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Empowering the Convergence of Wi-Fi and 5G for Future Private 6G Networks

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***Abstract*—Private Cellular networks are heavily discussed as one of the core innovations of current 5G and future 6G networks. However, in most potential deployment areas, future private cellular networks are competing with existing radio technologies, most of which are operated in unlicensed frequency bands, such as industrial Wi-Fi solutions. In contrast to these, private cellular networks are promising a more robust and reliable alternative due to its centralized resource management and the use of licensed, dedicated frequency ranges. While today, Wi-Fi and 5G are bound to certain frequency ranges, in this paper, we aim to demonstrate the feasibility of combining both Wi-Fi and 5G for future private networks. In this work, we leverage the open-source Wi-Fi stack OpenWiFi to enable Wi-Fi operation in exclusively licensed frequency ranges at 3,7 GHz to exclude interference of other Wi-Fi systems. First, we show with experiments that an unmanaged operation of Wi-Fi and private 5G within the same band severely degrades the Wi-Fi systems performance. Thus, we propose and implement a Multi-RAT broker to manage a cooperative and reliable operation of both technologies towards heterogeneous private 6G networks. The Multi-RAT broker controls resource allocation in the time and frequency domains for both technologies based on technology, channel and application knowledge. An experimental study combining robots equipped either with 5G or Wi-Fi finally shows that the proposed Multi-RAT broker supports dynamic network reconfiguration as well as configuration of bandwidths and frequency ranges at runtime to serve different applications without compromising system functionality.**

***Index Terms*—OpenWiFi, Private Cellular Networks, Coexistence**

I. Introduction

Wi-Fi systems have become an indispensable part of everyday life, both privately and professionally. In the industrial environment in particular, more and more systems need to be connected with increasing requirements, especially for the real-time capability and reliability of wireless systems. Classical Wi-Fi systems are operated in license-free frequency ranges (2.4 GHz and 5 GHz), which have a high interference potential due to the free usage and the wide distribution of the systems. An alternative for reliable, wireless networking of a wide variety of systems is promised by the 5th Generation of mobile networks (5G), which for the first time allows companies and organizations to set up their own, private 5G campus networks in frequency ranges with local exclusive use rights (3.7-3.8 GHz in Germany), at considerable cost and effort. However, the right to use these frequencies is not tied to a specific technology, so that the much more widespread

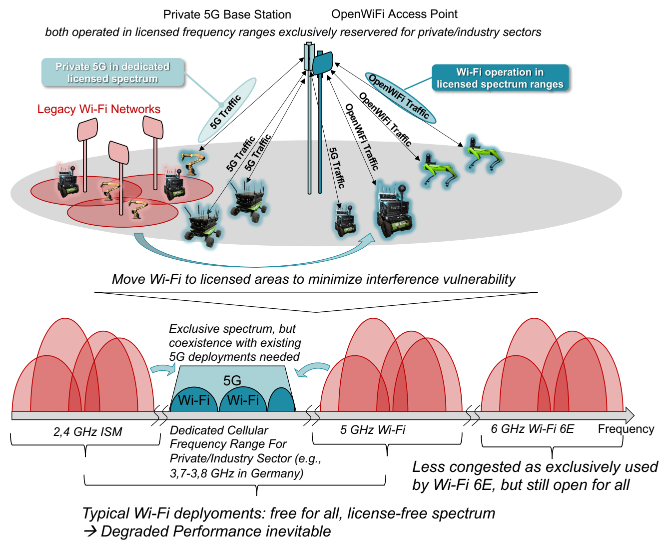

Fig. 1. Wi-Fi is significantly handicapped by interfering shared ISM bands. But how would Wi-Fi behave in licensed frequency bands?

Wi-Fi technology can also be used [1] and the advantages of an exclusive frequency allocation can be exploited at the same time (cf. Fig. 1).

