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Performance of 5G and Wi-Fi 6 coexistence: spectrum sharing based on optimized duty cycle

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ABSTRACT

Smart mobile device usage is increasing rapidly; hence, cellular operators face the challenge of spectrum resource shortage. To address this issue, researchers have explored several approaches to achieving a highly efficient utilization of wireless communication network resources. One promising solution lies in the fair coexistence of 5G/Wi-Fi 6 in the unlicensed 5 GHz band. This research investigates a duty cycle mechanism to perform fair spectrum sharing between these two wireless technologies, intending to optimize performance metrics such as throughput, capacity, bit error rate (BER), and latency. The results of this study demonstrate a significant improvement in system performance when employing the proposed coexistence method compared to using 5G alone in a single cell. Specifically, a 40% increase in throughput and a 14% improvement in capacity are reported. Moreover, for a single cell using Wi-Fi 6 only, the BER was reduced by 19%, and the latency was less than one millisecond. Additionally, the duty cycle mechanism reported here is used to prioritize call services, with the blocking probability for voice-over internet protocol (VoIP) and video stream calls being improved. Furthermore, the adaptive bandwidth reservation reduced the blocking probability of video calls from 21.8% to 0.9% compared to the fixed method; no VoIP calls were blocked.

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1. INTRODUCTION

In the real world, the implementation of wireless communication networks should include considering the excessive cost of using multiple resources for multiple technologies as well as the cost of licensed spectrum utilization. To address this issue, different technologies, such as 5G and Wi-Fi 6, can coexist in the same cell with a specific control mechanism in the unlicensed band. It is necessary to find proper solutions to satisfy the coverage increase of the network by providing an applicable model for different coexisting technologies; this would enhance the performance of the overall network while utilizing the unlicensed spectrum.

Related studies have demonstrated the application of the coexistence conception. Airtime and throughput fairness are essential for managing the heterogeneous coexistence of licensed assisted access (LAA) and Wi-Fi networks in numerous aggregation scenarios such as Bluetooth and Wi-Fi coexisting at 2.4 GHz, 5G/6G, and Wi-Fi 6E coexisting at 6 GHz, and new radio-unlicensed (NR-U) and gigabit Wi-Fi coexisting at 60 GHz. It is crucial to ensure the interference-free coexistence of these technologies for a seamless user experience [1], [2]. For efficient, fair, and harmonious coexistence among unlicensed and current users of frequency bands, several challenges have been discussed [3]. Replacing LAA with NR-U can solve the problem of bandwidth wastage caused by reservation signals and preserve fairness in channel access for both scheduled and random-access systems. However, ensuring fair coexistence between these systems in unlicensed bands is not guaranteed, and novel mechanisms are required to improve the sharing of resources [4]. To manage the coexistence of long-term evolution LAA (LTE-LAA) and Wi-Fi networks in the 5 GHz bandwidth, an innovative approach involving traffic optimization and interference analysis has been proposed [5], [6]. The significance of collaboration among standardization groups in devising coexistence methodologies is emphasized. Furthermore, to resolve the coexistence issue in future spectrum allocations, it is essential to develop methods that effectively address the coexistence problem [7]. It has been found that Wi-Fi does not receive fair airtime when operating LTE-unlicensed (LTE-U) transmissions that use a duty cycle (DC) approach on the same channel [8].

Concerning coexistence performance, researchers have focused on high-performance user throughput only in crowded areas by modifying the coexistence methods [9], [10]. Analytical models are simulated using two different random walk approaches to assess the collision probability faced by Wi-Fi stations and their consequent throughput performance [11]. A scenario of establishing a typical indoor field trial in the 5.8 GHz unlicensed band has been proposed to improve the performance of LTE-U and Wi-Fi, including coverage and capacity, and to ensure fair coexistence with Wi-Fi systems [12], [13]. A detailed analysis was performed with the aid of the discrete event simulator NS-3 on the coexistence between LTE and Wi-Fi networks over the 5 GHz unlicensed spectrum band [14]. The performance of DC and listen before talk (LBT) mechanisms in achieving an efficient and fair coexistence in unlicensed channels is evaluated. The studies [15], [16] focus on determining the maximum total throughputs under throughput fairness and 3GPP fairness with the DC mechanism adopted and explicit expressions obtained. Comparing the optimal throughput performance of DC and LBT mechanisms indicate that the transmission opportunity value plays a crucial role in the evaluation. One coexistence model between LTE and Wi-Fi has been proposed that have one cell divided into two virtual zones: LTE is the primary zone with a licensed spectrum to manage all the data connections, while Wi-Fi is the secondary zone with an unlicensed spectrum to handle user data [17]. The coexistence concept of wireless systems for spectrum sharing fixed satellite services (FSS) and 5G coexistence above 3.6 GHz has faced multiple challenges. However, the proposed techniques were able to make the 5G system operable [18]. A new approach was proposed to designing multiple access (MA) strategies for coexistence between enhanced mobile broadband (eMBB+) and massive machine type communication (mMTC+) data services in a terminal-centric, cell-free massive MIMO (CF-mMIMO) network. The proposed time-frequency spreading technique for mMTC+ devices and QoS-based power control mechanisms aims to efficiently multiplex the two types of traffic within the same time-frequency resource grid, with simulations demonstrating the effectiveness of the proposed scheme [19]. The indoor coexistence scenario proposed by 3GPP is illustrated, and more challenges are observed [20]. LTE and Wi-Fi can coexist in an unlicensed spectrum with applications of the smart grid; however, Wi-Fi performance was found to be degraded [21]. The call admission control in cellular networks and LTE networks is used to maximize resource utilization [22], [23].

Most of these previous works use the duty cycle approach to improve cell performance and achieve fair coexistence of LTE-U and Wi-Fi. They assume a dedicated value or range for the duty cycle of each network, for example $\tau = 0.2 \text{ or } 0.5 \text{ or } 0.9$ as mentioned in [9], [14], [20]. However, the effect of this approach has been studied only on throughput and latency as performance metrics; the studies do not deal with the impact of coexistence performance on distinct types of services.

