DEVELOPING CAPACITY SHARING STRATEGY FOR VEHICULAR NETWORKS WITH INTEGRATED USE OF LICENSED AND UNLICENSED SPECTRUM

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Abstract

A widely deployed cellular network, supported by direct connections, can offer a promising solution that supports new services with strict requirements on access availability, reliability, and end-to-end (E2E) latency. The communications between vehicles can be made using different radio interfaces: One for cellular communication (i.e., cellular communication over the cellular network based on uplink (UL)/downlink (DL) connections) and the other for direct communication (i.e., D2D-based direct communications between vehicles which allows vehicular users (V-UEs) to communicate directly with others). Common cellular systems with licensed spectrum backed by direct communication using unlicensed spectrum can ensure high quality of service requirements for new intelligent transportation systems (ITS) services, increase network capacity and reduce overall delays. However, selecting a convenient radio interface and allocating radio resources to users according to the quality of service (QoS) requirements becomes a challenge. In this regard, let’s introduce a new radio resource allocation strategy to determine when it’s appropriate to establish the communication between the vehicles over a cellular network using licensed spectrum resources or D2D-based direct connections over unlicensed spectrum sharing with Wi-Fi. The proposed strategy aims at meeting the quality of service requirements of users, including reducing the possibility of exceeding the maximum delay restrictions and enhancing network capacity utilization in order to avoid service interruption. The proposed solution is evaluated by highlighting different conditions for the considered scenario, and it is demonstrated that the proposed strategy improves network performance in terms of transmitted data rate, packet success rate, latency, and resource usage.

Keywords: 5G Cellular networks, unlicensed spectrum, NR-U, spectrum sharing, Mode selection.

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1. Introduction

Communication between vehicles attracted the attention of both academia and industry due to its capacity to improve road safety and traffic effectiveness [1–4]. The third-generation «3G» Partnership Project (3GPP) provides highly dependable and efficient vehicular communications depending on the fifth-generation (5G) networks [5, 6]. The exclusive usage of the licensed spectrum as a single resource is insufficient to meet the diverse stringent requirements for various user requirements in different application scenarios, such as stringent requirements for vehicular communication in terms of data rate and latency, as a result of the increase in diverse and unprecedented future service demands. To address this issue, 3GPP has already introduced the standardization of New Radio in unlicensed spectrum through the so-called NR-based access to unlicensed spectrum (NR-U) [7]. The unlicensed 2.4 GHz, 5 GHz, and 60 GHz bands spectrum are utilized
to provide additional radio bands to boost the capacity of future cellular systems, data offloading, and support new use cases with a variety of services requirements. 5G systems, on the other hand, support non-3GPP radio access protocols like Wi-Fi [8, 9], allowing operators to merge cellular data services and Wi-Fi by sharing unlicensed spectrum to improve network performance in a cost-effective manner. Thus, through diverse Radio Access (RATs) Technologies, 5G would enable network operators to provide network services in industry and automotive systems. Short-range communication, on the other hand, prefers to use an unlicensed spectrum. There are two reasons for this. First, due to channel fading on 5 GHz unlicensed spectrum, which is often greater than the lower carrier’s licensed spectrum. Second, regulatory restrictions limit the ability to broadcast over unlicensed frequency.

Another effective technique for improving cellular network performance is to allow two users in close proximity to connect directly rather than through the base station. It has been demonstrated that D2D communications can achieve proximity gain, hop gain, and reuse gain [10–12]. Unlicensed spectrum can be used to improve network performance in terms of possible data rate, latency, and resource utilization because D2D-based direct connections frequently occur when transmitters and receivers are in close proximity. This paper considers an optimized radio resource access strategy for scenarios in which vehicles can communicate using two different radio interfaces: cellular communication, which uses licensed spectrum resources, and D2D-based direct communications between vehicles sharing an unlicensed spectrum with Wi-Fi network.

The proposed solution focuses on channel selection, which is accomplished by determining the best communication and radio channel access option for each vehicle, which is either a cellular network using licensed spectrum or D2D-based direct communications using unlicensed spectrum simultaneously with Wi-Fi. This will result in several advantages, including ensuring the quality of service requirements for vehicle connections, maximizing network capacity, minimizing overall delays, and preventing service outages due to resource shortages. Based on all of the foregoing considerations, the important contributions of this study are summarized as follows.