Currently, however, there are no Wi-Fi systems supporting campus network frequencies. An initial goal of this work is to first evaluate the widely known and established Wi-Fi technology in the exclusive frequency range of 5G campus networks. This is implemented and tested using the open-source Wi-Fi implementation OpenWiFi [2], which leverages existing components of Linux operating systems. It is combined with a high-performance software-defined radio platform to provide a fully configurable, observable, and functional implementation of the Wi-Fi standard IEEE 802.11n (Wi-Fi 4) that enables intervention in deep processes of the Wi-Fi system, such as physical channel access. In the present work, this system will now be used to enable and evaluate operation in licensed 5G campus network frequencies. This however raises the question of coexistence with a 5G system in the campus network frequency range. For interference-free simultaneous operation of a 5G and a Wi-Fi system in this spectrum, a mechanism is needed that guarantees that both systems operate separately side by side in different frequency

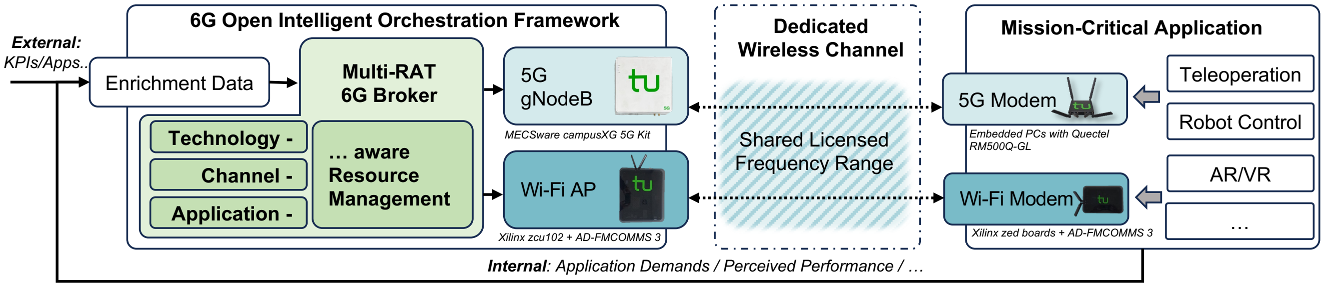

Fig. 2. Architecture of proposed Open Multi-RAT Resource Broker as part of future Open 6G Intelligent Orchestration concepts

bands. First approaches for a coexistence mechanism between a Wi-Fi and a cellular system are already given for the implementation of an algorithm between Long Term Evolution (LTE) and Wi-Fi in the unlicensed frequency range. The aim of this work is to develop a coexistence mechanism that enables the simultaneous operation of Wi-Fi and 5G technologies. To guarantee interference-free operation, a higher-level entity in the form of a resource manager is used, which follows a *Radio Resource Management* approach to allocate resources in the time and frequency domains to the two competing technologies. The functionality of the developed mechanism will be evaluated using performance measurements of data rates and selected test scenarios demonstrating the benefits of using a management of available resources. The remainder of this work is structured as follows: Section II gives a brief overview of the state of the art regarding coexistence of cellular and Wi-Fi systems. In section III-B the Multiple Radio Access Technology (Multi-RAT) broker approach of this work, as well as the underlying OpenWiFi system and the effects of operating it in the licensed 3.7 GHz band are detailed. Section IV shows a robotic exploration case study utilizing the proposed Multi-RAT broker instance. Finally, a conclusion is drawn and a short outlook is given in section V.