Our paper discusses an approach to allowing spectrum sharing between 5G and Wi-Fi 6 in the unlicensed 5 GHz band. The duty cycle mechanism is considered with the fair coexistence of 5G and Wi-Fi 6. We calculate the optimum value of the duty cycle period which maximizes the overall cell's throughput, focusing on determining the impact of duty cycle schemes on Wi-Fi 6 performance in coexistence scenarios where Wi-Fi 6 networks may cause performance degradations, and we study the various performance parameters that reflect the effect of coexistence. The performance metrics discussed here: throughput, latency, bit error rate (BER), and capacity are evaluated for the whole cell. After that, we determine which services will be available according to bandwidth; either a voice-over internet protocol (VoIP) call or a video call will be admitted depending on two call admission control algorithms: fixed and adaptive bandwidth reservation. We found that the blocking probability was improved for the coexisting model in the case of adaptive bandwidth reservation over the fixed method. This study was carried out due to the high demand for mobile phones in today’s world. In addition to the increase of internet of things (IoT) devices, mobile data traffic has increased significantly in the past few years, with a 33% increase in mobile network data traffic in Q3 2023 (143 EB per month) compared to Q3 2022 [24].

This study is organized as follows: the method is presented in section 2, which is divided into three subsections: section 2.1 presents the description of the system model, subsection 2.2 the system analysis, and subsection 2.3 the coexistence services. Section 3 presents the results and discussions of performance metrics and the coexisting impact on services. Section 4 presents the conclusion and future work.

2. METHOD

2.1. System model

The proposed system is designed to evaluate the coexistence of spectrum sharing between two different networks: 5G and Wi-Fi 6. The model divides the environment into two zones [17]: the inner zone for Wi-Fi 6 and the outer zone for 5G as illustrated in Figure 1. It is essential to highlight that the total bandwidth of the cell is evenly divided between these two zones, reflecting where users exist:

a. The inner zone (Zone 1), defined as a Wi-Fi 6 zone, encompasses high-traffic areas like homes, businesses, and regions near the base station, using 256-QAM.
b. The outer zone (Zone 2) is a 5G zone with lower traffic density (like macro areas) utilizing 64-QAM. The total cell bandwidth is fully utilized, with a division between Wi-Fi 6 and 5G zones.

As the inner zone is closer to the BS and has higher traffic, it utilizes the outer zone bandwidth twice.

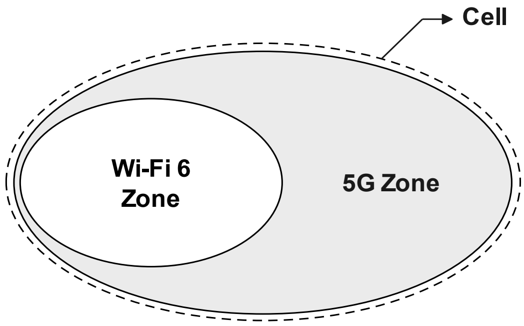


Figure 1. The system model has two zones: the inner zone for Wi-Fi 6 and the outer zone for 5G NR

We assume that in a setup where Wi-Fi 6, a singular 5G base station (BS), and linked 5G user equipment (UE) are in operation, a channel shares the 5 GHz unlicensed spectrum band. To support orthogonal frequency division multiplexing (OFDM)-based downlink communication, the 5G BS allows the channel bandwidth to be shared by several orthogonal sub-carriers (SC), each with bandwidth B. At the same time, Wi-Fi 6 occupies transmissions based on the IEEE protocol 802.11ax. To prevent interference and ensure satisfactory system performance, a proposed time-sharing protocol allows the Wi-Fi 6 to be allocated at fraction τ, where τ spans between 0 and 1.

Significantly, the BS's adoption of OFDM mitigates intra-user interference, ensuring non-conflicting transmissions among users in the 5G network. The duty cycling technique is implemented to manage the coexistence of Wi-Fi 6 and 5G networks. This may allow optimal performance and quality of service for users.

The duty-cycle mechanism defines the ON and OFF behavior, as shown in Figure 2, which involves alternating between ON and OFF periods. During the ON period, the 5G network is permitted to transmit, while the Wi-Fi 6 network is restricted. Alternatively, during the OFF period, the Wi-Fi 6 network is allowed to transmit, while the 5G network is prohibited. This mechanism helps achieving fair coexistence between the two networks in the unlicensed band.

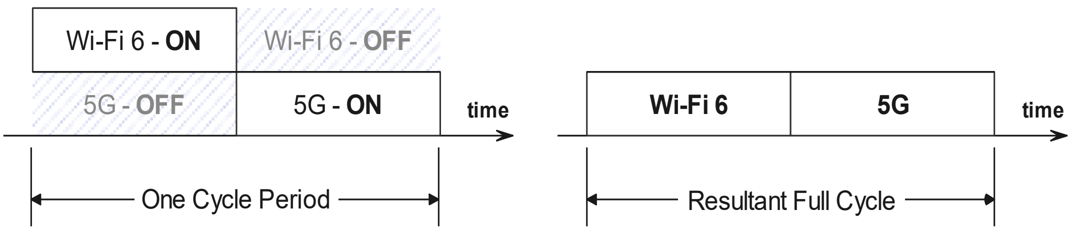


Figure 2. Duty-cycle mechanism

2.2. System analysis

Given the design of the coexistence network, only a single base station (SBS) is active over the entire channel at any specific time slice, with the presumption of uniform transmission time among all users. When SBS allocates unlicensed subcarrier(s) to a user i, the instantaneous throughput of the 5G user is expressed as (1),

$$R_i = B\sum_{j=1}^{N} x_{i,j} \log_2\left(1 + \frac{P_j|h_{i,j}|^2}{N_0 B}\right) \quad (1)$$

where P_j denotes the power allocated to subcarriers; $h_{i,j}$ denotes channel gain; $x_{i,j}$ denotes the subcarrier j allocated to the user i; N_0 denotes the noise spectral density; B defines channel bandwidth; and $\frac{P_j|h_{i,j}|^2}{N_0 B}$ denotes signal-to-noise ratio (SNR) , as described in Table 1. The throughput of 5G UE may be expressed as (2),

$$S_i = (1-\tau)R_i \quad (2)$$

The term $(1-\tau)$ is considered the period for 5G transmission. Each Wi-Fi 6 user's average throughput will be represented as (3),

$$S_w = \frac{\tau}{W} R_{w6} \quad (3)$$

Here, W is the number of Wi-Fi 6 users, τ is the period for Wi-Fi 6 transmission, and R_{w6} is Wi-Fi 6 throughput with discrete time Markov chain analysis [25]. The Wi-Fi 6 throughput is given by (4),

$$R_{w6} = \frac{E[L]\, P_S\, P_{tr}}{(1-P_{tr})T_i + P_S\, P_{tr}\, T_S + P_{tr}(1-P_S)T_C} \quad (4)$$

where P_{tr} is the probability that at least one user is transmitting in a timeslot, and P_s represents the probability that a transmission on the channel is successful in a timeslot. $E[L]$ is the average frame payload size; T_c is the collision time; and T_s denotes the successful transmission time. T_i is the time when the timeslot is empty.