A novel low-latency radio access strategy is proposed to determine when it is suitable to use cellular links and share licensed spectrum with existing cellular networks or to use D2D-based direct links and share unlicensed spectrum with Wi-Fi users. In this regard, when deploying vehicular links in a heterogeneous network with licensed and unlicensed spectrum, the optimal communication mode must be determined, i.e. whether vehicle users should communicate over the cellular network (i.e., communicate directly using D2D or via base station through two-hop transmission) and use licensed spectrum or direct transmission using D2D based communication and use unlicensed spectrum taking into account the connectivity, the availability of resources, and the latency.

A widespread cellular network, supported by D2D communications, can offer an efficient solution to support communication between users. There are many works put forward to investigate the mode selection and radio resource sharing in D2D communications considering different factors including interference conditions when radio resources are shared between different users on a large scale, and the quality of communication is taken into consideration, both when using cellular links and D2D links in the licensed spectrum [13–16]. The selection of a channel assignment and power control for D2D links in licensed spectrum cellular networks are discussed [13]. They proposed different algorithms for mode selection and transmission power regulation, by ensuring SINR for cellular and D2D links. The authors in [14] proposed a mode selection and radio resource allocation strategy for D2D transmission across the licensed spectrum, with the goal of increasing network capacity and throughput while staying below the interference limit. The authors in [15] proposed and evaluated novel model selection approaches for D2D-enabled cellular communications utilizing a licensed spectrum. A radio resource sharing technique that aims to improve data rate across shared resources while meeting the priority constraints of cellular service has been introduced by [16].

On the other hand, [17] has proposed a mode selection and radio resource allocation algorithm for Wi-Fi technology and D2D-based cellular networks in unlicensed spectrum to reduce overall interference while ensuring signal-to-noise and interference ratio requirements for all users, including D2D underlying cellular networks and Wi-Fi networks. The coexistence of NR-U
and Wi-Fi focuses on determining whether LTE-U achieves its coexistence goal through fairness and network optimization in terms of system throughput, and latency is evaluated by [18–20] using various parameters, such as power detection threshold, bandwidth, and channel access method. Similarly, the authors in [21] investigated the coexistence between LTE-U and Wi-Fi in the unlicensed spectrum by taking into account improving the performance of the network through trade-offs between throughput and latency metrics.

The coexistence of LTE-U and Wi-Fi in unlicensed spectrum is considered in [22] by allowing D2D users to share a portion of unlicensed spectrum resources to meet the expected security requirements. The authors in [23] evaluated and studied the coexistence of IEEE 802.11ad Wireless Gigabit (WiGig) and NR-U in the 60 GHz bands by taking into account various NR-U parameters, such as beam forming, channel access, and bandwidth. Online learning is distributed in order to determine the best-unlicensed channel for uplink traffic, a channel selection algorithm based on multi-armed bandit learning techniques is presented for NR-U users [24]. The performance of 5G-U in support of rigorous IoT use cases is studied and discussed in [25] where alternative spectrum management strategies are compared, and they show that coordinated use of licensed and unlicensed bands provides significant performance improvements for IoT services. However, none of the above works assumes a vehicular scenario in which communication over the cellular network is carried out through different communication methods (i.e., direct communication using D2D or via a base station through two-hop transmission), making use of heterogeneous radio access technologies with both licensed and unlicensed spectrum and considering different important aspects such as the quality of the links between vehicular users, the available resources, and the latency.

2. Materials and methods

Let’s consider a Next-Generation Cellular Wireless Access Network (NG-RAN) with a flow of vehicles numbered as \( i = 1, \ldots, C \) move along a straight highway under a single gNB coverage [26], as illustrated in Fig. 1.

