


## Article

# Unlicensed Spectrum Allocation for LTE and Wi-Fi Coexistence with HAP

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**Abstract:** In order to accommodate the ever-increasing traffic demands, numerous approaches have been developed to improve spectrum utilization. Among others, the coexistence of LTE (Long-Term Evolution) and Wi-Fi, addressed by the 3GPP (3rd Generation Partnership Project) with hyper access points (HAPs) as bridges, is well recognized as a promising candidate solution. Aimed at improving the spectrum utilization of the unlicensed bands by following LTE-Unlicensed (LTE-U), this article contributes to the determination of the optimal time ratio,  $\delta$ , for the time-division multiplexing of LTE and Wi-Fi over unlicensed bands. Symmetric allocation with a duty cycle of 50% cannot be an optimal option. Asymmetric allocation according to the quality of service (QoS) requirements and traffic demands should be considered. The problem is formulated as an optimization problem optimizing the total throughput. The lower and upper bounds of  $\delta$  are obtained according to the QoS requirements of Wi-Fi and the admission control requirements of LTE. The detailed procedure for finding an adequate  $\delta$  is developed and presented. A series of simulations are conducted to demonstrate the feasibility and effectiveness of the proposed approach. Simulation results show that the proposed approach improves the total throughput without compromising the fairness of Wi-Fi, as intended. Ten percent of improvement in throughput compared with LTE-U can be achieved.

**Keywords:** Long-Term Evolution (LTE); Wi-Fi; LTE-Unlicensed (LTE-U); Hyper-AP (HAP)



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## 1. Introduction

Wireless communication is a continuing trend with the growing number of wireless devices. A wide variety of devices and applications have been introduced as the technology is getting mature and popularized. As a consequence, traffic conveyed over the wireless networks grows explosively. Technology to accommodate the ever-increasing traffic is a pressing yet challenging issue. Unlike wired networks, the radio spectrum for wireless communication is inherently scarce and expensive. Many approaches are studied. One possible solution to ameliorate spectrum utilization is advanced modulation and coding technology. Another exciting alternative is the introduction of novel designs to radio apparatus, such as the work by Mahmud et al. [1]. Based solely on resonators, their two-element filtering antenna array design had achieved improved transceiving efficiency. However, there are physical limitations to the modulation and coding technology, as well as new radio apparatus designs.

As a prospective mechanism, the coexistence of LTE (Long-Term Evolution) and Wi-Fi (wireless fidelity) has received considerable attention for its potential to achieve better spectrum utilization. This study advances the same philosophy and contributes to determining an optimal time ratio for the time-division multiplexing between the LTE

and Wi-Fi networks. Symmetric allocation with a duty cycle of 50% cannot be an optimal option. Asymmetric allocation according to the quality of service (QoS) requirements and traffic demands should be considered. As a de facto standard, LTE is an all-IP system with a higher data rate, high-level security, improved spectrum efficiency, lower latency, QoS support, and so forth. LTE was initially designed to operate in the licensed band. To accommodate more traffic, a promising alternative is to allow the LTE to cooperate in the unlicensed band with the Wi-Fi networks.

However, there is a fundamental obstacle to this approach. The transmission mechanism of Wi-Fi is intrinsically different from that of LTE. The unlicensed band is already occupied by numerous wireless systems, particularly the Wi-Fi system. LTE adopts a non-contention MAC (media access control) protocol to avoid packet collision among users. It uses the scheduling mechanism in centralized control units, such as eNBs (evolved Node B). The eNBs decide how to allocate resources to users. Each user can utilize the allocated resources to transmit data. On the other hand, Wi-Fi employs the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism to resolve the packet collision problem. CSMA/CA is intrinsically a contention-based MAC protocol for shared, broadcast-based media. In Wi-Fi, when a node has data to transmit, it detects the channel status. If the channel is idle, the node is allowed to transmit data. Otherwise, it will exercise a back-off algorithm waiting for other opportunities to transmit data.

Our contributions are threefold.

1. A utility function is defined, and an optimization problem is formulated for the time-division multiplexing between Wi-Fi stations and LTE networks. Then a new scheme is proposed for adequate allocations of spectrum resources utilizing HAPs as bridges. This scheme is peculiarly beneficial to LTE-U (LTE-Unlicensed) systems that plan to maintain the QoS requirements of Wi-Fi users. The proposed scheme can further preserve the access right of Wi-Fi QoS stations (QSTAs).
2. The disadvantages to Wi-Fi users due to the inclusion of LTE users in the unlicensed band for LTE-U can be minimized. It is argued that the Wi-Fi networks would be less advantageous when LTE and Wi-Fi coexist in the same unlicensed band. In recognition of these problems, this study conducts an analytical analysis to determine an optimal ratio for the time-division multiplexing between LTE and Wi-Fi networks, seeking to maximize the total throughput and maintain fairness in the coexistence of Wi-Fi and LTE-U.
3. Simulation results confirm that the scheme would have better throughput while keeping fair access between LTE and Wi-Fi stations in either heavily or lightly loaded Wi-Fi environments. By adequately assigning weights to the utility function, when loads of Wi-Fi stations are high, our scheme favors Wi-Fi stations to preserve the access right of Wi-Fi stations. On the other hand, when loads of Wi-Fi stations are light, the remaining resources are allocated to LTE stations for maximal bandwidth efficiency.

The rest of the paper is organized as follows. Section 2 presents related works. In Section 3, we define the system model and the formulated optimization problem for the time-division multiplexing between LTE and Wi-Fi networks. The proposed method is described in detail in Section 4. Section 5 presents the simulation settings and shows the numerical results accompanied by analysis and discussion. Finally, we draw some conclusions in Section 6.

## 2. Related Technology and Works

The concept of unlicensed LTE was first introduced in the 3rd Generation Partnership Project (3GPP) Release 10. Years of advancement led to three main variants, namely LTE-U, Licensed Assisted Access (AAC), and MulteFire [2–4].

### 2.1. LTE-Unlicensed (LTE-U)

LTE-U [2] and Wi-Fi share the same unlicensed spectrum in a time-division manner. A certain portion of individual repeated cycles is allocated to LTE, and the rest is allocated

to Wi-Fi. LTE-U is favorable in that no PHY/MAC layer change is required. Carrier sense adaptive transmission (CSAT) [5] is a medium access procedure proposed by Qualcomm. Based on modifications of the carrier aggregation [6], CSAT enables the coexistence of LTE and Wi-Fi. The CSAT technique calculates the most appropriate coexistence period, ensuring that Wi-Fi is minimally affected. First, the LTE-U eNB performs CSAT to detect and analyze channel conditions of the unlicensed band, including the number of adjacent LTE-U eNBs, Wi-Fi APs, the types and lengths of packets, and so on. Next, according to the measurements, the adaptive duty cycle (ADC) will be divided into the on/off cycle, which defines the access periods of LTE-U eNB and Wi-Fi. The percentage of allocation (the duty cycle of the ADC) is a critical parameter for system performance. An informed choice of the allocation percentage is traffic dependent. It strongly affects the total system throughput and the fairness between the LTE and Wi-Fi networks. This issue is precisely the primary concern of this study.

## 2.2. Licensed Assisted Access (LAA)

Another mechanism proposed to exploit the unlicensed band is the Licensed-Assisted Access (LAA) [3] drafted in 3GPP Release 13. The core concept of LAA is Listen-Before-Talk (LBT). To reduce the interference to the Wi-Fi system while accessing the unlicensed band, four mechanisms are specified in LAA, namely carrier selection (CS), listen-before-talk (LBT), discontinuous transmission (DTX), and transmit power control (TPC) [7]. LBT can be regarded as the LTE version of the carrier sense multiple access (CSMA) schemes. Unlike the CSAT scheme, it operates in a distributed manner rather than a centralized one. It provides a flexible and adaptive coexistence solution among heterogeneous networks through quick channel sensing and dynamic spectrum access. The LBT scheme gives all the contending nodes equal spectral access opportunities in the long term. However, it sacrifices spectral utilization in exchange for reducing the probability of collision.

## 2.3. MulteFire

MulteFire [4] is a standalone LTE system designed to operate entirely in the unlicensed band, in which both the control signal and data transmission are delivered in the unlicensed band. It is distinguished for improving LTE performance and simplifying LTE deployment in the unlicensed band. Basically, the MulteFire builds on 3GPP standards and utilizes the LBT mechanism to coexist with Wi-Fi or LAA users. One of the most important application areas of MulteFire is industrial IoT, which demands fast transmission and broad bandwidth for collecting a large volume of data to support intelligent industrial operations using advanced data analysis tools. Due to the use of LTE technology, MulteFire enjoys certain advantages, including high capacity, better coverage, seamless mobility, industrial-grade reliability, and LTE-based security. In [8], the challenges and solutions of deploying the MulteFire in the unlicensed band are discussed.

## 2.4. Related Works on the Coexistence of LTE and Wi-Fi

Many studies are devoted to the coexistence of LTE and Wi-Fi in the unlicensed band. The following is a brief survey of existing approaches.