Table 1. Simulation parameters

Parameter	Value/range
5G NR Bandwidth (BW)	80 Mbps
Wi-Fi 6 Bandwidth (BW)	160 Mbps
Unlicensed spectrum	5: 5.85 GHz "midband"
Bitrate range	1 Mbps: 1 Gbps
Carrier frequency (FC)	5 GHz
User count	420 users
VoIP minimum bandwidth	96 Kbps
Video minimum bandwidth	480 Kbps
SNR range	-30 dB: 30 dB
Noise spectral density (N0)	-174 dBm
No. of transmitting antennas (N_T)	4 antennas
No. of receiving antennas (N_R)	4 antennas
Fading type	Rayleigh fading channel
Transmission rate (T_R)	1 Mbps: 100 Mbps
Number of bits (N_B)	1 kB
Propagation delay (D_{PR})	1ms
Energy per bit-to-noise power (γ)	0: 30 dB
Modulation order (5G)	64
Modulation order (Wi-Fi 6)	256

2.2.1. Optimization framework

We address the optimization problem of calculating the optimum duty-cycle period that maximizes throughput for the coexistence of 5G and Wi-Fi 6 networks. This involves determining a duty cycle period that balances the transmission opportunities between the two technologies to minimize interference and maximize overall network performance. The main considerations of the optimization problem include:

- Throughput maximization: Making sure that the duty cycle duration is optimized to maximize the overall data throughput of both 5G and Wi-Fi 6 networks.
- Network coexistence: Encouraging coexistence techniques that let both networks function well in frequency bands they share.
- Interference management: Improving the quality of service for both Wi-Fi 6 and 5G networks by minimizing mutual interference between them.

The core objective revolves around formulating an optimization structure to enhance the collective throughput of 5G UEs and Wi-Fi 6 users. The proposed optimization may be explained as (5):

$$\max U(\tau, x_{i,j}) = \sum_{i=1}^{U} \log(S_i) + \sum_{w=1}^{W} \log(S_w) \tag{5}$$

with the following constraints:

$$\text{C1:} \quad x_{i,j} \in \{0,1\}, \forall i, \forall j \tag{5a}$$

$$\text{C2:} \quad \sum_{i=1}^{U} x_{i,j} \leq 1, \forall j \tag{5b}$$

$$\text{C3:} \quad \sum_{i=1}^{U} \sum_{j=1}^{N} x_{i,j} \leq N \tag{5c}$$

$$\text{C4:} \quad \tau_0 \leq \tau \leq 1 \tag{5d}$$

The first constraint (power constraint): $x_{i,j}$ is the subcarrier allocation result, and $x_{i,j} = 1$ if subcarrier j is allocated to the user i, $x_{i,j} = 0$ otherwise. The second constraint is known as the lower bound. The third constraint is known as the upper bound. The fourth constraint (duty cycle constraint) is the period for each network to be (ON) range from 0:1, where one cycle period=1 guarantees fairness among 5G and Wi-Fi 6 systems. By substituting (2) and (3) in (5), then:

$$\max U(\tau, x_{i,j}) = U \log(1-\tau) + \sum_{i=1}^{U} R_i + w \log(\tau) + w(\log(R_w) - \log(w)) \tag{6}$$

The optimization problem can be solved by taking the first derivative of (6) and making it equal to zero. Using MATLAB, this optimization problem can be solved to evaluate the optimum value of τ, which maximizes throughput. Then, various performance metrics may be considered to assess the system's performance.

2.3. Performance metrics

2.3.1. Throughput

Throughput measures the rate of successful data transmission from a source to a destination over a network. In environments where 5G and Wi-Fi 6 coexist, achieving high throughput is essential for ensuring the smooth performance of bandwidth-intensive applications such as video streaming and large file transfers. Throughput is directly affected by factors such as the modulation schemes employed, and available bandwidth. For example, both 5G and Wi-Fi 6 utilize advanced modulation techniques like 256-QAM and 64-QAM, enabling higher data rates but requiring a good SNR to maintain high throughput. Equations (1) and (4) calculate the throughput for 5G and Wi-Fi 6 respectively. The sum of (2) and (3) gives the throughput of the overall cell.

$$S_{Cell} = (1-\tau)R_i + \frac{\tau}{W} R_{w6} \tag{7}$$

2.3.2. Latency

Latency, which is the delay before data transfer begins after receiving instruction, is a crucial element in determining user experience quality, particularly in real-time applications such as online gaming, and video streaming. Maintaining low latency is essential in the context of 5G and Wi-Fi 6, which are designed to support ultra-low latency communications. Overall latency is influenced by several factors, including propagation delay (time for a signal to travel through the medium), processing delay (time required for network devices to process packets), and queueing delay (time spent waiting in queues for transmission). For instance, applications that are sensitive to latency, such as VoIP or real-time video streaming, need to be given priority over other types of data to ensure quality of service (QoS):

$$NL = D_T + D_{PR} + D_Q + D_P \quad (8)$$

$D_T = \frac{N_B}{T_R}$, $D_{PR} = \frac{D}{S}$, D_T denotes the transmission delay; N_B is the number of bits to be transferred; T_R is the transmission rate; D_{PR} is the propagation delay; D is the bits' travel distance; S is the speed of packets; D_Q is the queuing delay; and D_P is the processing delay.

2.3.3. Bit error rate

The maintenance of a low BER is essential for ensuring the accuracy of data transmission in wireless communication, particularly in applications that require high reliability, such as financial transactions or medical data transmission. The coexistence of 5G and Wi-Fi 6 can make maintaining a low BER more challenging due to potential interference between the two networks. Several factors affect BER, including the modulation scheme, SNR, and environmental conditions. Highly advanced modulation schemes, like those used in 5G and Wi-Fi 6, allow for higher data rates but are more susceptible to errors in the presence of noise or interference:

$$P_e = \frac{M-1}{M\log_2 M}\left(1 - \sqrt{\frac{3\gamma \log_2 M/(M^2-1)}{\frac{3\gamma \log_2 M}{M^2-1}+1}}\right) \quad (9)$$

where M denotes modulation order; γ equals E_b/N_0; and E_b is the bit energy.