The proposed model also includes within cell coverage a Wi-Fi network (i.e., potential access points and Wi-Fi users placed randomly in the network) operating at 5.8 GHz unlicensed spectrum. For certain traffic, the arrivals of vehicles follow a Poisson process with the intensity of arrival rate \( \lambda_a \). Each vehicle randomly generates packets with rate \( \lambda_p \), and packet size, \( P_{max} \). Based on various metrics (such as speed, location, direction, and connection quality) through the periodic exchange of status information, vehicles are maintained and managed by gNB. Let’s assume that the communication between vehicles can be performed using two radio interfaces either cellular in licensed spectrum or D2D based communication in unlicensed spectrum. In a cellular communication with licensed spectrum, vehicles communicate via base station through two-hop transmission by UL and DL or communicate directly using D2D, and use the licensed spectrum resources as
in [27, 28] while in D2D-based communication with unlicensed spectrum, vehicles conducts data transmission directly to other vehicles and Wi-Fi users can share unlicensed spectrum resources. Let’s introduce the index \( a_i \) to reflect the connectivity and user access status, such that \( a_i = 1 \) if vehicle \( i \) communicate with other using the cellular communication with licensed spectrum and \( a_i = 0 \) if vehicle \( i \) communicate with other in a D2D-based communication with unlicensed spectrum. Let’s part the time domain into mini-slots (i.e. 0.25 ms) to execute channel selection and data transmission with instantaneous start time [29]. Let’s intend on the one hand to define the operating mode, \( a_i \) i.e. cellular or direct mode, for each vehicle \( i \), and on the other hand, specifying the available subchannels in the spectrum that are licensed for a cellular network and the unlicensed bands to be used for vehicle \( i \) in addition to the Wi-Fi users who are already using the Wi-Fi network.

Based on this, the overall data rate achieved in licensed and unlicensed spectrum by vehicles within \( n \)-th cell can be expressed as:

\[
C_n = \sum_i \alpha_i R_{ij}^L + (1 - \alpha_i) R_{ij}^U. \tag{1}
\]

The first term is the data rate achieved when vehicle \( i \) is connected to the cellular network and the licensed spectrum is used, while the second term is the data rate achieved by vehicle \( i \) when communicating over the unlicensed spectrum. Assuming the Shannon bound, the capacity of the link between vehicle \( i \) vehicle \( j \) using licensed or unlicensed spectrum denoted respectively by, \( R_{ij}^L \) and \( R_{ij}^U \) can be estimated as in equation (2), (3):

\[
R_{ij}^L = \beta^L \log(1 + \xi_{ij}^L), \tag{2}
\]
\[
R_{ij}^U = \rho \beta^U \log(1 + \xi_{ij}^U), \tag{3}
\]

where \( \rho \) is the fractions of time that \( i \)-th vehicle can occupy the unlicensed spectrum. \( \beta^L \) and \( \beta^U \) denote bandwidth of licensed and unlicensed spectrum, respectively. Subsequently, SINR for links between vehicles using licensed spectrum, \( \xi_{ij}^L \) and unlicensed spectrum \( \xi_{ij}^U \) are defined as following:

\[
\xi_{ij}^U = \frac{P_{Tx}(i)\alpha_{Tx(i)}^{-1}R_{Tx(i)}Ax(j)}{\beta^U \cdot P_n}, \tag{4}
\]
\[
\xi_{ij}^L = \sum_{i' \neq i} P_{Rx}(j)\alpha_{Rx(j)}^{-1}R_{Rx(j)}Ax(i') + P_n. \tag{5}
\]

Where \( Tx(i) \) and \( Rx(j) \) denote the transmitter \( i \) and receiver \( j \), respectively. \( P_{Tx} \) is the transmitted power of the transmitter \( i \) in \( x \in \{ \text{licensed and unlicensed spectrum} \} \), \( \alpha_{Tx(i),Tx(j)}^{-1} \) is the path loss between transmitter \( Tx(i) \) and receiver \( Rx(j) \), \( P_{Rx}(i) \) is received signal power at the receiver \( Rx(j) \) from transmitter links \( i' \neq i \) and \( P_n \) is the receiver noise level.