II. Related Work

There is rich literature of concepts for realizing a fair coexistence mechanism between LTE and Wi-Fi in the unlicensed spectrum. These ideas can be adapted to develop an algorithm for the technologies Wi-Fi and 5G in the licensed private 5G spectrum. In [3], the authors introduce the concept of *Content Centric Networking* to define which technology uses which resources. This exchange of information is done periodically. Ratios guarantee the minimal available resources for each technology in every time step. [4] describes an algorithm where the mobile communication technology uses the multi-fractional spectrum access where a ratio for almost blank subframes is defined. For the time of the almost blank subframe the mobile communications part is not allowed to send any data. In between this time the Wi-Fi component can transmit data. By using the special subframe transmission time for the Wi-Fi-system is guaranteed. The ratio and the amount of necessary resources can be detected by using packet sniffing. [5] describes an algorithm where the mobile communications technology uses a Listen Before Talk (LBT) scheme to access the channel. Because of the long sending period of the LTE the sending period of the Wi-Fi technology will be reduced. To counteract this a muting period is introduced which is used after the transmission of the LTE component where the LTE system is omitted to transmit, which gives an opportunity for the Wi-Fi system to send data. [6] describes an algorithm for the coexistence of Wi-Fi 6E and 5G NR-U systems in the licensed greenfield spectrum 6 GHz. The usage of the greenfield spectrum has the same advantage as the 3,7 GHz band that there is no operation of Wi-Fi or mobile communication technology at the moment which enables more flexibility for realizing the coexistence mechanism. For channel access both technologies are using the Multiple user (MU) Orthogonal Frequency Division Multiple Access (OFDMA) for the uplink and the LBT mechanism is implemented for the downlink. [7] describes a mechanism called Channel-Aware Rating Mechanism (CHARM) which tries to realize a coexistence mechanism between LTE and Wi-Fi in the Industrial, Scientific and Medical (ISM) band by using a standard-compliant srsRadio Access Network (RAN) software and the OpenWiFi-platform. The OpenWiFi platform is used to generate standard-compliant Wi-Fi traffic which is used to train a Deep Neural Network (DNN). Dependent on the detected traffic by scanning the spectrum the LTE-system distinguishes between frequency switch, a coexistence mode, a bandwidth switch and a TX gain switch to realize the coexistence of both technologies in the same frequency band. In [8] the authors propose a coexistence scheme for LTE and Wi-Fi by utilizing an LTE concept of Multimedia Broadcast Multicast Single Frequency Network (MBSFN). They also use the OpenWiFi platform, together with a Software Defined Radio (SDR) based open-source LTE implementation. While also using both technologies in the same frequency band, they assume a fixed bandwidth allocation and realize a coexistence by defining time slots within radio frames for both technologies. [9] describes a completely different concept where a higher level entity is used for machine type communications to schedule multiple networks, and frequency bands to guarantee the execution of time critical applications. The higher level entity has an overview of parameters of the operating technologies and can control them in real-time. The aforementioned concept is the base of this contribution.

Opposed to most of these current approaches which all involve using both technologies in the same frequency channels at alternating time slots, we propose a mechanism to dynamically allocate frequency resources to both technologies and therefore avoid a direct competition for the same frequency resources.

III. 6G Multi-RAT Resource Management

This section details the proposed Multi-RAT broker approach for realizing a coexistence between 5G and OpenWiFi in private frequency bands. The system architecture is shown in Fig. 2. A modular concept allows integrating the Multi-RAT resource broker into an overarching *6G Open Intelligent Orchestration* concept [10], allowing the usage of multiple input of *Enrichment Data* in the form of application demands and Key Performance Indicators (KPIs) as well as information about the current network and its perceived performance and channel qualities to realize technology-, channel- and application-aware resource management decisions. In section III-A, the experimental setup for the analysis of this work is shown, while section III-B details a performance measurement of the utilized OpenWiFi system. Section III-C displays the impact of overlapping both technologies without resource management, while section III-D details the Radio Resource Management (RRM) approach of this work and its capabilites.

A. Experimental Setup

The components of the experimental evaluation of this work are shown in Fig. 3.

Two network components are used, on the one hand a commercial private 5G indoor system by German Manufacturer *MECSWare* [11], and on the other hand a Xilinx zcu102 Field Programmable Gate Array (FPGA) board together with an SDR frontend (Analog Devices FMCOMMS 3) as the OpenWiFi Access Point (AP), allowing up to 27 MHz continuous bandwidth in a frequency band between 70 MHz and 6 GHz. Both network infrastructures have a backend connection to the Multi-RAT resource broker running on Commercial off the shelf (COTS) server hardware displayed in the middle. The technologies are used with one User Equipment (UE) each, represented by the legged robot with an integrated Quectel RM500Q-GL 5G modem, and the Automated Guided Vehicle (AGV) with a Xilinx Zedboard and the same SDR frontend as OpenWiFi Station (STA) device. These are equipped for exploration tasks as typically used in e.g. Search and Rescue (SAR) missions, consisting of multiple camera systems. These uplink focused loads are emulated as a case study in section IV.