2.3.4. Capacity

The maximum achievable data rate that a network can support under ideal conditions is known as capacity, often defined by the Shannon-Hartley theorem. In an environment where 5G and Wi-Fi 6 coexist, capacity is a critical measure as it determines the efficient usage of the available spectrum to serve the network's users. Higher capacity means that more users can be supported simultaneously, and higher data rates can be achieved, which is particularly important in high-density areas such as stadiums or urban areas. Several factors influence the capacity of a network, including available bandwidth, SNR, and the efficiency of the modulation schemes used. Both 5G and Wi-Fi 6 aim to maximize capacity through advanced technologies such as massive multiple input multiple output (MIMO) in 5G and multi-user MIMO (MU-MIMO) in Wi-Fi 6:

$$C = E\left\{\begin{matrix} max \\ T_r(\mathrm{R}_{xx}) = N_T \end{matrix} \log_2 det\left(\mathrm{I}_{N_R} + \frac{SNR}{N_T}\mathrm{H}\mathrm{R}_{xx}\mathrm{H}^H\right)\right\} \quad (10)$$

where T_r is the transmission power for each transmit antenna, N_T is the number of transmitting antennas, I_{N_R} is an $N_R \times N_R$ identity matrix, N_R is the number of receiving antennas, R_{xx} is the autocorrelation of the transmitted signal vector, H^H is the correlated channel, and H is a random matrix whose channel capacity is time-varied randomly. Then, the effect of the channel can be expressed by a channel matrix H, which can be given as,

$$\mathrm{H} = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N-1,0} & a_{N-1,1} & \cdots & a_{N-1,N-1} \end{bmatrix} \quad (11)$$

where

$$a_{k,m} = H_0[k-m] + H_1[k-m]e^{-\frac{j2\pi m}{N}} + \cdots + H_{L-1}[k-m]e^{-\frac{j2\pi m(L-1)}{N}} \quad (12)$$

Note that $m, k = 0,1,\cdots,N-1$.

2.4. Coexistence services

2.4.1. Voice services

Voice services are also called voice-over IP (VoIP). VoIP usually requires low latency and high reliability. The network that offers the best conditions for VoIP can be prioritized based on factors such as signal strength, network load, and interference levels.

2.4.2. Video services

Streaming video services need high bandwidth and low packet loss to ensure smooth viewing. Experience can guide the selection of the network that provides the necessary bandwidth and reliability for streaming video based on factors such as network congestion and available resources. Minimum values of the bandwidth are considered for two types of services: VoIP calls and video calls. The minimum required bandwidth for a voice call would be 96 kbps, and the minimum bandwidth needed for a video call would be 480 kbps. In the following section, two bandwidth reservation methods – fixed bandwidth and adaptive bandwidth – are considered through simulation to compare their effects on the network.

a. Fixed bandwidth reservation

Figure 3 illustrates the fixed bandwidth reservation method. In the case of a voice call, the call will be admitted if the following condition is satisfied: The minimum VoIP call BW added to accumulated VoIP calls BW is less than the difference between the fixed threshold and the maximum bandwidth in the available range. Otherwise, the new call will be rejected, as there is not sufficient BW to accept it. Once the new VoIP call is admitted, the accumulated VoIP BW will be increased by the new admitted call BW.

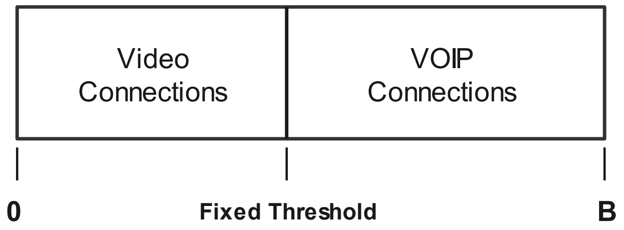


Figure 3. Fixed bandwidth reservation for VoIP and video calls

Similarly, a new video call will only be admitted if the minimum video call BW added to accumulated video calls BW is less than the fixed threshold value. Otherwise, the new call will be rejected. Then, in the case of admitting the new video call, the accumulated video BW will be increased by the new admitted call BW. The flow chart in Figure 4 simplifies Algorithm's 1 logic of service allocation, using the fixed bandwidth reservation method.

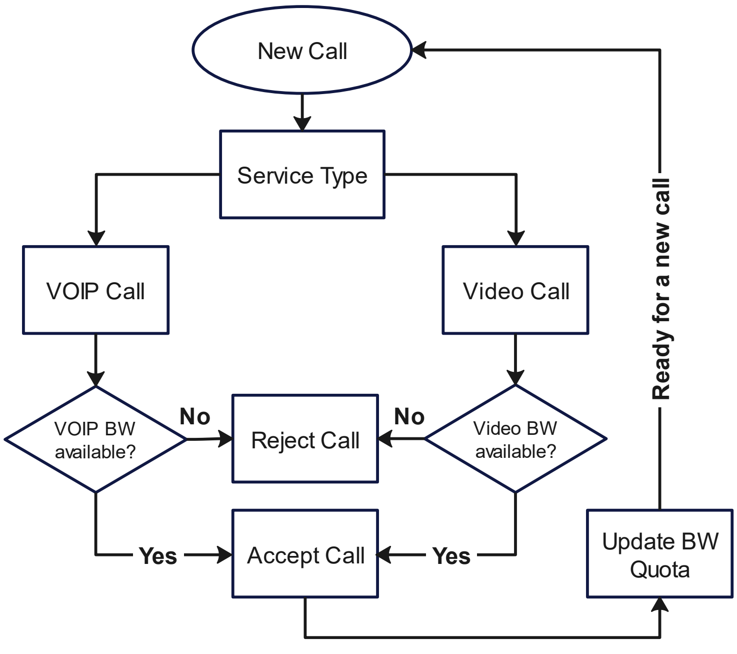


Figure 4. Services flow-chart using the fixed bandwidth reservation

Algorithm 1. Services allocation using fixed bandwidth reservation
```
Determine the optimum timeshare value for Wi-Fi 6=τ
For each new call, check if it is 5G or Wi-Fi 6 Call:
  New 5G call (within the time frame of 1 − τ)
    Is this a 5G VoIP Call?
      If (Allocated 5G VoIP BW + min 5G VoIP BW) < (5G BW - Threshold)
        Accept 5G VoIP Call
        Update Allocated 5G VoIP BW
      Else
        Reject 5G VoIP Call
    Is this a 5G Video Call?
      If (Allocated 5G Video BW + min 5G Video BW) < 5G BW
        Accept 5G Video Call
        Update Allocated 5G Video BW
      Else
        Reject 5G Video Call
  New Wi-Fi 6 call (within the time frame of τ)
    Is this a Wi-Fi 6 VoIP Call?
      If (Allocated Wi-Fi 6 VoIP BW + min. Wi-Fi 6 VoIP BW) < (Wi-Fi 6 BW - Threshold)
        Accept Wi-Fi 6 VoIP Call
        Update Allocated Wi-Fi 6 VoIP BW
      Else
        Reject Wi-Fi 6 VoIP Call
    Is this a Wi-Fi 6 Video Call?
      If (Allocated Wi-Fi 6 Video BW + min Wi-Fi 6 Video BW) < Wi-Fi 6 BW
        Accept Wi-Fi 6 Video Call
        Update Allocated Wi-Fi 6 Video BW
      Else
        Reject Wi-Fi 6 Video Call
Go to the next new call
```

b. Adaptive bandwidth reservation

In the previous section, it was shown that the fixed method of bandwidth reservation provides excellent performance for VoIP calls; however, multiple video calls were blocked. Therefore, we discuss in this section the adaptive bandwidth reservation method that is illustrated in Figure 5, which aims to enhance the blocking probability of incoming calls by focusing on video calls. To consider the adaptive method, minimum and maximum values are proposed for the threshold range. The adaptive threshold value moves along that range and should not exceed the maximum defined limit.