This paper considers a radio resource allocation strategy, keeps track of the available radio resource to be used for the transmission i.e., the vehicles are assumed to use the licensed radio sources, and in case they are not available due to the increased demands for the licensed sources, the vehicles will share the unlicensed radio resources with Wi-Fi users. As in [30, 30], let’s assume that Wi-Fi users can generally start transmitting at any point after a Carrier-sense multiple access with collision avoidance (CSMA/CA) procedure. Thus, Wi-Fi devices notify the controller of their intention to start transmission with information on the start and occupancy times of the channels. On the other hand, let’s assume that each vehicle continuously sensing the channel while in RRC (Radio Resource Control) mode. In particular, this sensing is performed using the LBT procedure Category 4 as specified in [31] through which, every vehicle \( i \) must perform a Clear Channel Assessment (CCA) check (i.e., vehicle \( i \) senses the spectrum for a certain window, called CCA period before accessing the channel to be used to transmit a generated packet by
vehicle $i$ after identifying that the channel is unoccupied and available. For this purpose, CCA uses Energy Detection (ED) to check if the channel is busy or channel is idle.

For this purpose, each vehicle $i$ measures the received energy $P_{RX}(i)$ and compares it to a predetermined $P_{TH}$ threshold. If the received energy, $P_{RX}(i) < P_{TH}$, the channel is unoccupied and can be added by vehicle $i$ to the list of favourite channels that can be used for transmission, $\Omega_i$. Other channel is considered busy and cannot be used for transmission. To allocate radio resources using spectrum that is licensed and unlicensed for use in transmission, the proposed radio access strategy considers in Algorithm1 is as follows:

1. The communication between the vehicles to be established using licensed spectrum resources must ensure that the amount of required RBs by vehicle $i$ are sufficient for the transmission i.e., for every vehicle $i \in C$, the following condition is checked by algorithm1 (lines 11, 12):

$$\Gamma_i < N_{RB}^L - p^i(t).$$

(7)

Where $N_{RB}^L$ is the total number of RBs available for the communication between vehicles in licensed spectrum, $p^i$ is the total number of RBs that have been allocated to vehicles in licensed spectrum and determined by algorithm1 (line 15). $\Gamma_i$ is the number of the amount of required RBs, given by:

$$\Gamma_i = \sum_{l} P(l) \cdot P_s,$$

(8)

$P(l)$ is the number of packets by need to be transmitted by vehicle $i$, $P_s$ is the packet size, $S_E$ is the spectral efficiency related to the modulation and coding scheme for use in the communication between vehicles in licensed and unlicensed spectrum.

2. Communication between the vehicles over cellular network using licensed spectrum resources or D2D-based direct connections over unlicensed spectrum sharing with Wi-Fi must meet latency requirements $W_{TH}$. For this purpose, the latency when the vehicles use licensed spectrum or share unlicensed spectrum with Wi-Fi users are computed by algorithm1 (lines 4–9). The latency in $x \in \{\text{licensed and unlicensed spectrum}\}$ denoted $W_x(i,l)$, for each packet generated by vehicle $i$, can be estimated as follows:

$$W_x(i,l) = \left\{D_{x,Q}(i,l) + D_{x,T}(i,l)\right\},$$

(9)

where $D_{x,Q}(i,l)$ is the time that the packet $l$ takes in the queue since it was generated and $D_{x,T}(i,l)$ is the time vehicle $i$ takes to transmit the packet $l$.

Based on the above conditions, the radio resource allocation criterion is as follows: if there are sufficient physical resources to be used for serving the communication between the vehicles over cellular network using licensed spectrum resources, the algorithm will move on to check if the packet latency $W(i,l)$ for vehicle $i$ generated by vehicle $i$ using licensed spectrum is less than threshold value $W_{TH}$, i.e., $W(i,l) < W_{TH}$ (line 13), the corresponding the communication between the vehicles will use licensed spectrum resources over cellular network (line 14). Otherwise the proposed strategy will share unlicensed spectrum with Wi-Fi users. Especially, if vehicle $i$ has a packet $l$ with least short remaining time (packet $l$ with lowest $W(i,l) = W_{TH} - T_g(i,l)$), the algorithm will allocate the best subchannel $n$ in terms of the channel quality (i.e., the channel is sensed idle by the vehicle $i$ and not being used by nearby ongoing transmissions) to vehicle $i$ from the available subchannel set $\Omega_i$ (lines 6–10). Otherwise, if no channels are sensed by vehicle $i$ as idle, the vehicle will be considered in outage (lines 11–14).