In [9], Alsenwi et al. proposed a novel Hopfield neural network-based mechanism as an efficient and fair coexistence mechanism in the unlicensed bands for an LTE-U base station alongside Wi-Fi access points (APs). The coexistence problem was modeled as an optimization problem, in which both the LTE-U data rate and the QoS of the Wi-Fi network are considered for fairness. Another scheme, named mLTE-U, was proposed in [10]. The proposed approach adopts an adaptive LBT scheme. After a variable transmission opportunity (TXOP), mLTE-U has a variable muting period, which the Wi-Fi networks can exploit to gain access to the media. A Q-learning technique is employed to achieve fair coexistence between mLTE-U and Wi-Fi networks. The proposed scheme can decide on an appropriate mixture of TXOP and muting period for fair coexistence. In [11], Mosleh et al. address issues neglected in previous works, such as the uncertainties in LAA-based

coexistence systems. It could be that only partial or no information on MAC and physical layer protocol are available in the systems. The lack of such accurate information may inaccurately estimate the key performance indicators. A novel machine learning mechanism that combines a neural network with a logistic regression algorithm is proposed in the paper. It can track and estimate key performance indicators (KPIs) and probability of coexistence (PoC) of LTE-LAA and Wi-Fi networks without the information of MAC and physical layer parameters. A reinforcement learning-based sub-channel selection technique is introduced in [12] for a coexistence scenario with multiple LAA and Wi-Fi competing for channel access in an unlicensed band. The proposed scheme allows access points and eNBs to select the best sub-channel by the MAC protocol considering the physical layer's parameters.

In [13], a novel proportional fair allocation scheme was proposed to guarantee fair coexistence between LTE-U and Wi-Fi networks. It allocates the channel access time in a proportional-fair manner to each entity without message-passing between LTE-U and Wi-Fi networks. In [14], a cross-layer proportional-fairness-based framework is proposed to achieve throughput-oriented proportional fairness between the LTE-U and Wi-Fi networks. When LTE-U eNBs operate with the LBT scheme to access the channel, the interactions between the LTE-U and Wi-Fi networks can be modeled by two interactive Markov chains. He et al. analyzed the throughput of LTE-U and Wi-Fi and formulated a utility function of throughput, transforming the problem into an optimization problem. The architecture with Hyper-AP (HAP) is proposed in [15]. In [16], the operation of HAP is divided into a contention-free period and a contention period for LTE-U and Wi-Fi users, respectively. To improve system throughput and user fairness, Chen et al. take the resource allocation and user association into consideration to maximize the network utility based on the Nash bargaining solution (NBS). To decide what percentage of a repeated cycle in the time domain should be allotted to the LTE users, the NBS (Nash bargaining solution) algorithm is utilized to solve the allocation of limited resources among many contestants. We would refer to the scheme as NBS. Any competitor in the game would like to obtain a maximum benefit. When one of the participants receives profits, it will cause others to lose some profits. After the bargaining process, the distributions of resources will achieve a balance status among contestants. In [17], Al-Khansa and Artail propose a semi-distributed LTE-Unlicensed scheme in which the Wi-Fi-like carrier sense, back-off, and QoS mechanism are equipped in the LTE base station. The proposed scheme also uses the almost blank sub-frame (ABS) to control the interference. For performance evaluation, it uses the ns3 to simulate LAA and Wi-Fi coexistence scenarios. The results show that it can achieve fairness between LTE-U and Wi-Fi users in a small cell environment. In [3], the four main functionalities of LAA, i.e., CS, LBT, DTX, and TPC, are investigated. Q-learning mechanisms are used for carrier selection that takes DTX or both DTX and TPC into account to provide an efficient coexistence scheme. Using the Markov model, Qin et al. [18] model and analyze the coexistence of LTE and Wi-Fi, including throughput, access probability, and collision probability. Our study and [18] share the observation of the change in throughput as the number of STA varies. In [19], an optimal detector for detecting Wi-Fi APs is designed based on second-order statistics (SOS) of orthogonal frequency-division multiplexing (OFDM) signals and using the singular value decomposition (SVD) method. Theoretical expressions are derived for the detection and the false alarm probabilities. The flexible carrier sensing adaptive transmission (CSAT) framework and algorithm are designed for spectrum access and sharing. In [20], a coexistence model of LTE and Wi-Fi with two virtual zones is suggested. The inner zone is the secondary zone, which represents Wi-Fi with an unlicensed spectrum and the outer zone is the primary zone, which represents LTE with a licensed spectrum. The numerical solution of the model is presented using MOSEL-2 simulation and the mathematical solution is derived to validate the model. A threshold minimum bit rate established the user admission. Samy et al. [21] address the detection of selfish behaviors in Wi-Fi/LTE coexistence environments, such as the tampering of the back-off mechanism, traffic class parameters, the clear channel access (CCA) threshold, and

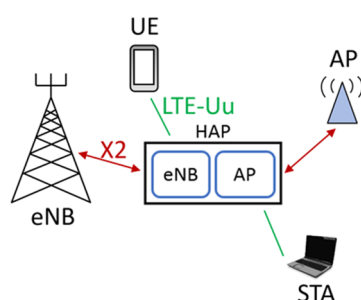
others. Their approach applies correlation-based signal detection to accurately infer the operational parameters of LTE transmissions without decoding. The researches mentioned above have their contributions. However, many of the proposed mechanisms sacrifice Wi-Fi users when facing a dilemma in improving fairness or increasing the throughput.

### 3. The Time-Division Multiplexing Problem

Aimed at improving the spectrum utilization of the unlicensed bands by following LTE-Unlicensed (LTE-U), this article contributes to the determination of the optimal time ratio,  $\delta$ , for the time-division multiplexing of LTE and Wi-Fi over unlicensed bands. We explain the typical environments this study intended and formulate the finding of the optimal  $\delta$  value as a one-dimensional mixed integer programming problem.

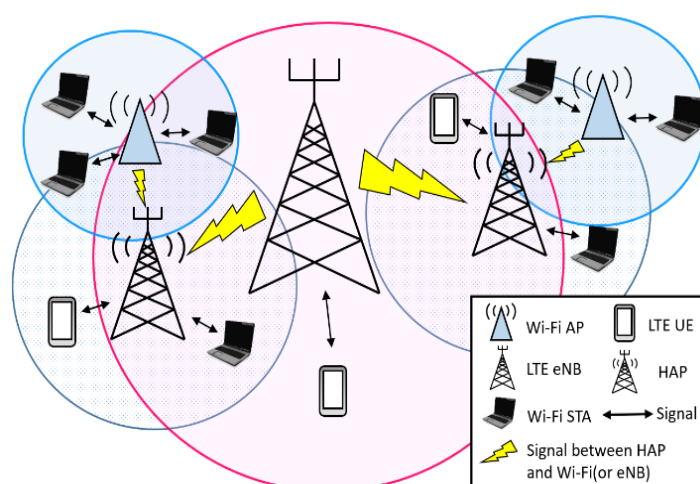
#### 3.1. System Model

HAP is equipped with both LTE and Wi-Fi communication interfaces, as shown in Figure 1. The HAP is an eNB capable of the function of Wi-Fi AP. Thus, the HAP can coordinate the spectrum allocation and manage the switching of interfaces between Wi-Fi and LTE. The Wi-Fi interface of HAP can only access the unlicensed band. In contrast, the LTE interface of the HAP can access both licensed and unlicensed bands through carrier aggregation technology.



**Figure 1.** Hyper access point (HAP) architecture.

The scenario for the coexistence of Wi-Fi and LTE in an indoor environment is shown in Figure 2. In this scenario, there is one LTE eNB,  $N_{UE}$  LTE users,  $N_{HAP}$  hyper-APs,  $N_{AP}$  access points, and  $N_{STA}$  Wi-Fi stations. We employ a new wireless AP architecture called Hyper-AP (HAP) [15,16]. There are two types of Wi-Fi stations, namely QSTA and non-QoS STA, depending on whether they have QoS support. Among the  $N_{STA}$  Wi-Fi stations, there are  $N_{QSTA}$  QSTAs.



**Figure 2.** A scenario of a coexistence environment.

To be consistent with the LTE-U standard, this paper adopts the concept of carrier sense adaptive transmission (CSAT) to control the time-division multiplexing between LTE and Wi-Fi. The LTE-U standard, proposed by Qualcomm, enables LTE users and Wi-Fi stations to effectively and fairly access the unlicensed band. An unlicensed band can be divided into repeated Repetition Intervals in the time domain. Each repetition interval can be further divided into a contention period (CP) and a contention-free period (CFP), as shown in Figure 3. LTE users are allowed to access the unlicensed band during the contention-free period with the point coordination function (PCF) mechanism. On the other hand, Wi-Fi stations can transmit data using the traditional CSMA/CA mechanism during the contention period. The length of the repetition interval is denoted by  $L$  in Figure 3. We denote the ratio of the CP to the repetition interval by  $\delta$ . That is,  $\delta = CP/L$ . The ratio for the contention-free period is then  $(1 - \delta) = CFP/L$ .

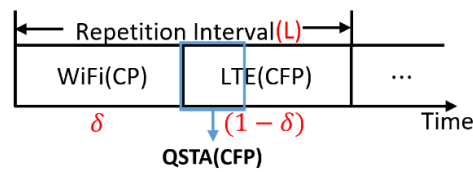


Figure 3. Repetition interval.