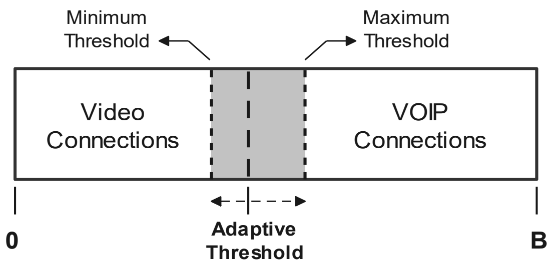


Figure 5. Adaptive bandwidth reservation for VoIP and video calls

In the case of a VoIP call, the call will be admitted if the following condition is satisfied: The minimum VoIP call BW added to accumulated VoIP calls BW is less than the difference between the adaptive threshold and the maximum bandwidth in the available range. Otherwise, the new call will be rejected as there is not sufficient BW to accept it. Once the new VoIP call is admitted, the accumulated VoIP BW will be increased by the new admitted call BW.

Similarly, a new video call will only be admitted if the minimum video call BW added to accumulated video calls BW is less than the adaptive threshold value. Otherwise, the new call will be rejected. Then, in the case of admitting the new video call, the accumulated video BW will be increased by the new admitted call BW. Finally, the algorithm will check the ability to increase the adaptive threshold value to allow more video calls to be accepted without affecting the space allocated to the next possible VoIP call. The flow chart in Figure 6 simplifies the Algorithm's 2 logic of service allocation, using the adaptive bandwidth reservation method.

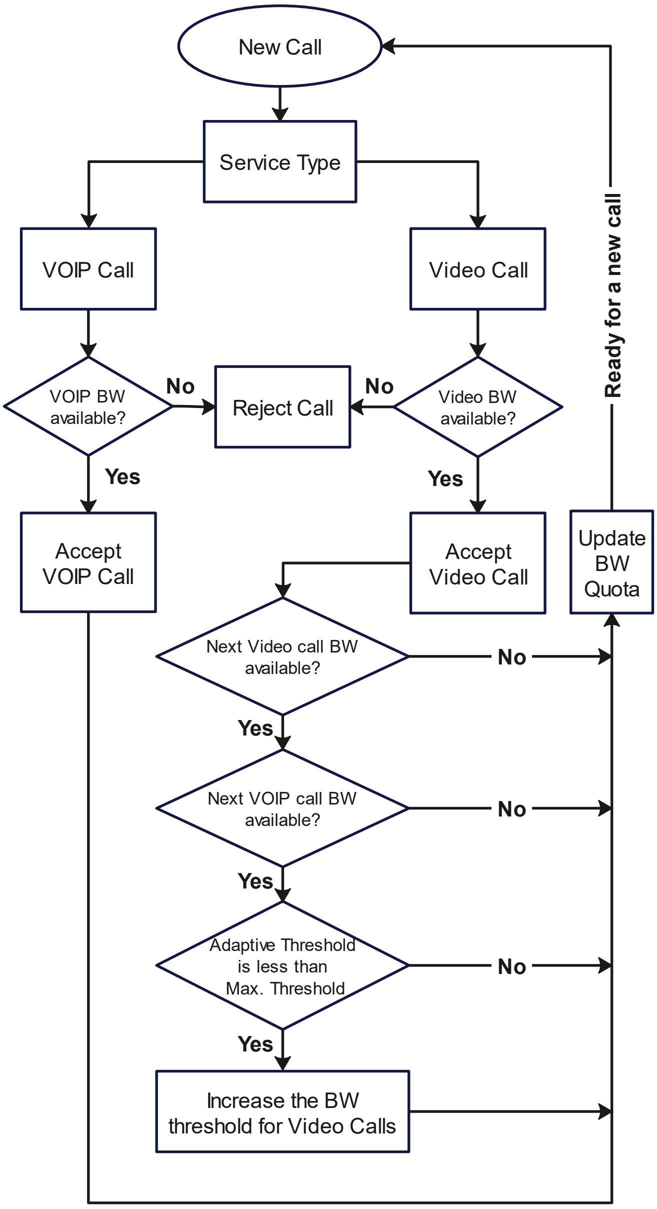


Figure 6. Services flow-chart using adaptive bandwidth reservation

Algorithm 2. Services allocation using adaptive bandwidth reservation

```
Determine the optimum timeshare value for Wi-Fi 6=τ
Define Maximum and Minimum Threshold values
Adaptive Threshold=Mean of Maximum and Minimum Threshold
For each new call, check if it is 5G or Wi-Fi 6 Call:
  New 5G call (within the time frame of 1 − τ)
    Is this a 5G VoIP Call?
      If (Allocated 5G VoIP BW + min 5G VoIP BW) < (5G BW - Threshold)
        Accept 5G VoIP Call
        Update Allocated 5G VoIP BW
      Else
        Reject 5G VoIP Call
    Is this a 5G Video Call?
      If (Allocated 5G Video BW + min 5G Video BW) < 5G BW
        Accept 5G Video Call
        Update Allocated 5G Video BW
          If (Allocated 5G Video BW + min 5G Video BW >= Adaptive Threshold) AND
          (Allocated 5G VoIP BW < Adaptive Threshold - min 5G VoIP BW) AND (Adaptive
          Threshold < Maximum Threshold)
```

```
              Adaptive Threshold += min 5G Video BW
       Else
         Reject 5G Video Call
   New Wi-Fi 6 call (within the time frame of τ)
     Is this a Wi-Fi 6 VoIP Call?
       If (Allocated Wi-Fi 6 VoIP BW + min. Wi-Fi 6 VoIP BW) < (Wi-Fi 6 BW - Threshold)
         Accept Wi-Fi 6 VoIP Call
         Update Allocated Wi-Fi 6 VoIP BW
       Else
         Reject Wi-Fi 6 VoIP Call
     Is this a Wi-Fi 6 Video Call?
       If (Allocated Wi-Fi 6 Video BW + min Wi-Fi 6 Video BW) < Wi-Fi 6 BW
         Accept Wi-Fi 6 Video Call
         Update Allocated Wi-Fi 6 Video BW
           If (Allocated Wi-Fi 6 Video BW + min Wi-Fi 6 Video BW >= Adaptive Threshold)
           AND (Allocated Wi-Fi 6 VoIP BW < Adaptive Threshold - min Wi-Fi 6 VoIP BW) AND
           (Adaptive Threshold < Maximum Threshold)
              Adaptive Threshold += min Wi-Fi 6 Video BW
       Else
         Reject Wi-Fi 6 Video Call
 Go to the next new call
```