B. OpenWiFi Radio Access

The OpenWiFi implementation of Ghent University in Belgium is an open source implementation of the IEEE 802.11 standard [12]. In this realization, the a, g and n versions of the Wi-Fi standard are implemented. In the open stack, which is based on an SDR platform, the functionality of a Wi-Fi chip with dedicated hardware by default is realized as a software solution based on a Linux 802.11 Media Access Control (MAC) subsystem.

A fundamental feature of OpenWiFi is its low latency even below COTS Wi-Fi Modules. This allows the system to be used in the context of Time Sensitive Networking (TSN), which reduces the time synchronization between access point and station [13] [14].

Fig. 4 shows a performance evaluation of this setup. One main advantage over traditional COTS Wi-Fi systems is the higher flexibility of the system, allowing fine-grained bandwidth settings independent of the parameters the standard

Fig. 3. Experimental setup for OpenWiFi and private 5G coexistence in the 3.7 GHz band

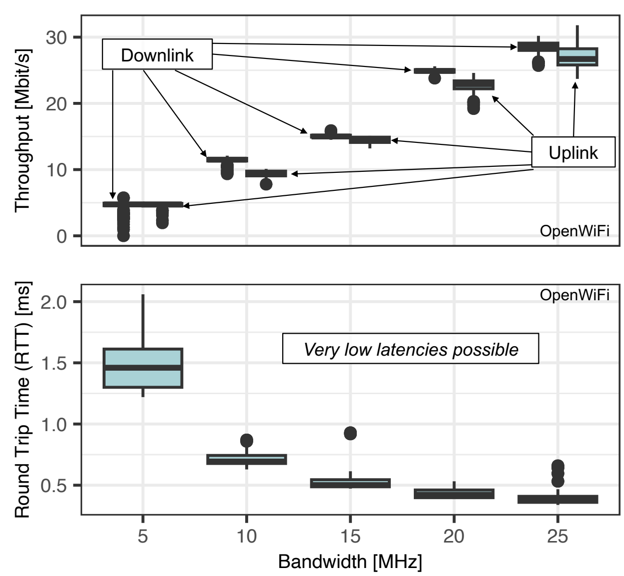

Fig. 4. Experimental Throughput and RTT for different bandwidths of OpenWiFi

would allow, only limited by the SDR platform in use. This is also true for the frequency band in use, which allows an operation in the 3.7 GHz frequency range in this work. The throughput performance with a default 20 MHz channel with around 25 Mbit/s is about the same as the authors in [8] achieve with the same hardware platform. While this performance, as a development and research implementation, is inferior compared to COTS Wi-Fi and also 5G systems, its achievable latency and RTT can be as low as 0.5 ms, decreasing with higher bandwidth as indicated in Fig. 4.

C. OpenWiFi and 5G in competition

5G and Wi-Fi systems, especially before the introduction of IEEE 802.11ax (Wi-Fi 6), operate fundamentally different regarding their channel access. While Wi-Fi, and therefore the OpenWiFi system, uses an LBT approach in typically unlicensed, free-for-all spectrum, 5G uses a scheduling approach assuming there are no contestants for the same spectral resources. This poses the question of how these two systems behave when they are both active in the same frequency band. We conducted a measurement study to identify the influences of both technologies on each other, when being operated in the same frequency bands. To achieve this, we used a commercial private 5G indoor system by German Manufacturer *MECSWare* [11]. Both systems were configured with 20 MHz bandwidth. Additional test parameters are listed in table I. We analyzed both the achievable throughput and ping round trip times when the other system is active for different states of overlapping channels. The throughput was generated using the open source iperf3 traffic generator [15]. Fig. 5 shows the throughput of both systems with adjacent channels and 25% channel overlap up to full overlapping channels. It can be seen that the 5G system shows no influence from the Wi-Fi system regardless of the overlapping state. The Wi-Fi system however has a severely decreased throughput of 75% as soon as the 5G systems channel is overlapping with the Wi-Fi channel.