**Algorithm 1:** Radio resource Allocation Strategy

1. **Inputs:**
   - The set of all potential vehicles using D2D Links
   - The set of orthogonal channels in licensed spectrum and unlicensed spectrum.
2. **Initialization:** $p^i(t) = 0$
3. While there are packets to be transmitted by user $i$
4. For each vehicle $i \in C$
5. For each packet $l$ of vehicle $i \in C$
6. Compute $\Gamma_i$ using eqs. (8);
7. Compute $W(i,l)$ using eqs. (9);
8. End
9. End
10. Select packet $l$ generated by user $i$ as follows $l_i = \arg\min D(i,l)$
11. If $\Gamma_i = N_{KB}^0 - P_i(t)$ \{verify that the RBs required by user $i$, $\Gamma_i$ are available in the licensed spectrum\}
12. If $W(i,l) \leq W_{TH}$
13. $\alpha_i = 1$ \{User $i$ operate in licensed spectrum\}
14. $P_i(t) = P_i(t) + \Gamma_i$
15. Else
16. $\alpha_i = 0$ \{User $i$ move to operate in unlicensed\}
17. End
18. Else
19. $\alpha_i = 0$ \{User $i$ move to operate in unlicensed\}
20. Select packet $l$ generated by vehicle $i \in N$, as follows: $l_i = \arg\min (i,l)$.
21. Select $n \leftarrow \arg\max n \in \Omega_i, R(n)$
22. End
23. End
24. Output: $\alpha_i$

3. Results and discussion

The performance evaluation of the suggested radio access strategy using MATLAB simulations is addressed in this section. Our simulation model considers a single gNB hexagonal layout cell supporting 5G NRs with a channel cell regulated at 60 RBs for UL, 60 RBs for DL, and 12 subcarriers with an interval $\Delta f = 30$ kHz [32]. Let’s assume that a number of vehicles are moving along a two-lane highway and are expected to enter cell coverage using the Poisson process at a rate of $\lambda_p$. The proposed network also includes a number of Wi-Fi users and Wi-Fi access points distributed randomly within the range of cellular coverage. Let’s use the IEEE 802.11n protocol that operates on the 5 GHz range with orthogonal unlicensed channels as well as an RTS/CTS protocol. The key simulation parameters are summarized in Table 1, which are similar to the licensed spectrum parameters in [27] and unlicensed spectrum and WiFi parameters in [17–32].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius</td>
<td>800 m</td>
<td>$\Delta f$</td>
<td>30 kHz</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>400 MHz</td>
<td>Number of WiFi UEs</td>
<td>1–50</td>
</tr>
<tr>
<td>RBs per cell</td>
<td>$N_{UL}^{KB} = 60$ RBs</td>
<td>Channel bandwidth</td>
<td>400 MHz</td>
</tr>
<tr>
<td></td>
<td>$N_{DL}^{KB} = 60$ RBs</td>
<td>CWminw</td>
<td>16</td>
</tr>
<tr>
<td>Noise power</td>
<td>$-174$ dBm/Hz</td>
<td>CWmaxw</td>
<td>1024</td>
</tr>
<tr>
<td>Transmit power of CU</td>
<td>27 dBm</td>
<td>Mw</td>
<td>7</td>
</tr>
<tr>
<td>Unlicensed Transmit power</td>
<td>24 dBm</td>
<td>WiFi bit rate</td>
<td>300 Mbps</td>
</tr>
<tr>
<td>Slot duration</td>
<td>0.25 ms</td>
<td>PHY Header</td>
<td>192 bits</td>
</tr>
<tr>
<td>Vehicle arrival rate $\lambda_p$</td>
<td>2 vehicles/s</td>
<td>MAC Header</td>
<td>124 bits</td>
</tr>
<tr>
<td>Packet arrival rate $\lambda_a$</td>
<td>Varied from 1 to 8 packets/s</td>
<td>SIFS</td>
<td>16 ms</td>
</tr>
<tr>
<td>$P_s$</td>
<td>1200 bytes</td>
<td>DIFS</td>
<td>50 ms</td>
</tr>
<tr>
<td>$P_{TH}$</td>
<td>$-69$ dBm</td>
<td>ACK$_{Tout}$</td>
<td>50 ms</td>
</tr>
</tbody>
</table>