### 3.2. Problem Formulation

The objective of this study is to achieve good throughput performance without compromising the fairness between LTE users and Wi-Fi stations. Therefore, the utility function is defined as the sum of the weighted throughputs of Wi-Fi and LTE subject to constraints that both Wi-Fi and LTE can meet their QoS requirements. The optimization problem is formulated as follows:

$$\max_{\delta} U(\delta) = \mathbb{E}\{\alpha \cdot \text{Throughput}_{\text{Wi-Fi}} + (1 - \alpha) \cdot \text{Throughput}_{\text{LTE}}\} \quad (1a)$$

Subject to the following constraints:

$$\text{Throughput}_i^{\text{Wi-Fi}} \geq \text{Throughput}_{th}^{\text{Wi-Fi}}, \forall \text{ Wi-Fi station } i \quad (1b)$$

$$T_j^{\text{LTE}} \cdot \mathbb{E}(s_j^{\text{LTE}}) \geq s_{th}^{\text{LTE}}, \forall \text{ LTE user } j \quad (1c)$$

$$P(d < D | N_{STA}) \geq P_{th} \quad (1d)$$

$$0 \leq \alpha, \delta \leq 1 \quad (1e)$$

where  $\text{Throughput}_{\text{Wi-Fi}}$  is the throughput of all Wi-Fi stations;  $\text{Throughput}_{\text{LTE}}$  is the throughput of all LTE users;  $\text{Throughput}_i^{\text{Wi-Fi}}$  denotes the throughput of Wi-Fi station  $i$ ;  $\text{Throughput}_{th}^{\text{Wi-Fi}}$  refers to the throughput threshold of Wi-Fi station;  $T_j^{\text{LTE}}$  means the duration that LTE user  $j$  can access the unlicensed band;  $\mathbb{E}(s_j^{\text{LTE}})$  represents the expected throughput of LTE user  $j$ ;  $s_{th}^{\text{LTE}}$  symbolizes the throughput threshold of LTE users;  $P(d < D | N_{STA})$  is the probability that a Wi-Fi station transmits successfully with a transmission delay  $d$  less than a maximum saturation delay  $D$  when the number of stations is  $N_{STA}$ ;  $P_{th}$  represents the threshold of successful transmission probability of Wi-Fi stations;  $\alpha$  is the weight assigned to Wi-Fi throughput.

The constraint (1b) assures that the throughput of Wi-Fi station  $i$  must be above a certain threshold  $\text{Throughput}_{th}^{\text{Wi-Fi}}$ . The throughput of Wi-Fi station  $i$  is defined as (2).

$$\text{Throughput}_i^{\text{Wi-Fi}} = \delta \cdot L \cdot P(d < D | N_{STA}) \cdot \mathbb{E}(s_i^{\text{Wi-Fi}}) \quad (2)$$

where  $\mathbb{E}(s_i^{\text{Wi-Fi}})$  is the expected throughput of Wi-Fi station  $i$ . Constraint (1c) assures that the throughput of LTE user  $j$  must be larger than a certain threshold  $s_{th}^{\text{LTE}}$ . Constraint (1d)

guarantees that the successful transmission probability of Wi-Fi stations must be above a certain threshold. Constraint (1e) represents that the value of  $\alpha$  and  $\delta$  is between 0 and 1.

#### 4. The Proposed Scheme

In our approach, we improve the concept of carrier sense adaptive transmission (CSAT), which performs time-division multiplexing between LTE and Wi-Fi to share the same unlicensed spectrum. More specifically, we evaluate the upper and lower bounds of the time ratio,  $\delta$ , of the multiplexing according to the traffic demands of LTE and Wi-Fi. We can then decide on an optimal  $\delta$  value by optimizing a utility function considering both Wi-Fi's minimal QoS requirements and the total throughput.

The contention-free period (CFP) is exploited and modified compared to the LTE-U standard to support the Wi-Fi system's QoS provisioning and resolve the bias problem of the CSAT mechanism towards LTE networks. It is not solely reserved for LTE users but is further divided into two sub-intervals. The first subinterval is to provide a contention-free operation for Wi-Fi QSTAs. During the first sub-interval, QSTAs can access the unlicensed band by a PCF polling mechanism. The second CFP subinterval is LTE users' turn to access the unlicensed band. If no LTE users would like to access the resource, Wi-Fi stations can access the resource during the entire repetition interval. Therefore, the adjustment of the lengths of CP and CFP is the core issue of this study. For example, assuming that the transmission time for a polled QSTA is  $T_{QSTA}$ , the duration that  $N_{QSTA}$  of QSTAs would need  $T_{QSTA} \cdot N_{QSTA}$  in the CFP sub-interval if we want to guarantee that all QSTAs can be served as in Figure 3.

The procedure for LTE eNB to utilize the unlicensed band is as follows. If the eNB wants to deliver packets using the unlicensed band, firstly, it performs channel detection to select the least utilized channel. The nearby HAP informs the Wi-Fi AP using the selected channel. Then, based on the QoS requirement of Wi-Fi and the traffic demands of LTE, the Wi-Fi AP calculates an adequate  $\delta$  to maximize the total throughput and maintain fairness in the meantime. The  $\delta$  value will be passed back to the LTE eNB through HAP. As the eNB receives the  $\delta$  information, it can decide the start and end time of the CFP duration to access the unlicensed band.

Figure 4 shows the procedure for finding the optimal  $\delta$  in our approach. First, we define the utility function and some constraints which need to be satisfied. We calculate the transmission probability and throughput threshold of Wi-Fi stations. Next, the lower bound of  $\delta$  can be obtained using the constraints and threshold of Wi-Fi stations. The upper bound of  $\delta$  can be obtained by exercising the user filtering mechanism. By substituting all feasible solutions into the utility function, the solution maximizing the utility function is the optimal value of  $\delta$ . In the following, we explain successful access probability, threshold adjustment, lower and upper bounds of  $\delta$ , user filtering mechanism, and time complexity in detail.

##### 4.1. Successful Access Probability of Wi-Fi Stations

In the subsection, we examine the successful access probability of Wi-Fi stations. In Wi-Fi systems, stations compete with each other for the channel access opportunity to transmit packets. The station will invoke a back-off mechanism if the channel is busy or a transmission collision occurs. The back-off process will continue until the station successfully sends a packet or reaches the maximal number of retransmissions.

The above situation is called the saturation back-off mechanism, as shown in Figure 5. Assume that a station's packet transmission experiences a back-off delay  $d$  smaller than the maximal saturation back-off,  $D$ . We denote the probability as  $P(d < D)$ , where  $d$  is the back-off delay [22]. After this interval, the packet can be successfully transmitted. Therefore, the Wi-Fi successful transmission probability can be defined as the probability that  $d < D$ , as indicated in (3).

$$P(d < D \mid N_{STA}) = \sum_{i=0}^{R_y} \sum_{j=0}^{W_i} P(d < D \mid i \text{ col}, j \text{ slots}) \cdot P(j \text{ slots} \mid i \text{ col}) \cdot P(i \text{ col}) \quad (3)$$

where  $R_y$  is the retry limit and  $W_i = \sum_{k=0}^i (CW_k - 1)$  is the accumulated size of the contention window for the  $i$ -th retransmission.

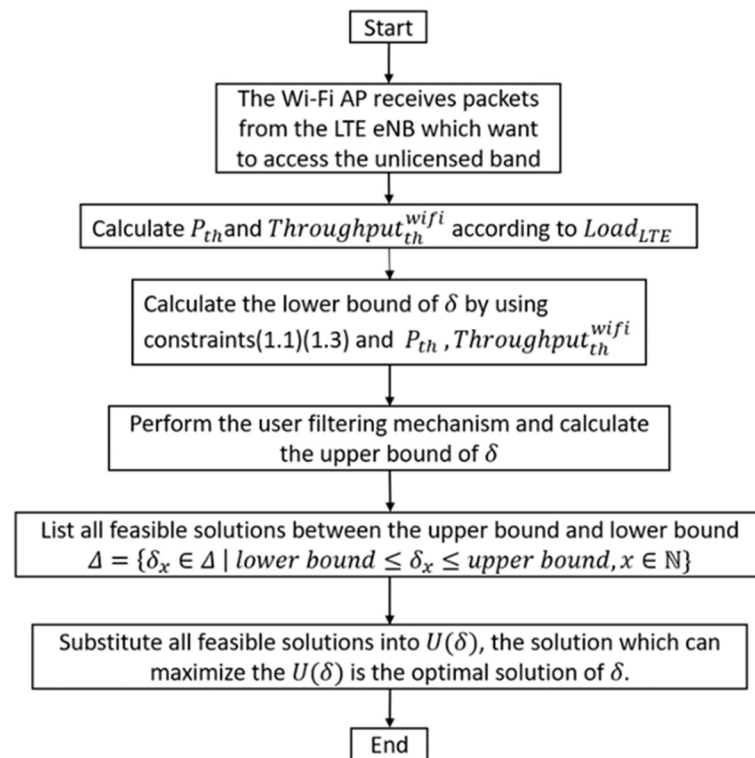


Figure 4. Flow chart for the evaluation of an optimal  $\delta$ .

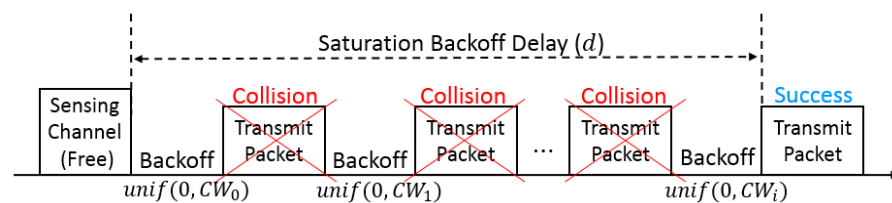


Figure 5. The saturation back-off delay.

