based on CCN architecture, LTE's UE broadcast spectrum sharing request to nearby Wi-Fi's APs and coexist with Wi-Fi willing to share unlicensed spectrums. In the second phase, Wi-Fi's AP can communicate to LTE' eNodeB to assign the next transmission time of each Wi-Fi and LTE-U connection. Two modes of the communication can be adopted: direct communication is suitable for the short distance between Wi-Fi's AP and LTE's eNodeB with rapid response, indirect communication is applicable for the long distance between Wi-Fi's AP and LTE's eNodeB.

In addition, we take the coexistence between Wi-Fi and LTE-U systems as a resource allocation problem and formulate a constraint optimization problem to ensure fairness between the two systems. The objective function is to maximize the amount of transmitted data in a communication cycle by adjusting the transmission time of different connections. We also propose two approaches to solve the optimization problem and make the results as the content of the communication between Wi-Fi's AP and LTE's eNodeB.

Finally, we verify our mechanism and approaches with theoretical calculations and simulations on NS-3. The results show that our mechanism and approaches can effectively enable the fair coexistence between Wi-Fi and LTE-U systems and improve the overall channel utilization in unlicensed spectrums.

In the future, we will continue to search the global optimal solution with low time complexity and verify our mechanism with actual devices. Moreover, we will further consider the fair coexistence of more wireless systems in heterogeneous wireless networks.

Table 7
The solution solved by the approaches in the third experiment.

Network		Solution	ε	Total data
CN.1	Approach 1	$t_1^w = 5,\ t_2^w = 3,$ $t_3^w = 11,$ $t_1^l + t_2^l = 11,$ $(t_1^l \geq 2, t_2^l \geq 2)$	1.844	4698.5 Mbit
	Approach 2	$t_1^w = 9,\ t_2^w = 2,$ $t_3^w = 9,$ $t_1^l + t_2^l = 10,$ $(t_1^l \geq 2, t_2^l \geq 2)$	1.8615	4297.6 Mbit
CN.2	Approach 1	$t_1^w = 1,\ t_2^w = 1,$ $t_3^w = 2,$ $t_4^w = 1,\ t_5^w = 12,$ $t_1^l + t_2^l + t_3^l = 13,$ $(t_1^l \geq 1, t_2^l \geq 1, t_3^l \geq 1)$	1.5828	5165.5 Mbit
	Approach 2	$t_1^w = 3,\ t_2^w = 1,$ $t_3^w = 2,$ $t_4^w = 2,\ t_5^w = 8,$ $t_1^l + t_2^l + t_3^l = 13,$ $(t_1^l \geq 1, t_2^l \geq 1, t_3^l \geq 1)$	1.4514	4873 Mbit
CN.3	Approach 1	$t_1^w = 2,\ t_2^w = 1,$ $t_3^w = 1,\ t_4^w = 9,$ $t_5^w = 2,\ t_6^w = 1,$ $t_7^w = 1,$ $t_1^l + t_2^l + t_3^l + t_4^l + t_5^l = 13,$ $(t_1^l \geq 1,\ \ t_2^l \geq 1,$ $t_3^l \geq 1, t_4^l \geq 1, t_5^l \geq 2)$	1.3991	4831.1 Mbit
	Approach 2	$t_1^w = 3,\ t_2^w = 1,$ $t_3^w = 1,\ t_4^w = 9,$ $t_5^w = 1,\ t_6^w = 1,$ $t_7^w = 1,$ $t_1^l + t_2^l + t_3^l + t_4^l + t_5^l = 13,$ $(t_1^l \geq 1,\ \ t_2^l \geq 1,$ $t_3^l \geq 1, t_4^l \geq 1, t_5^l \geq 2)$	1.4497	4782.9 Mbit

CRediT authorship contribution statement

Kuo Chi: Conceptualization, Writing - original draft. **Xiaojiang Du:** Methodology, Funding acquisition. **Guisheng Yin:** Writing - original draft. **Jie Wu:** Supervision. **Mohsen Guizani:** Writing - review & editing. **Qilong Han:** Writing - review & editing. **Yaling Yang:** Software, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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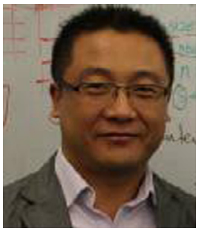
Kuo Chi received the B.S. degree from School of Mathematics and Statistics at Shandong University, China, in 2012 . Then he received M.S. degree from College of Computer Science and Technology at Harbin Engineering University, China, in 2014. Since 2014, He has been a doctoral candidate in College of Computer Science and Technology at Harbin Engineering University, Harbin, China. From 2017 to 2018, he studied as a visiting student in Department of Computer and Information Science at Temple University, Philadelphia, USA. His research interests include social network analysis, intelligent information processing and wireless network.

Xiaojiang Du is a Full Professor in the Department of Computer and Information Sciences at Temple University. He also serves as the Director of Security and Networking Lab. He is a Senior Member of IEEE. His research interests include: Internet of things security, mobile device security, wireless medical-device security system and network security, security and privacy in cloud computing and big data wireless networks, computer networks systems, controls, communications.

Guisheng Yin received the B.S. degree from College of Computer Science and Technology at Harbin Ship Engineering College, Harbin, China, in 1986. Then he received M.S. degree from College of Computer Science and Technology at Harbin Ship Engineering College, Harbin, China, in 1995 and received the Ph.D. degree from College of Automation at Harbin Engineering University, Harbin, China, in 2000. From 1998 to 1999, he worked as visiting research fellow in Advanced Science and Technology Research Center at University of Tokyo. Since 2006, he has been a professor in College of Computer Science and Technology at Harbin Engineering University, Harbin, China. His research interests include trusted software, data security, intelligent information processing.

Jie Wu is currently the Fellow of AAAS and the Fellow of IEEE. He serves as the Director of international affairs with the College of Science and Technology and also serves as the Director of the Center for Networked Computing, Laura H. Carnell Professor, Department of Computer and Information Sciences, Temple University. Prior to joining Temple University, he was a program director at the National Science Foundation and Distinguished Professor at Florida Atlantic University. His research interests include wireless networks, mobile computing, routing protocols, fault-tolerant computing, and interconnection networks.

Mohsen Guizani is currently a Professor at CSE Department in Qatar University, Qatar. He is the Fellow of IEEE, He is currently the Editor-in-Chief of the IEEE Network Magazine and serves on the editorial boards of several international technical journals and the Founder and Editor-in-Chief of Wireless Communications and Mobile Computing journal (Wiley). His research interests include wireless communications and mobile computing, computer networks, mobile cloud computing, security, and smart grid.



Qilong Han is currently a Professor and the Deputy Dean of the College of Computer Science and Technology, Harbin Engineering University. He has served as programmed committee members and the co-chairs of a number of international conferences/workshops for area including web intelligence, e-commerce, data mining and intelligent systems. He was Authored over 60 Publications as edited books and proceedings, invited book chapters, and technical papers in refereed journals and conferences. His research interests include: data security and privacy, mobile computing and distributed and networked systems.

Yaling Yang is currently an Associate Professor in the Department of Electrical and Computer Engineering at Virginia Tech, Blacksburg, VA, USA. She received the Ph.D. degree in computer science in 2006, from the University of Illinois at Urbana-Champaign, Champaign, IL, USA. Her current research interests include on design, modeling and analysis of networking protocols and systems. She is an US NSF Faculty Early Career Award winner and has been the principle investigator of five NSF funded projects. She is a member of IEEE.