2.5. Simulation setup

The simulation was conducted using MATLAB R2022a. Our MATLAB script defines a Wi-Fi 6 and 5G system model then calculates the optimum duty cycle using the nonlinear optimization function called "*fmincon*" and calculates performance metrics that include the following key elements:

a. MIMO configuration: 4×4 multiple input multiple output (MIMO) system was implemented to simulate the spatial diversity and increased data throughput typical of 5G and Wi-Fi 6 coexistence networks.
b. Modulation scheme: 64 QAM was selected as the modulation scheme for the 5G and 256 QAM for Wi-Fi 6 transmitted signal. This choice was made to simplify the performance analysis, although the framework can be extended to other modulation schemes.
c. Channel model: the wireless channel was modeled using a Rayleigh fading channel, which is appropriate for scenarios commonly encountered in indoor environments. The channel was configured with an SNR range from -30 to 30 dB, allowing for analysis across various signal quality conditions.

Figure 7 illustrates a procedure of the simulation sequence. Figure 8 shows a screenshot of the MATLAB simulation environment. Furthermore, Figures 4 to 5 show the flow chart for the MATLAB simulations performed to simulate fixed and adaptive bandwidth reservation methods. Additionally, both algorithms 1 and 2 explain in detail the logic behind the simulation for both methods. MATLAB simulation environment with key parameters is illustrated in Table 1.

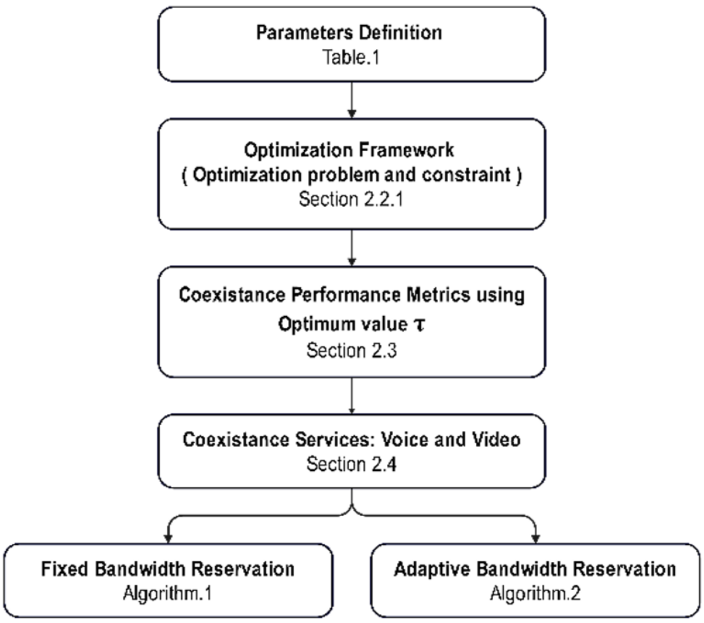
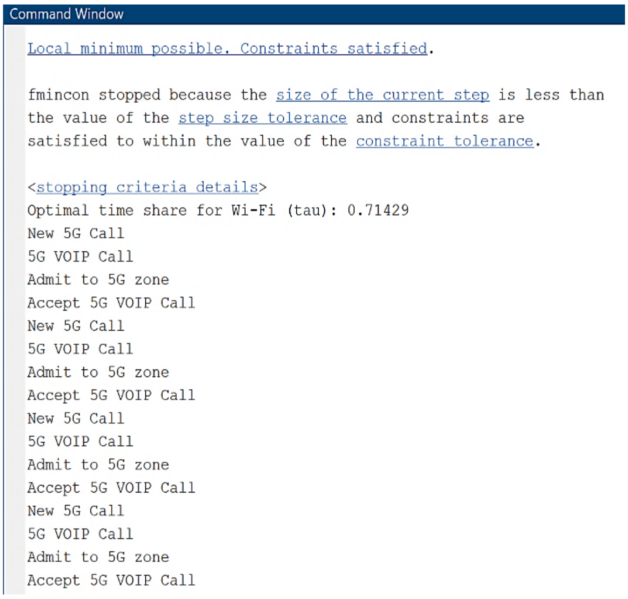


Figure 7. Flow chart of the simulation sequence



```
Command Window
Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than
the value of the step size tolerance and constraints are
satisfied to within the value of the constraint tolerance.

<stopping criteria details>
Optimal time share for Wi-Fi (tau): 0.71429
New 5G Call
5G VOIP Call
Admit to 5G zone
Accept 5G VOIP Call
New 5G Call
5G VOIP Call
Admit to 5G zone
Accept 5G VOIP Call
New 5G Call
5G VOIP Call
Admit to 5G zone
Accept 5G VOIP Call
New 5G Call
5G VOIP Call
Admit to 5G zone
Accept 5G VOIP Call
```

Figure 8. Screenshot of the MATLAB simulation environment

3. RESULTS AND DISCUSSION

In this study, we were able to solve the optimization problem in subsection 2.2.1 using MATLAB simulation. The optimum value for the Wi-Fi 6 duty cycle (τ) was found to be 0.71429. The results are divided into two phases: The first phase discusses performance metrics for each network separately (5G and Wi-Fi 6) along with the effect of the coexistence between 5G and Wi-Fi 6 (cell performance), and the second phase presents the coexistence services and their blocking probability.

3.1. Performance metrics results

A series of MATLAB experiments were conducted to evaluate the effectiveness of the optimum duty cycle on the performance metrics. These experiments have been conducted to study the performance of the duty cycle coexistence model for SNR from -30 dB up to 30 dB. The results in Figures 9 to 12 show the performance for each technology alone, in addition to the effect of coexistence on cell performance.