During the saturation back-off delay  $d$ , collisions may happen  $i$  times. The whole backoff procedure may take the total number of  $j$  slots which is the sum of the number of slots for each backoff before succeeded transmission. As a result, the probability of the successful transmission of Wi-Fi in (3) can be divided into three parts.  $P(i \text{ col})$  represents the probability of  $i$  collision.  $P(j \text{ slots} \mid i \text{ col})$  represents the probability that the sum-up numbers of back-off slots are equal to  $j$  when there are  $i$  collisions.  $P(d < D \mid i \text{ col}, j \text{ slots})$  is the probability of  $d < D$  with  $i$  collisions and  $j$  back-off slots [11]. The detailed derivation and evaluation of these terms are given in Appendix A.

The probability given in (3) serves as an important indicator regarding the loading of the Wi-Fi system. It will be used to decide on an adequate  $\delta$  value to optimize the time-division multiplexing between LTE and Wi-Fi.

#### 4.2. Wi-Fi Threshold Adjustment

To make the coexistence of LTE and Wi-Fi more flexible, we dynamically adjust the  $P_{th}$  and  $Throughput_{th}^{WiFi}$ , as shown in Figure 6. When the LTE eNB is heavily loaded, we would like to improve LTE users' opportunity to access the unlicensed band. Therefore, we examine if we can relax the restrictions on  $P_{th}$  and  $Throughput_{th}^{WiFi}$ . Conversely, if the loading of the LTE eNB is not heavy, there is no need to lower the thresholds. However, the premise of the above adjustment is that the Wi-Fi AP is not heavily loaded, such that the QoS requirements of the Wi-Fi system can be ensured.

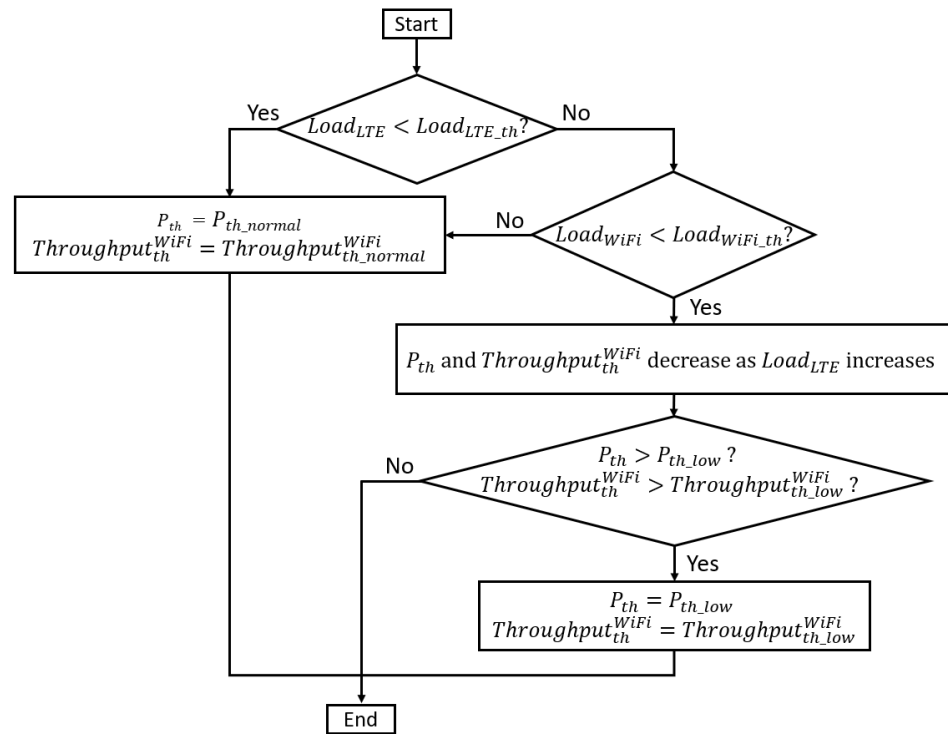


Figure 6. Evaluation of the threshold of time-division.

The load of LTE eNB is denoted as  $\rho_n$ , which is defined as the ratio of the number of resource blocks (RBs) requested by users to the total number of RBs available from eNB  $n$ , as shown in (4).

$$\rho_n = \frac{1}{N_{PRB}} \sum_{x=1}^{N_{UE}} \frac{D_x}{R(SINR_x)} \quad (4)$$

where  $N_{PRB}$  means the total number of RBs in eNB  $n$ ;  $N_{UE}$  is the number of LET users;  $D_x$  represents the number of RBs requested by user  $x$ ;  $R(SINR_x)$  denotes the transmission rate per RB for user  $x$ .

When the load of LTE eNB is not high, the threshold of  $P_{th}$ , and  $Throughput_{th}^{WiFi}$  are set to normal, i.e.,  $P_{th} = P_{th\_normal}$  and  $Throughput_{th}^{WiFi} = Throughput_{th\_normal}^{WiFi}$ .  $P_{th\_normal}$  and  $Throughput_{th\_normal}^{WiFi}$  are the normal threshold of successful transmission probability and the normal throughput threshold of Wi-Fi AP when the load of Wi-Fi AP is not highly. If the load of LTE exceeds the threshold, we would examine the load of Wi-Fi. If the Wi-Fi is not heavily loaded, the Wi-Fi threshold can be dynamically adjusted according to the overloading of LTE, as in (5) and (6).

$$P_{th} = P_{th\_normal} \times (1 - (Load_{LTE} - Load_{LTE\_normal})) \quad (5)$$

$$Throughput_{th}^{WiFi} = Throughput_{th\_normal}^{WiFi} \times (1 - (Load_{LTE} - Load_{LTE\_normal})) \quad (6)$$

In the dynamic adaptation of the  $P_{th}$  and  $Throughput_{th}^{WiFi}$ , the minimum allowed values are  $P_{th\_low}$  and  $Throughput_{th\_low}^{WiFi}$ , which represent the lowest threshold of successful transmission probability and the lowest throughput threshold of WiFi, respectively.

#### 4.3. Lower Bound and Upper Bound of $\delta$

According to the utility function  $U(\delta)$  defined in (1), we would like to find the lower and upper bounds of  $\delta$ , which is the ratio of transmission duration for WiFi stations and LTE users. As described in the previous sub-section, we can get the  $Throughput_{th}^{WiFi}$  dynamically in response to the loading change of LTE. After the threshold is obtained, the lower bound of  $\delta$  will be calculated.

First, considering the constraints (1b) and (2), we can substitute (2) into the constraint (1b) and obtain one of the lower bound conditions of  $\delta$ , as in (7), which is deduced as follows:

$$\begin{aligned} Throughput_i^{WiFi} &= \delta \cdot L \cdot P(d < D | N_{STA}) \cdot \mathbb{E}(s_i^{WiFi}) \geq Throughput_{th}^{WiFi} \\ \Rightarrow \delta &\geq \frac{Throughput_{th}^{WiFi}}{L \cdot P(d < D | N_{STA}) \cdot \mathbb{E}(s_i^{WiFi})} \end{aligned} \quad (7)$$

According to the explanation in Appendix A, we can get a  $D^*$ , which is the minimum duration satisfying the successful transmission constraint (1d). That is, the contention period,  $D = \delta \times L$ , must be greater than or equal to  $D^*$  to satisfy the threshold of successful transmission probability. We now have the following second bound:

$$\delta \geq \frac{D^*}{L} \quad (8)$$

Moreover,  $0 \leq \delta \leq 1$ , we finally have the lower bound of  $\delta$ , given in (9).

$$\delta \geq \min \left\{ 1, \max \left\{ \frac{Throughput_{th}^{WiFi}}{L \cdot P(d < D | N_{STA}) \cdot \mathbb{E}(s_i^{WiFi})}, \frac{D^*}{L} \right\} \right\} \quad (9)$$

Under the same concept, the upper bound of the time interval ratio  $\delta$  can be derived. The constraint on LTE throughput is given in (1c), that is,  $T_j^{LTE} \geq \frac{s_{th}^{LTE}}{\mathbb{E}(s_j^{LTE})}$ . During the contention-free period of a repetition interval, the sub-period at the front is for the QoS-STAs (QSTAs) to access the channel resources. Assume that there are  $N_{QSTA}$  QSTAs in the environment. The sum of the polling time for each QSTA plus the longest transmission time is  $T_{QSTA}$ . Therefore,  $T_{QSTA} \cdot N_{QSTA}$  is the longest duration that the channel is occupied by the Wi-Fi PCF mechanism. In each repetition interval, for all LTE users, the total time to access the unlicensed band is the competition-free period subtracted by the time interval occupied by the PCF mechanism, as follows:

$$\sum_{j=1}^{N_{UE}} T_j^{LTE} = (1 - \delta) \cdot L - T_{QSTA} \cdot N_{QSTA} \quad (10)$$

The upper bound of  $\delta$  can be obtained by using (10) and satisfying (1c) as shown in (11).