The same can be seen in the bottom part of Fig. 5, where the ping round trip times are measured for one system while the other generates traffic according to 90% of its maximum throughput using iperf3. Again, the 5G system does not show a decrease in performance, while the Wi-Fi systems round trip time increases as soon as the 5G system overlaps. This is due to the Wi-Fi system using its Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) channel access scheme which involves a LBT aspect. The Wi-Fi system has to sense

Parameter	OpenWiFi	5G
Transmit Power [dbm]	20	20
Bandwidth [MHz]	20	20
Protocol	UDP	UDP
Direction	Downlink	Downlink
AP/Base station	ZCU-Board	MECSWare
STA/UE	ZED-Board	Quectel RM-Q500-GL
Uplink-Downlink-Ratio	-	5:5
Target Data Rate [Mbit/s]	100 Mbit/s	100 Mbit/s

TABLE I
TEST PARAMETERS FOR OPENWIFI AND 5G COMPETITION

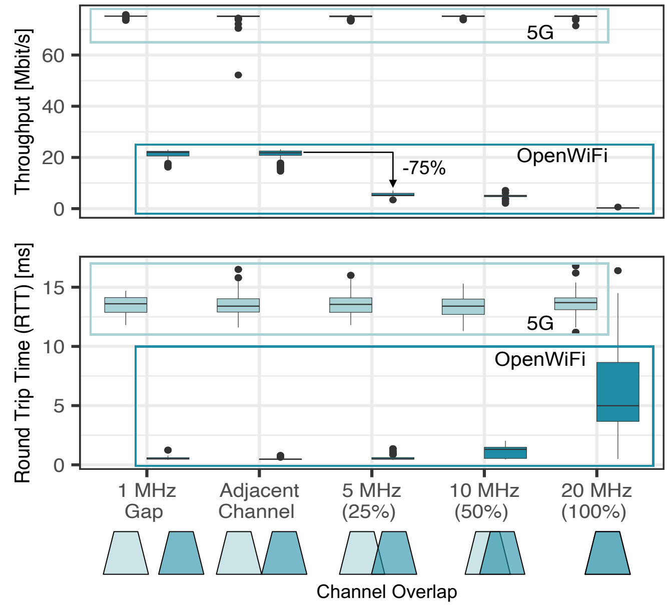

Fig. 5. In experiment, parallel activity of OpenWiFi and 5G in the 3.7 GHz band significantly reduce OpenWiFi performance while 5G remains untouched

the channel as idle before accessing it, thus it does not transmit when the 5G system is active. 5G however does not have this kind of channel sensing, as it is operated in typically exclusive spectral resources. The effect of the CSMA/CA can also be seen in Fig. 6, where the Inter Arrival Time (IAT) of the Wi-Fi systems STA and AP are shown for 25% and 100% channel overlap with the 5G system. It can be seen, that a lot less packets are even attempted to be sent with a higher channel overlap, indicating that the channel is sensed busy more often. In addition, the difference of the packet IAT between STA and AP indicates additional loss due to collisions on the channel for 100% channel overlap.

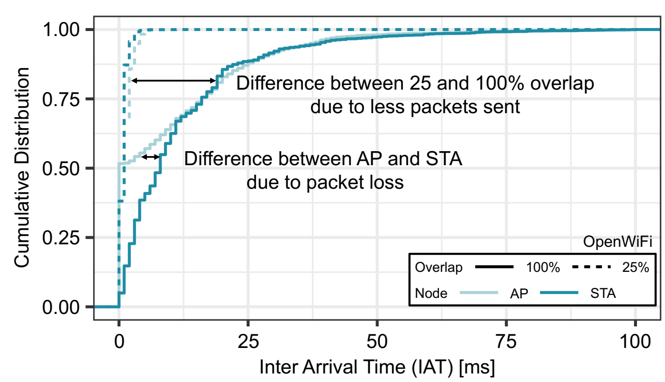

Fig. 6. With increased channel overlap, OpenWiFi experiences packet loss in experiment as well as an increased IAT due to increasing backoff.