Table 1
Simulation parameters
Fig. 2 depicts the system throughput for different number of vehicular users. From Fig. 2, it is obvious to note that the overall system throughput increases with the increase in number of vehicular users. It can also be observed that the proposed radio access strategy performs better than the reference approach with only licensed spectrum in terms of data rate. The proposed radio access strategy achieved data rate of 26 kbps when the $\lambda_a$ is 6 packets/s while for the reference approach the data rate is only 18 Kbps and in this case the proposed radio access strategy achieved a relative gain of 43% compared to the reference approach. The reason for this is that when the access rate, $\lambda_a$ increases, more users will access the network and this will result in more packets being generated and, as a result, increased demand for RBs to be used in transmissions. Furthermore, as the number of packets increases, the proposed solution ensures more radio resources for data transmission by utilizing unlicensed spectrum not occupied by Wi-Fi UEs, whereas the reference scheme provides fewer radio resources for data transmission.

Fig. 3, 4 show the system packet success rate and throughput for the vehicles when compared to various numbers of Wi-Fi UEs. It is possible to see from the results that as more Wi-Fi UEs are added to the system, the packet success rate and throughput for the communication between vehicles will decrease for all the considered approaches. The reason for this is because as the load increases, the number of Wi-Fi sessions, resulting in higher channel occupancy and less radio resources available to serve vehicles. The proposed strategy, on the other hand, is still practical and has lower latency and a greater packet success rate than the reference approach. Specifically, proposed radio access strategy achieved about 99% of the packets successfully delivered when the number of Wi-Fi UEs is 20. In the case of the reference approach using only licensed spectrum, it succeeded in achieving a delivery rate of about 95% of packets, when the number of Wi-Fi UEs is 20.

Fig. 5 depicts the average latency for vehicular service as a result of channel access latency, which is the time the packets spend in the system from the moment it is generated to the time it is transmitted. Fig. 5 shows that when the packet arrival rate $\lambda_a$ increases, the average latency increases for all schemes because more users will access the network and require more radio resources to be used for data transmissions. This leads to an increase in channel access time and therefore an increase in latency. The average arrival time for all approaches increases as the
number of vehicles increases, because an increase in the number of vehicles leads to an increase in the demand for more available radio resources to be used in data transmission, which may result in an increase in channel access time. It is possible to see from the results that the proposed radio access approach reduces radio access time when compared to the reference approach because it makes use of available unlicensed resources and thus provides access to more radio resources. For the proposed radio access strategy, the average latency around 29 ms when the packet arrival rate is 8 packets/s. Alternatively, for the reference with only licensed spectrum, the latency is reach 40 ms (i.e. proposed radio access strategy achieved a 27 % relative improvement compared to the reference approach).

The proposed solution is designed to work on a per-cell basis rather than within a multicellular environment. Given this, there is potential for future work to extend the proposed solution evaluation to multi-cell scenarios including different traffic classes. Based on existing work, our future work will provide different solutions for distributing radio resource allocation when multiple traffic classes share both licensed and unlicensed spectrum in multi-cell scenarios. In this respect, a strategy designed to work on a per-cell basis can be made by having a distinct controller for each cell, ensuring fair management of both licensed and unlicensed radio resources, leading to improved network performance.

4. Conclusions

This study illustrates a novel radio resource allocation strategy to determine when to establish communication between vehicles via D2D links over cellular networks using licensed spectrum resources or D2D-based direct connections using unlicensed spectrum sharing with Wi-Fi. The proposed strategy takes into account network capacity and latency constraints. To examine and validate the performance of the suggested strategy, extensive simulations were performed. The considered strategy has been compared to the benchmark approach which only considers the D2D-based direct connections over the licensed spectrum. The simulation results demonstrated the capability of the suggested strategy to efficiently allocate radio resources and improve network performance.
performance in terms of throughput, congestion, and latency. Specifically, through the results presented, let’s note that our proposed scheme achieved improvements that made it outperform the reference scheme with the licensed spectrum in terms of achieved throughput with gains of up to 43%. The results also showed that our proposed strategy is superior to the reference approach in terms of latency (that is, the proposed approach yields relative gains of up to 27%). Moreover, by applying the proposed radio access strategy, there is a marked improvement in the packet success rate, as about 99% of the successfully delivered packets are achieved while in the case of the reference approach using only licensed spectrum, the packet success rate is only about 95%.

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