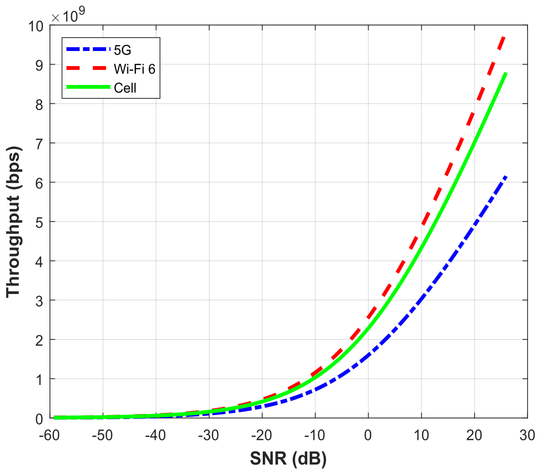


Figure 9. Throughput versus the SNR

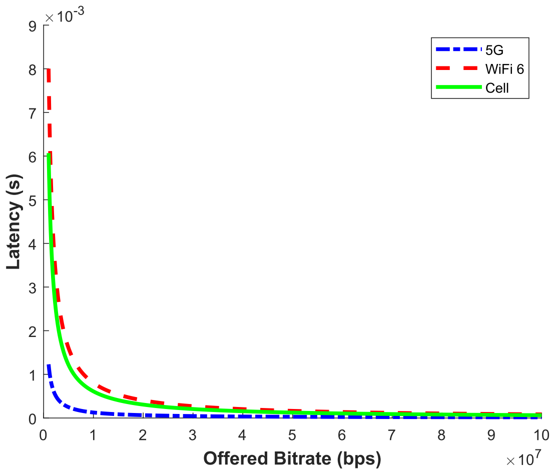


Figure 10. Latency versus the offered bitrate

Figure 9 represents the throughput for each technology and the throughput for the whole cell. It can be seen that Wi-Fi 6 showed better performance than 5G at different SNRs. This is because the inner zone bandwidth is twice the outer zone bandwidth; hence, most of the traffic is admitted successfully by the inner zone. Therefore, cell performance (with coexistence) is better than 5G alone by +42% and is extremely near to (90%) Wi-Fi 6 alone throughput. Table 2 shows sample readings from Figure 9 to determine the performance variations.

Figure 10 shows the cells' and both technologies' latency performance. Cell latency is better than Wi-Fi 6 latency. The best value for 5G is less than 1 msec. Table 3 shows sample readings from Figure 10 to determine the performance variations.

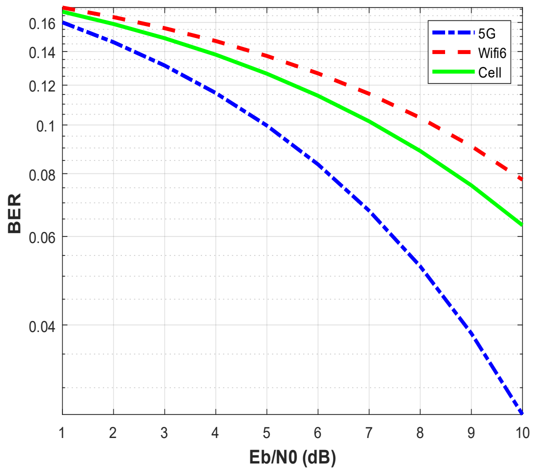


Figure 11. Bit error rate versus the Eb/N0

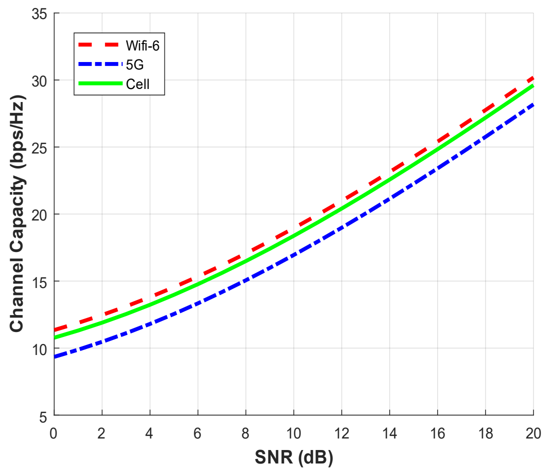


Figure 12. Channel capacity versus the SNR

Table 2. Throughput readings

SNR (dB)	Throughput ($\times 10^2$ Mbps)		
	5G NR	WI-FI 6	Cell
-20	2.929	4.686	4.184
-10	7.230	11.56	10.32
0	16	25.60	22.85
10	30.32	48.51	43.31
20	49.10	78.56	70.14

Table 3. Latency readings

Offered Bitrate (Mbps)	Latency ($\times 10^{-3}$ s)		
	5G NR	WI-FI 6	Cell
2	0.616	4.003	3.035
3	0.412	2.670	2.024
5	0.248	1.603	1.216
10	0.125	0.803	0.609
20	0.064	0.403	0.306

Figure 11 shows the BER performance. The BER values for the whole cell are better than the BER values for Wi-Fi 6 by ~19%. Table 4 shows sample readings from Figure 11 to determine the performance variations. Figure 12 shows the capacity performance. The capacity for the whole cell is better than the capacity for 5G by a range of 5%–14%, but it differs slightly from the Wi-Fi 6 capacity, and cell capacity is about 95%–98% of Wi-Fi 6. Table 5 shows sample readings from Figure 12 to determine the performance variations.

Table 4. BER readings

Eb/N0 (dB)	BER$\times 10^{-2}$		
	5G NR	WI-FI 6	Cell
2	14.61	16.39	15.88
4	11.57	14.69	13.80
6	8.347	12.66	11.43
8	5.231	10.33	8.876
10	2.653	7.780	6.315

Table 5. Channel capacity readings

SNR (dB)	Capacity (bps/Hz)		
	5G NR	WI-FI 6	Cell
2	9.883	11.88	11.31
4	12.55	14.55	13.98
6	16.95	18.95	18.38
8	22.26	24.26	23.69
10	28.18	30.18	29.61

3.2. Coexistence services results

3.2.1. Blocking probability (fixed method)

Figures 13 and 14 illustrate the probability of service being denied to users due to the non-availability of network resources for 5G calls and Wi-Fi 6 calls, respectively. Using MATLAB simulation, according to the flow chart shown in Figure 4 and its explanation in Algorithm 1, with 420 call requests. Table 6 shows the total number of calls admitted and blocked for each service.