This is stressed in Fig. 7, where at the top the maximum Contention Window (CW) is shown. It can be seen that with increasing overlap of the OpenWiFi and 5G channels, the possibility that a higher CW has to be used is increased due to increasing number of collisions. At the bottom of Fig. 7 the resulting number of backoff slots are shown, which naturally

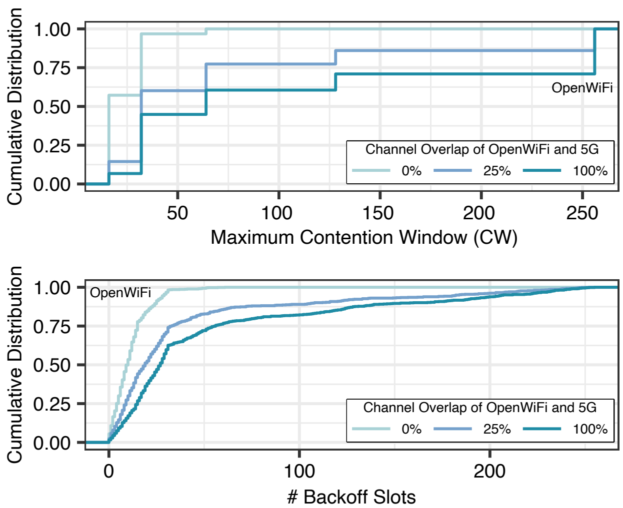

Fig. 7. Higher channel overlap causes Wi-Fi to increase its contention window and therefore backoff slots more often.

also increase with higher channel overlap, proving the higher IAT seen in Fig. 6.

D. Multi-RAT Broker for Cooperative Resource Management

In order to avoid the negative effects of overlapping channel usage, we propose a centralized Multi-RAT resource broker approach, which consists of a continuous resource utilization monitoring and the actual RRM which allows a dynamic reconfiguration based on changing conditions. This structure is shown in Fig. 8. The system implements an event based approach to schedule the available resources for the technologies Wi-Fi and 5G. Therefore, both the OpenWiFi AP and 5G base station provide an Application Programming Interface (API) for the central manager to query information about the technology's resource utilization and pending applications as enrichment data for the RRM process. Additionally, the manager itself provides an API to let the technologies push information about requirement changes to the manager system. Whenever an application is started or finished the current and necessary data rate by means of the currently running processes of the technologies is transmitted to the manager. According to this change of information the manager makes an independent analysis of the application data to detect simultaneity effects and tries to schedule the usable resources. The RRM component is active in the case where the capacity of one technology is not sufficient to server its applications requirements. This is determined by taking into account the current configuration as well as perceived channel quality of the UEs. The resource broker then defines the following parameters: transmission power, frequency, Time Division Duplex (TDD) pattern in the case of 5G and bandwidth. In this case the resource manager queries the running and pending application requirements of both technologies and allocates network resources for both technologies depending on the necessary resources for realizing the current applications and processes. Additionally, the resource manager calculates the

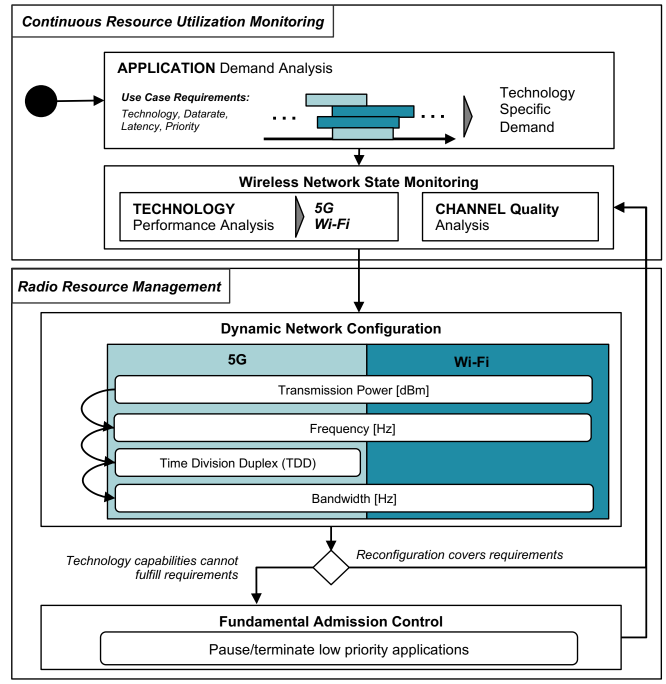

Fig. 8. Adaptive Multi-RAT Resource Management in order to combine both Wi-Fi and 5G in the same frequency band