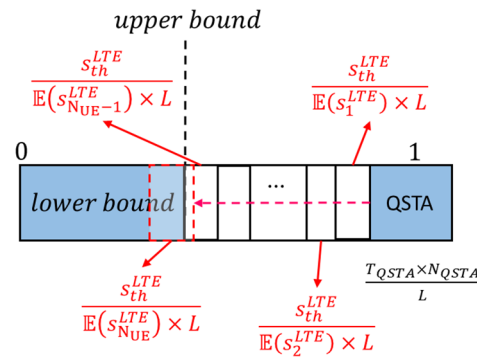
$$\delta \leq 1 - \left( \sum_{j=1}^{N_{UE}} \frac{s_{th}^{LTE}}{\mathbb{E}(s_j^{LTE})} + T_{QSTA} \cdot N_{QSTA} \right) \times \frac{1}{L} \quad (11)$$

Since the upper bound of  $\delta$  varies with the number of LTE users, the LTE user filtering mechanism described in the following subsection is used to limit the number of LTE users. Finally, we can combine the calculated upper and lower bound of  $\delta$ , i.e., Equations (9) and (11), to obtain the interval of the feasible solution of the time ratio  $\delta$ , as shown in (12).

$$\min \left\{ 1, \max \left\{ \frac{\text{Throughput}_{th}^{WiFi}}{L \cdot P(d < D) N_{STA} \cdot \mathbb{E}(s_i^{WiFi})}, \frac{D^*}{L} \right\} \right\} \leq \delta$$

$$\leq 1 - \left( \sum_{j=1}^{N_{UE}} \frac{s_{th}^{LTE}}{\mathbb{E}(s_j^{LTE})} + T_{QSTA} \cdot N_{QSTA} \right) \times \frac{1}{L} \quad (12)$$

In the previous subsection, we calculated the lower bound of  $\delta$  by using Wi-Fi stations' successful transmission probability and throughput requirement. Therefore, the length of CFP in a repetition interval should not be less than this limit. We also use the minimum demands of QSTA users to calculate the upper bound of  $\delta$ . However, the minimum resource requirement of LTE is based on the sum of the minimum requirements of each LTE user who uses the unlicensed band as in constraint (1c). When the LTE demand is too high, the upper bound of  $\delta$  in (11) may be lower than the lower bound in (9). Therefore, we propose a filtering mechanism to prevent this situation. After calculating the upper and lower bounds of  $\delta$  in each round, if the upper bound is less than the lower bound, the user filtering mechanism will be invoked to confine the number of LTE users who can access the unlicensed band in each round. Then the best time ratio  $\delta$  can be found by the utility function. The concept is illustrated in Figure 7.

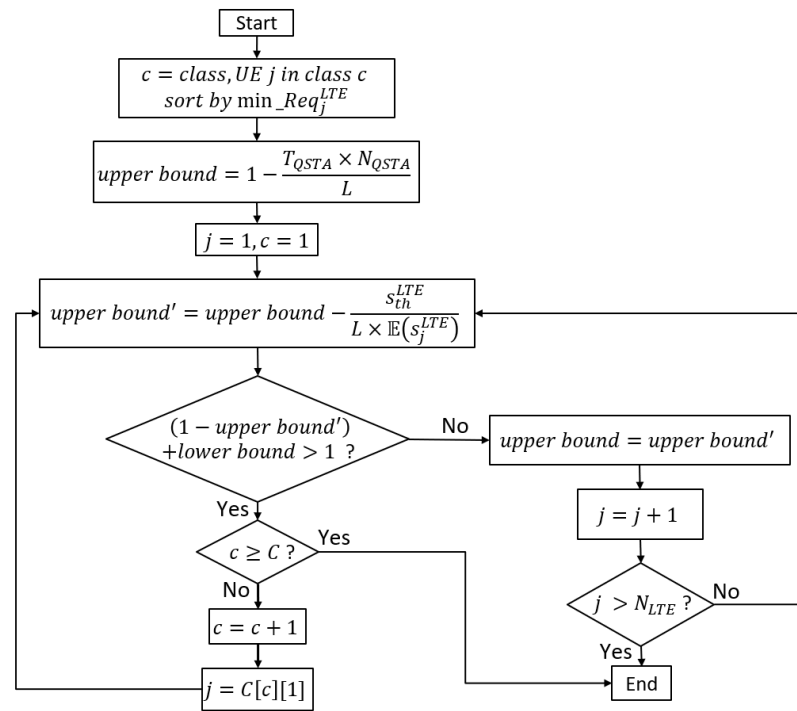


**Figure 7.** The occupation time proportion for user filtering mechanism.

#### 4.4. User Filtering Mechanism

To screen LTE users for admission control of the unlicensed band, it is necessary to sort the LTE users by their access priority. The LTE users who need to transmit timing-sensitive packets, such as voice over IP (VoIP), are assigned the highest priority. The next priority is for LTE users located at the cell's edge or with an inferior signal to interference plus noise ratio (SINR). According to the above priority classification, all LTE users are roughly classified into different classes, and we assume there are  $C$  priority classes. Then in each class, the priority of each user will be ordered by its minimum bandwidth requirement. After the LTE user precedence is settled, the upper bound of  $\delta$  can be adjusted accordingly.

Firstly, the upper bound of  $\delta$  is initialized to 1. In the contention-free period, the Wi-Fi QSTAs have the highest priority to access the channel. Therefore, before considering the LTE users, the upper bound of  $\delta$  should be subtracted by  $\frac{T_{QSTA} \cdot N_{QSTA}}{L}$ , which is the ratio occupied by Wi-Fi QSTAs. After that, for each additional LTE user  $j$ , the upper bound of  $\delta$  must be recalculated by subtracting  $\frac{s_{th}^{LTE}}{\mathbb{E}(s_j^{LTE})} \cdot L$ , which is the resource quota used by LTE user  $j$ . If the value of the upper bound is not less than the value of the lower bound, the user can access the unlicensed band and continue the filtering scheme to find the next user in the same class. As illustrated in Figure 8, when considering the LTE users by the priority order one by one, the upper bound of  $\delta$  will approach the lower bound. If no other users are allowed to access the unlicensed band in the class, then we switch to the next priority category and continue the filtering process. If all categories have been filtered, no additional LTE users can be selected. The remaining LTE users are not allowed to access the unlicensed band, and the upper bound of the  $\delta$  is obtained.



**Figure 8.** User filtering mechanism flow chart.

#### 4.5. Determination of the Optimal $\delta$

Next, we will explain how to find out the optimal solution of  $\delta$ . The physical resource block (PRB) is the minimum time unit that an LTE device can use. It is 180 kHz wide in frequency and 0.5 ms long (1 slot) in time. The contention-free period, during which LTE users can access the unlicensed band, must be a multiple of  $T_{slot}$ , as follows:

$$(1 - \delta) \cdot L = x \cdot T_{slot}, \quad x \in \mathbb{N} \quad (13)$$

In (12), we can obtain the upper and lower bounds of  $\delta$  which limits the possible solution of  $\delta$ . According to (13), a feasible solution is a set of points within  $\delta$ 's upper and lower bounds. We denoted this set by  $\Delta$ . We examine the utility values for all points in  $\Delta$ . The optimal  $\delta$  maximizing the utility function can be found by comparing all the calculated values. This is essential for a one-dimensional mixed integer programming problem. The process for finding the optimal  $\delta$  is given in Algorithm 1.

---

**Algorithm 1:** Determination of the Optimal  $\delta$

---

- 1: //List all feasible solutions between the upper and lower limits
  - 2:  $\Delta = \{\delta_x \in \Delta \mid \text{lower bound} \leq \delta_x \leq \text{upper bound}, x \in \mathbb{N}\}$
  - 3: **Initial:**  $U = 0$
  - 4: **for**  $x = 1; x \leq \text{sizeof}(\Delta); x++$  **do**
  - 5:    $U' = U(\delta_x)$
  - 6:   **if**  $U' > U$  **then**
  - 7:      $U = U'$
  - 8:      $opt = x$
  - 9:   **end if**
  - 10: **end for**
  - 11:  $\delta_{opt}$  is the optimal solution.
-

#### 4.6. Time Complexity

We analyze the time complexity of the coexistence mechanism proposed in this paper. According to the optimization process for  $\delta$ , as shown in Figure 5, we list the time complexity of each step.

First, we will determine the throughput threshold  $P_{th}$  and transmission probability threshold  $Throughput_{th}^{WiFi}$  of Wi-Fi based on the load of LTE eNB and Wi-Fi AP. Assuming that there are  $n$  LTE users in the environment, the time complexity of calculating the load of LTE eNB is  $O(n)$ , and the time complexity of determining the threshold of Wi-Fi stations is  $O(1)$ . Therefore, the time complexity of the step is  $O(n)$ . The next step is to compute the lower bound of  $\delta$  according to the throughput threshold  $P_{th}$  of Wi-Fi. To do this, we need to calculate the successful transmission probability of Wi-Fi stations,  $P(d < D | N_{STA})$ . Suppose that the maximum retry limit is  $R$  and the number of STA is  $m$ , the loop that calculates the successful transmission probability will execute  $\sum_{i=0}^R \sum_{j=0}^{CW_0 * (2^{i+1} - 1)} \sum_{l=0}^c \sum_{k=0}^i 1$  times, where  $CW_0$  represents the initial size of the contention window, and  $c$  denotes a constant count for sampling the probability in (5). The complexity of calculating the lower bound of  $\delta$  is equal to the complexity of calculating the successful transmission probability of Wi-Fi stations. In computing  $P(d < D | N_{STA})$  of (3), the time complexity is  $O(R2^R)$  as in (5).