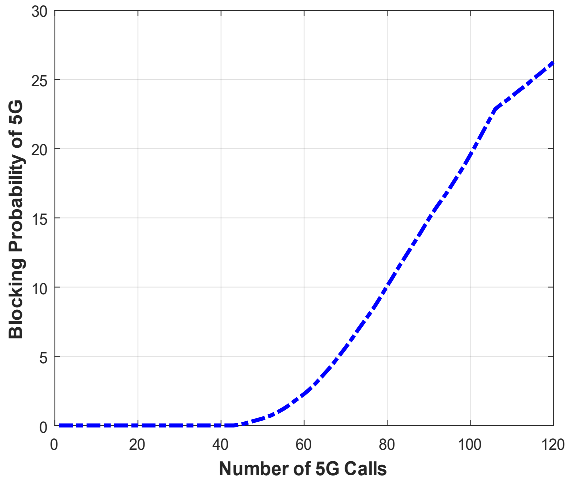


Figure 13. Blocking probability for 5G calls (fixed threshold)

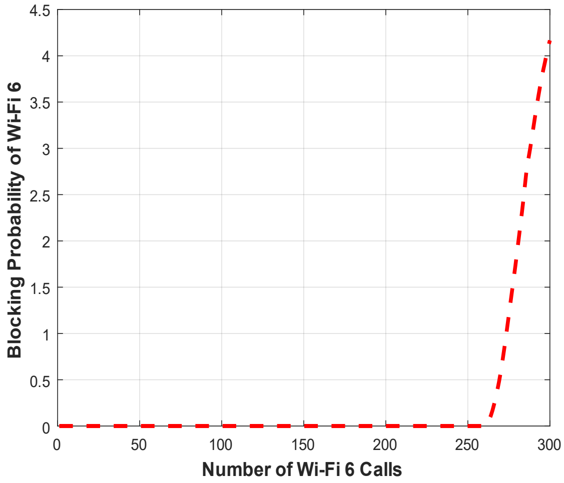


Figure 14. Blocking probability for Wi-Fi 6 calls (fixed threshold)

Table 6. VoIP and video services statistics utilizing the fixed bandwidth reservation method

Network	VoIP Calls			Video Calls		
	Total	Admit	Block	Total	Admit	Block
WI-FI 6	135	135	0	165	150	15
5G NR	51	51	0	69	31	38

3.2.2. Blocking probability (adaptive method)

Figures 15 and 16 illustrate the probability of service being denied to users due to the non-availability of network resources for 5G calls and Wi-Fi 6 calls, respectively. Using MATLAB simulation, according to the flow chart shown in Figure 6 and its explanation in algorithm 2, with 420 call requests. Table 7 shows the total number of calls admitted and blocked for each service.

Here, it can clearly be seen that using an adaptive threshold for bandwidth reservation enhanced the blocking probability, as it was reduced from 12.6% to 0.5%. The blocking probability for video calls was also reduced from 21.8% to 0.9%. In other words, the acceptance of incoming calls improved 25 times when considering adaptive bandwidth reservation compared to the fixed method.

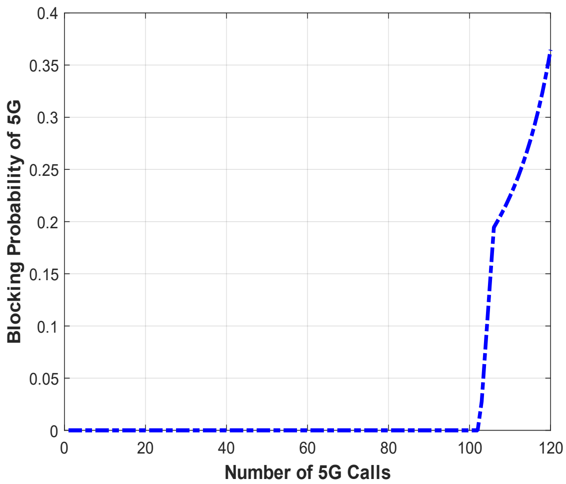


Figure 15. Blocking probability for 5G calls (adaptive threshold)

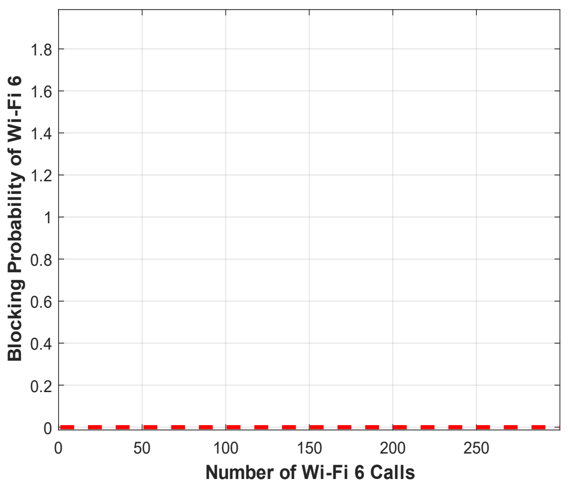


Figure 16. Blocking probability for Wi-Fi 6 calls (adaptive threshold)

Table 7. VoIP and video services statistics utilizing the adaptive bandwidth reservation method

Network	VoIP Calls			Video Calls		
	Total	Admit	Block	Total	Admit	Block
WI-FI 6	139	139	0	161	161	0
5G NR	56	56	0	64	62	2

4. CONCLUSION AND FUTURE WORK

In this paper, a study was presented on the coexistence of Wi-Fi 6 and 5G networks based on a duty cycle mechanism for managing spectrum sharing. Our study investigated the performance of these networks based on several parameters, including throughput, latency, bit error rate, and capacity. Simulation results indicate the effect of the duty cycle mechanism on increasing the overall capacity of the networks, thereby allowing more efficient use of resources and significantly improving the blocking probability. This ensures that new connection requests are managed efficiently. The application of the duty cycle mechanism in controlling the coexistence between 5G and Wi-Fi 6 networks leads to significant improvements in performance. This mechanism provides high-quality services for users, such as VoIP calling and video streaming services. When using adaptive bandwidth reservation, the blocking probability was reduced from 21.8% to 0.9% compared to the fixed method, and no VoIP calls were blocked. These improvements may subsequently reflect on the usage of IoT services.

For future work, additional coexistence mechanisms may be examined and validated. The comparison of the suggested mechanism with the mechanism reported here may be considered as good practice. The aim is to improve the quality of services through the coexistence of 5G and Wi-Fi 6 networks.

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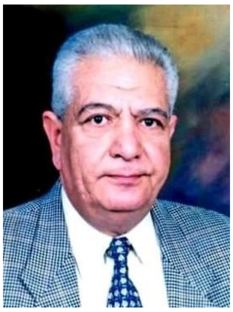

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