maximum possible achievable Medium Access Control (MAC) layer throughput for both technologies. For this, equations 1 and 2 are used for Wi-Fi and 3 for 5G, respectively.

$$T_{\text{Transmission}} = DIFS + \frac{CW_{\text{Min}} * T_{\text{Slot}}}{2} + \frac{PHYHeader}{1Mbit/s} + \frac{Size_{\text{Packet}} + MAC_{\text{Overhead}}}{Bitrate} + SIFS + T_{\text{Ack}} \quad (1)$$

For Wi-Fi, at first the time duration for a transmission process is calculated (Eq. 1), incorporating the Short Inter Frame Space (SIFS), Distributed Inter Frame Space (DIFS), CW and Slot durations as well as packet and header sizes listed in table II.

Parameter	Value
SIFS [μs]	10
T_{Slot} [μs]	9
DIFS [μs]	28
CW_{Min}	15
PhyHeader [Bit]	20
Mac_{Overhead} [Byte]	36
$Size_{\text{Ack}}$ [Byte]	14
$Size_{\text{Packet}}$ [Byte]	1500
Bitrate [Mbit/s]	depends on bandwidth and Modulation and Coding Scheme (MCS)

TABLE II
PARAMETERSET FOR THEORETICAL WI-FI THROUGHPUT (IEEE 802.11G [16])

To determine the MAC layer throughput, the packet size is then divided by the transmission process duration (Eq. 2).

$$DR_{WiFi} = \frac{Size_{\text{Packet}}}{T_{\text{Transmisson}}} \quad (2)$$

For 5G, the throughput calculation is given in Eq. 3 [17], where J denotes the maximum number of aggregated carriers,

v_{Layers} the number of active Multiple Input Multiple Output (MIMO) layers, Q_{m} the modulation order, f the scaling factor (one in this work), R_{max} the maximum code rate, N_{PRB} the number of resource blocks depending on the numerology μ and bandwidth, T_{s} the average duration of an Orthogonal Frequency-Division Multiplexing (OFDM) symbol, and OH a factor for the overhead.

$$DR_{5G} = \sum_{j=1}^{J} \Bigg(v^{(\mathrm{j})}{}_{\mathrm{Layers}} \cdot Q^{(j)}{}_{\mathrm{m}} \cdot f^{(j)} \cdot R_{\mathrm{max}} \cdot \frac{N^{BW(j),\mu}{}_{\mathrm{PRB}} \cdot 12}{T_{\mathrm{s}}{}^{\mu}} \cdot (1 - OH^{(\mathrm{j})}) \Bigg) \quad (3)$$

The values used in this work are shown in table III.

Parameter	Value
J	1
v_{Layers}	2
Q_{m}	depends on channel quality
f	1
R_{max}	depends on channel quality
N_{PRB}	depends on TDD pattern and bandwidth
μ T_{s}	$0.001/14 * 2^{\mu}$
OH	0.08 (Downlink), 0.14 (Uplink)

TABLE III
PARAMETERSET FOR THEORETICAL 5G THROUGHPUT

If the calculated application demand cannot be fulfilled by the network it requires using, the resource manager at first aims to optimize the network itself before, if necessary, spare resources from the other technology are used to shift the bandwidth ratio between the two. If it is not possible to fulfill the requirements for both technologies, the resource manager tries to serve as many application requirements as possible for both technologies, starting with prioritized ones.