The procedure of finding out the upper bound of  $\delta$  is to sum up the throughput of all LTE users. Therefore, the complexity of this part is  $O(n)$ . On the other hand, when considering the user filtering mechanism, there are two parts to the procedure. The first part is to sort all the LTE users according to their assigned priorities using the Quicksort algorithm. Therefore, the complexity is  $O(n \log n)$ . The second part is simply filtering the sorted users in which the complexity is  $O(n)$ . Thus, the complexity of performing the user filtering mechanism is  $O(n \log n)$ .

Finally, we can get the list of all feasible solutions between the upper and lower bounds. All these feasible solutions will be substituted into the utility function and find out the optimal  $\delta$  which maximizes the utility function. The complexity of finding the optimal  $\delta$  is  $O(n)$ .

According to the above analysis, the most time-consuming procedure is the calculation of the successful transmission probability of Wi-Fi stations and performing the LTE user filtering mechanism. Therefore, the time complexity of the coexistence mechanism proposed in this paper is  $\max\{O(R2^R), O(n \log n)\}$ .

#### 5. Performance Evaluation

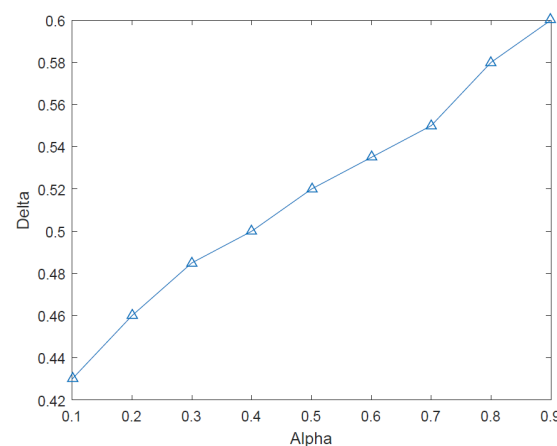
In this paper, we use MATLAB to simulate the performance of the proposed mechanism. We will compare our approach with NBS, LAA, and LTE-U. The simulation environment and the setting of parameters refer to [3,16,23] for NBS, LAA, and LTE-U, respectively. Table 1 lists related parameter settings in our simulations. In the LAA simulation, the four functions of LAA are fully emulated. We simply set the carrier sense adaptive transmission (CSAT) period for the LTE-U simulation to the repeating interval.

The repetition interval is set according to [16]. Regardless of the value of  $\delta$ , the longer the repetition interval is, the longer the contention period (CP) and the contention-free period (CFP) are. The length of the repetition interval will not have a critical impact on LTE users because the licensed band is available for the LTE users during the contention-free period. However, the Wi-Fi stations can only access the resource on the unlicensed band. Therefore, when the contention-free period (CFP) increases, the packet transmission delay will also increase accordingly for the Wi-Fi stations. On the contrary, if the repetition interval is too short, the coexistence mechanism will be performed frequently, leading to high overhead. In our simulation, the repetition interval is set to 100 ms [16].

**Table 1.** Simulation parameters.

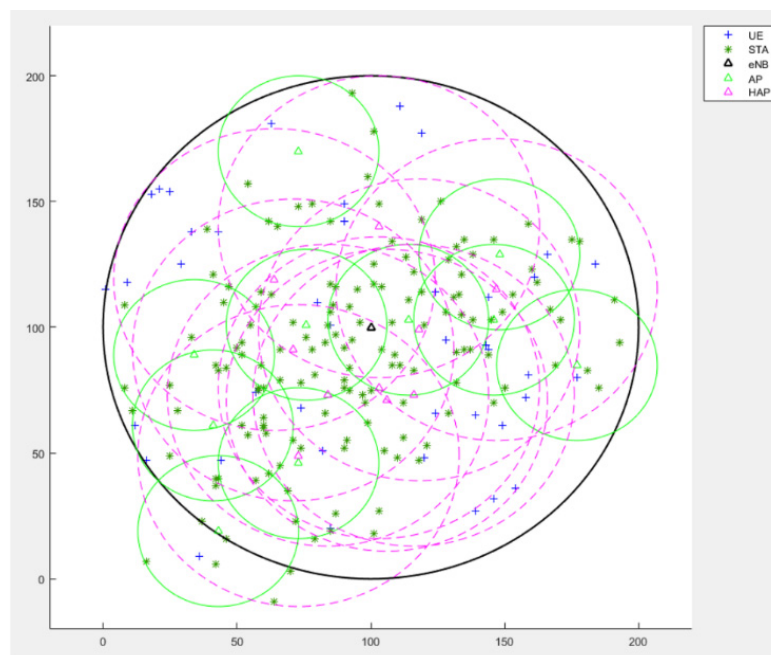
Parameter	Value
Number of eNBs	1
Number of HAPs	10
Number of Wi-Fi APs	10
Radius of eNB	120 m
Radius of HAP	60 m
Radius of AP	30 m
Transmit power on licensed band	30 dBm
Transmit power on unlicensed band	24 dBm
The bandwidth of licensed band	10 MHz
The bandwidth of unlicensed band	20 MHz
Path loss model	LTE : $140.7 + 36.7 \times \log_{10} d$ Wi-Fi: ITU InH [13]
Number of LET users	20–60
Number of Wi-Fi stations	5–25
Min. contention window	16
Max. contention window	1024
$\alpha$	0.5
$P_{th\_normal}$	0.8
$Throughput_{th\_normal}^{Wi-Fi}$	2 Mbps
Repetition Interval	100 ms

Previously, we defined a utility function with which the weighting factor  $\alpha$  decides the relative weightings of the throughputs of Wi-Fi and LTE systems. The setting of  $\alpha$  will affect the individual throughput of Wi-Fi and LTE systems. Intuitively, the optimal value of  $\delta$  is also affected by the settings of  $\alpha$ . We would like to know the impact of the setting of  $\alpha$  on the resulted  $\delta$ . Therefore, we simulate the following scenario to figure out the relationship between  $\alpha$  and  $\delta$ . In the scenario, there are 15 Wi-Fi stations and 50 LTE users. Generally speaking, if  $\alpha$  is larger, the communication system is friendlier to Wi-Fi stations. LTE users get more resources if  $\alpha$  is smaller. As shown in Figure 9, the relationship between  $\alpha$  and  $\delta$  is almost linear. When  $\alpha$  is small, the throughput contribution of Wi-Fi stations in the utility function is also small. Therefore, the duration of accessing the unlicensed band for LTE users will be longer such that the optimal value of  $\delta$  is smaller. In our scheme, the throughput thresholds will be set to meet the basic requirements for Wi-Fi and LTE systems. When we change the value of  $\alpha$  from 0.1 to 0.9, the value of  $\delta$  by the calculation mechanism is from 0.43 to 0.6, respectively.  $\alpha$  will be set to 0.5 in subsequent experiments.

**Figure 9.** The  $\delta$  versus weight value  $\alpha$ .

A typical scenario in Figure 10 is used to examine the feasibility and effectiveness of the proposed scheme. In the simulation scenario, there is one LTE eNB, which is a small

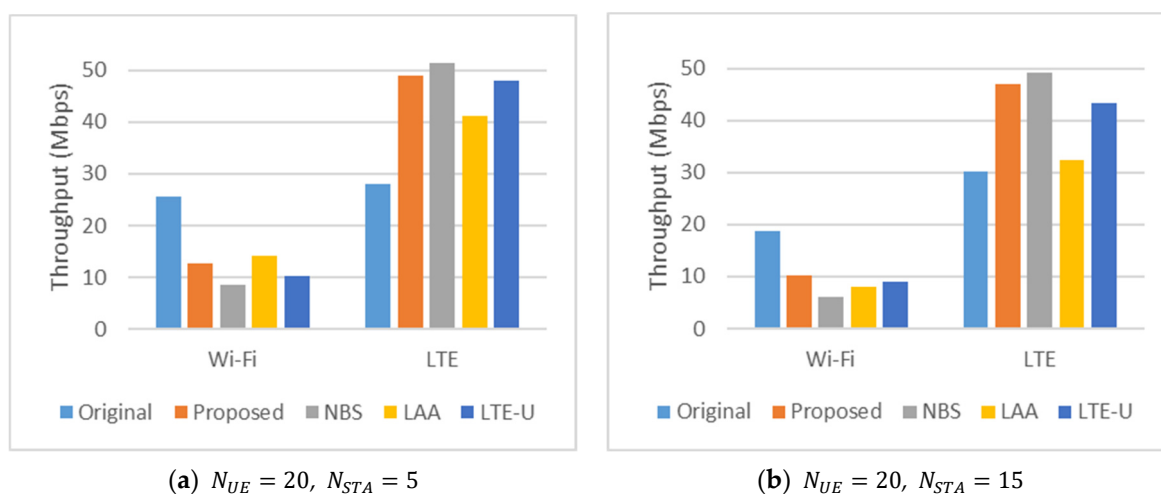
base station. Moreover, multiple Wi-Fi APs are deployed, and we suppose there is a HAP located between each AP and eNB serving as a bridge. We compare our approach with other well-known schemes. The overall throughput will be compared under different loading situations. To be more realistic, we change the number of LTE users and Wi-Fi stations in different experiments to observe the performance variation in typical environments. We compare the proposed scheme with other coexistence mechanisms, including the original scheme without a coexistence mechanism (denoted as original), NBS (Nash bargaining solution) [16], LAA (Licensed Assisted Access) [24,25], and LTE-U (LTE-Unlicensed) [2,5,6]. Overall throughput is the primary performance index for the comparative study.



**Figure 10.** Simulation scenario.

Figure 11 shows the throughput of Wi-Fi and LTE using different mechanisms in a lightly loaded environment. Because of the low load environment, the throughput of the original scheme between Wi-Fi and LTE is much closer in the absence of a coexistence mechanism. When the coexistence mechanism is adopted, the throughput of Wi-Fi degrades because some resources of the unlicensed band are allocated to LTE users. On the other hand, LTE can utilize the license-free band to improve throughput. Therefore, the throughput of LTE increases significantly. Our proposed scheme is based on the utilization function to adjust the time ratio for time-division multiplexing between the Wi-Fi and LTE to maximize the overall throughput. However, the LTE performance of NBS is a little better than our proposed scheme since NBS sacrifices Wi-Fi performance. The proposed solution provides a fairer access method for Wi-Fi and LTE. Interestingly, the technology of LAA makes Wi-Fi and LTE have the same priority to access the unlicensed band. Compared with the proposed scheme, it can give more access opportunities to Wi-Fi stations in a lightly loaded situation. As a result, the throughput of Wi-Fi is better than those of other schemes. Due to the LBT mechanism, LTE users with LAA will compete with Wi-Fi stations to access the unlicensed band, which wastes bandwidth resources. Therefore, the throughput of LTE decreases dramatically. On the other end, instead of using the LBT mechanism to prevent LTE from interfering with Wi-Fi stations, NBS and our proposed scheme integrated the HAP to coordinate LTE users and Wi-Fi stations to access the unlicensed band. Doing so can avoid interference between LTE and Wi-Fi. Differently, LTE-U is based on the CSAT scheme, which can calculate a suitable duty cycle according to channel status. But without HAP to coordinate LTE users and Wi-Fi stations, Wi-Fi stations cannot know when LTE users will utilize the unlicensed band. Therefore, it will increase the collision rate in the

unlicensed band, decreasing the throughput of Wi-Fi. We have a similar observation when Wi-Fi is heavily loaded.



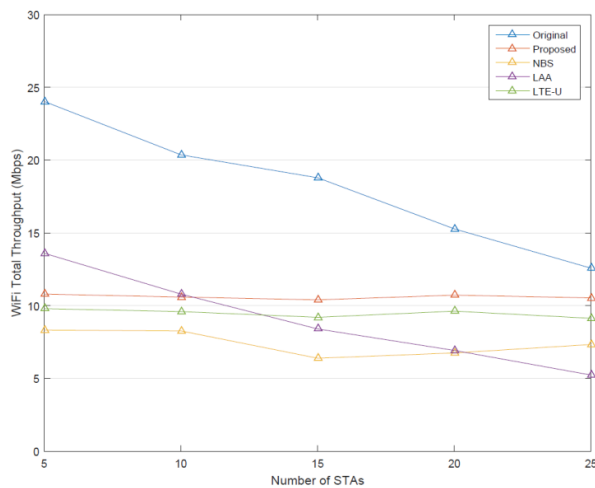
**Figure 11.** The throughput of Wi-Fi and LTE.

Table 2 presents the same experiment results from a different perspective. It is evident that the proposed scheme possesses the highest total throughput compared with other approaches, as intended. Notice that NBS has a secondary total throughput close to the proposed approach. However, NBS's fairness is inferior to the proposed scheme, as we shall see in later experiments.

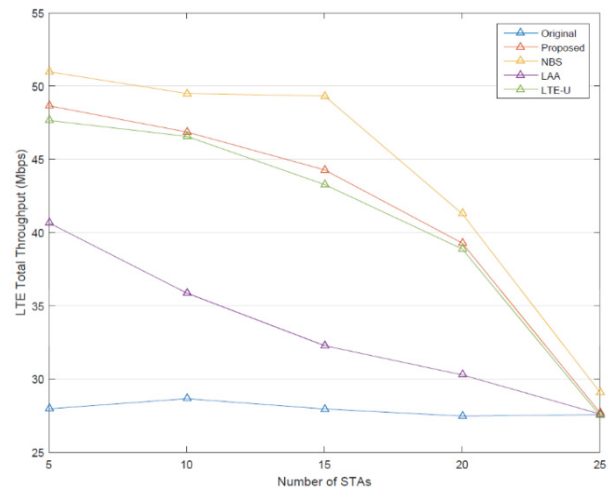
**Table 2.** Total throughput (Mbps).

	$N_{UE} = 20, N_{STA} = 5$			$N_{UE} = 20, N_{STA} = 15$		
	Wi-Fi	LTE	Total	Wi-Fi	LTE	Total
Original	25.7	28.1	53.8	18.8	30.1	48.8
Proposed	12.7	49.0	61.7	10.1	47.1	57.2
NBS	8.6	51.4	60.0	6.1	49.1	55.2
LAA	14.1	41.1	55.2	8.1	32.4	40.5
LTE-U	10.3	48.0	58.3	9.0	43.4	52.3

To understand the effect of the number of Wi-Fi stations on the overall throughput, the number of STAs gradually increased without changing the number of LTE users. Figure 12a shows the change in the overall Wi-Fi throughput. Under the original mechanism without a coexistence mechanism, the throughput dropped rapidly with the increase in STAs. Because LAA utilizes the pure contention-based mechanism named LBT, the Wi-Fi throughput also dropped significantly due to the increment of the number of STAs. LTE-U adopts the CSAT mechanism to coexist with Wi-Fi, which can detect and analyze the number of neighboring base stations, including LTE-U base stations and Wi-Fi APs. Based on the observation, the access time will be divided into several adaptive duty cycles in which LTE users and Wi-Fi stations operate in a time-division manner such that the neighboring base stations can equally share resources. Therefore, the increase of STAs does not significantly impact the overall Wi-Fi throughput. Like LTE-U, the proposed method also finds an adequate  $\delta$  value to dynamically adjust the resources that Wi-Fi can obtain. The adjustment of  $\delta$  is closer to the optimal resource allocation, so it performs better than LTE-U. The NBS algorithm also calculates the period that LTE users can use the unlicensed band. The LTE users obtain more resources according to the time ratio calculated by NBS, so the Wi-Fi system's throughput performance is slightly worse.



(a) Total throughput of Wi-Fi

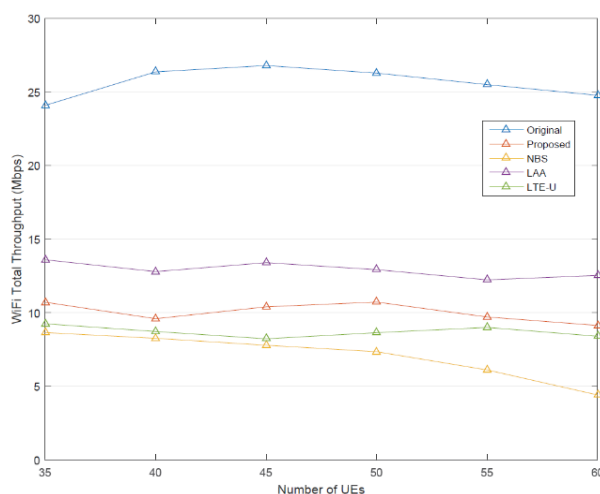


(b) Total throughput of LTE

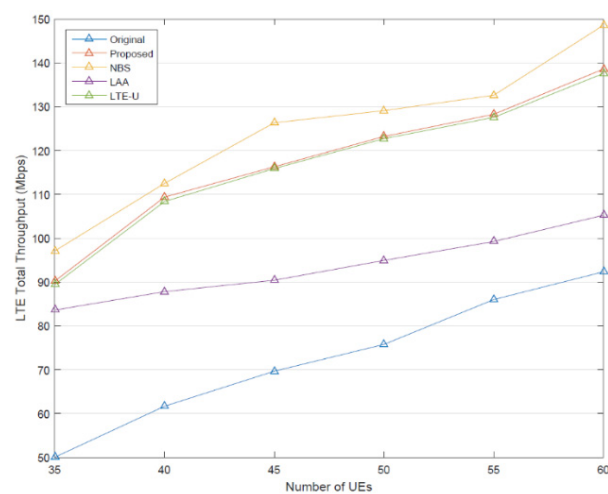
**Figure 12.** Total throughput under a different number of stations with 20 LTE users.

We also examine the performance of each scheme with heavily loaded LTE in Figure 12b. The number of LTE users is set to 50. When the LTE load is greater than the threshold  $Load_{LTE\_th}$ , the Wi-Fi thresholds,  $P_{th}$  and  $Throughput_{th}^{Wi-Fi}$ , will be adjusted according to (5) and (6). As the load of LTE increases, the thresholds decrease to relax the conditions for LTE to use unlicensed bands. However, when the load of Wi-Fi is also very high, the Wi-Fi thresholds need to be adjusted back to normal values to protect Wi-Fi. We have results that resemble the patterns in Figure 11.

In the next experiment, the Wi-Fi load is maintained at a low level, and the LTE load varies from low to high. As can be seen from Figure 13, since the mechanism proposed in this paper focuses on fairness, it will maximize the overall throughput while meeting the minimum Wi-Fi and LTE QoS requirements. Therefore, the decline in Wi-Fi throughput will be lower than that in NBS. The throughput will decline as the number of LTE users increases until the LTE load exceeds the threshold. In this scenario, the Wi-Fi load is very low, and the number of STAs is only 5. LTE users will benefit from accessing the unlicensed band. The proposed scheme will dynamically adjust the time ratio  $\delta$  when the LTE load exceeds the threshold to maximize the overall throughput. Therefore, the period for LTE to access the unlicensed band will increase, as well as the LTE throughput.



(a) Total throughput of Wi-Fi



(b) Total throughput of LTE

**Figure 13.** Total throughput under a different number of LTE users with 5 Wi-Fi stations.

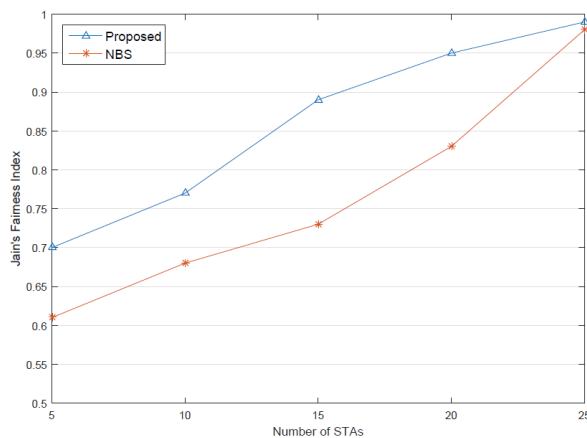
Next, we would like to assess how friendly the coexistence mechanisms are to Wi-Fi. The fairness indices for different schemes are examined [26]. Jain's fairness index [27,28] is employed for the evaluation. The fairness index equation is given in (14).

$$F = \frac{(\sum_{i=1}^n x_i)^2}{n \times \sum_{i=1}^n x_i^2} \quad (14)$$

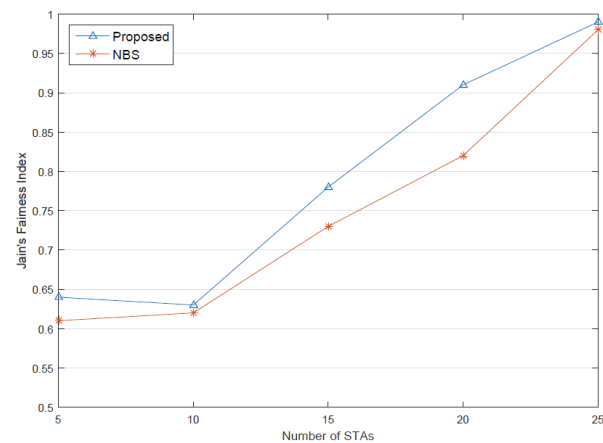
$$x_i = \frac{\text{Throughput}_i}{\text{Throughput}_i^{\text{opt}}} \quad (15)$$

where  $x_i$  represents the throughput proportion of entity  $i$ , which can be expressed as the user throughput divided by the optimal user throughput in the network and  $n$  is the number of LTE users and Wi-Fi stations. For Jain's fairness index, the value of this fairness index is between 0 and 1, and the larger the value is, the fairer it is.

There are 20 LTE users in this simulation, and the number of Wi-Fi stations increases from 5 to 25. The result is shown in Figure 14a. As shown in the figure, as the number of users increases, both our proposed scheme and NBS can improve the fairness index. When the number of Wi-Fi stations is small, Wi-Fi is in a light load condition. Wi-Fi stations do not need too many resources. Therefore, the thresholds of Wi-Fi remained at a relatively low level. LTE can then allocate more resources to the unlicensed band. It can significantly improve the throughput. When the Wi-Fi is lightly loaded, the difference in throughput between LTE and Wi-Fi will be significant, resulting in relatively poor fairness. As the number of Wi-Fi stations increases, Wi-Fi will ask for more resources in the unlicensed bands. The Wi-Fi throughput and the fairness index of both schemes will also improve. Our proposed scheme pays more attention to the issue of fairness. Hence, the fairness index is higher than that of NBS.



(a) 20 LTE users



(b) 50 LTE users

**Figure 14.** Jain's Fairness Index under a different number of stations with 20 LTE users.

Figure 14b shows the change in the fairness index when the LTE is heavily loaded. There are 50 LTE users, and the number of Wi-Fi stations increased from 5 to 25. When the Wi-Fi load is light, and the LTE load is heavy, LTE will get more resources and result in a lower fairness index to maximize the overall throughput. Figure 14b shows that if the number of Wi-Fi stations is 10, the fairness index is dropped slightly in our proposed scheme compared to when the number of Wi-Fi stations is 5. The reason is that the Wi-Fi load is still not too heavy to adjust the time ratio  $\delta$  to give Wi-Fi more resources. Therefore, LTE obtains more resources to maximize the overall throughput and causes a lower fairness value in this situation. As the Wi-Fi load increases, Wi-Fi stations can have more sharing of the resources according to both schemes' adjustments. The fairness index is improved. The improvement of our proposed schemes is better than that of NBS, as shown in the figure.

## 6. Conclusions

Due to the difference in radio access technologies, the introduction of LTE to the unlicensed band often degrades Wi-Fi performance. Moreover, the lack of communication between LTE and Wi-Fi systems is even more detrimental to the two systems' coexistence. Therefore, this study uses HAP as a relay point between LTE and Wi-Fi. Integrating the two interfaces can communicate with these two different systems. Wi-Fi can be informed when LTE wants to use the unlicensed band. Transmission abortion due to interference can be avoided. In the proposed scheme, we formalize the utility function for the overall throughput and propose an algorithm to adjust the time ratio  $\delta$  of the contention period (CP) and the contention-free period (CFP) in a repetition interval such that the maximization of overall throughput can be achieved.

We simulated several scenarios to examine the proposed scheme's performance and compare it with other methods. The simulation results show that the proposed scheme outperforms others in overall throughput. When the Wi-Fi load is low, the LTE throughput can be significantly improved by utilizing the unlicensed band. Another critical issue is how friendly the coexistence mechanism is to Wi-Fi. Most previous schemes can enhance the performance of LTE while sacrificing the performance of Wi-Fi in the unlicensed band. The proposed scheme has considered the fairness issue in the coexistence of Wi-Fi and LTE. Therefore, in the last two simulations, the results show that the proposed scheme's fairness index is better than NBS by adjusting the accessing periods of Wi-Fi and LTE. We show that the proposed scheme can improve the LTE throughput and consider the fairness of the resource allocation in the unlicensed band in the coexistence of Wi-Fi and LTE.

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## Appendix A

$P(i \text{ col})$  is the probability of  $i$  collision. After the  $i$ -th collision, Wi-Fi stations can transmit the packets successfully at the  $(i + 1)$ -th retransmission. Therefore,  $P(i \text{ col})$  can be expressed as the probability of  $i$  collision multiplied by the probability of no collision. That is, it is the probability of the successful transmission.

$$P(i \text{ col}) = \left(1 - (1 - \tau)^{N_{STA}-1}\right)^i (1 - \tau)^{N_{STA}-1} \quad (\text{A1})$$

where  $\tau$  is the probability of a Wi-Fi station transmitting packets. It can be obtained using the Markov chain [29].

$P(j \text{ slots} | i \text{ col})$  represents the probability that the sum-up numbers of back-off slots are equal to  $j$  when there are  $i$  collisions [22].

$$P(j \text{ slots} | i \text{ col}) = P\left(\sum_{k=0}^i \text{unif}(0, CW_k - 1) = j\right) \quad (\text{A2})$$

where  $\text{unif}(0, CW_k - 1)$  stands for a discrete random variable uniformly distributed in the range  $\{0, 1, \dots, CW_k - 1\}$ , and  $CW_k$  represents the size of the contention window for the  $k$ -th back-off.

$P(d < D \mid i \text{ col}, j \text{ slots})$  is the probability of  $d < D$  with  $i$  collisions and  $j$  back-off slots [11].

$$P(d < D \mid i \text{ col}, j \text{ slots}) = \begin{cases} 0.5 + 0.5 \cdot \operatorname{erf}\left(\frac{D - m_{ij}}{\sqrt{2}\sigma_{ij}}\right), & \frac{D - m_{ij}}{\sigma_{ij}} \geq 0 \\ 0.5 \cdot \operatorname{erfc}\left(\frac{D - m_{ij}}{\sqrt{2}\sigma_{ij}}\right), & \frac{D - m_{ij}}{\sigma_{ij}} < 0 \end{cases} \quad (\text{A3})$$

where  $m_{ij}$  is the sum of the average duration of all slot times in  $d_{ij}$ , as shown below:

$$m_{ij} = jm_n + iT_c + T_s \quad (\text{A4})$$

where  $m_n$  is the average duration within which the Wi-Fi station does not transmit a packet,  $T_c$  is the duration of a collision and  $T_s$  is the duration of a successful transmission.

With the assumption of independence between different slot times, the standard deviation  $\sigma_{ij}$  can be computed according to (A5).

$$\sigma_{ij}^2 = j\delta_n^2 \quad (\text{A5})$$

where  $\sigma_n$  is the standard deviation of the duration within which the Wi-Fi station does not transmit packets.

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