IV. Results of Experimental Case Study

The process described in Section III-D is demonstrated in a case study emulating two robotic systems as shown in Fig. 3, one legged robot with a multi-purpose camera system consisting of a teleoperation camera with four angles, a 360° camera, a thermal camera, a zoom camera and a LIDAR scanner equipped with a 5G modem, and an AGV with two teleoperation cameras and a 360° camera equipped with an OpenWiFi module. An overall available bandwidth of 60 MHz is assumed. All of these applications are emulated as uplink focused User Datagram Protocol (UDP) streams. Table IV represents the parametrization of the different use cases by defining the inter arrival time, the packet size and the resulting data rate which are realized as periodic applications to generate network traffic for this test scenario

Fig. 9 shows the timeline of the application traffic, the bandwidth configuration as well as the theoretical maximum throughput and actual throughput of both systems.

The timeline can be described as eleven events t_0 to t_9, which are detailed as follows:

- $\boldsymbol{t_0}$: The entry point of the scenario. Due to previous network usage, 20 MHz bandwidth is assigned to OpenWiFi and 40 MHz to the 5G system with a downlink focused TDD ratio of 4:1. Both robot systems are started to be teleoperated for an exploration task using their camera systems. The legged robot is publishing a LIDAR point cloud for localization as well as a thermal and zoom camera stream via 5G to give a deeper insight into its current environment.
- $\boldsymbol{t_1}$: This high uplink data traffic cannot be served by the current 5G configuration, thus the broker system decides that an internal reconfiguration of the 5G network's TDD pattern is feasible to overcome this insufficiency.
- $\boldsymbol{t_2}$: After a short solution dependent interruption of the

Robot	Technology	Application	Data Rate [MBit/s]
Legged Robot	5G	Teleoperation Cameras	20
Legged Robot	5G	Thermal Camera	10
Legged Robot	5G	Zoom Camera	10
Legged Robot	5G	LIDAR Point cloud	20
Legged Robot	5G	360° Camera	60
AGV	OpenWiFi	Teleoperation Cameras	6
AGV	OpenWiFi	360° Camera	16

TABLE IV
EMULATED APPLICATION PARAMETERS USED IN CASE STUDY

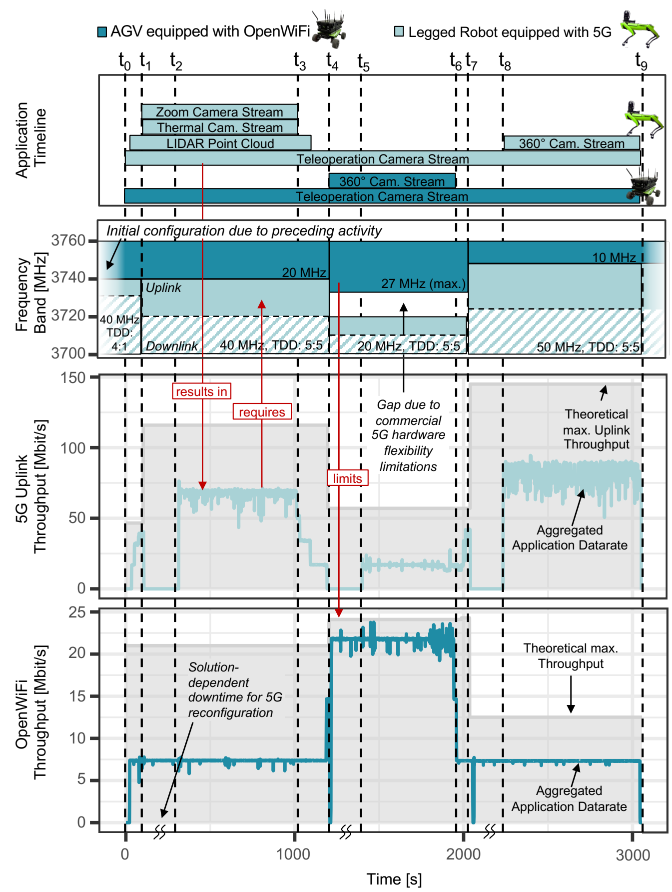

Fig. 9. Experimental case study proves that Radio Resource Management allows flexible reconfiguration of Wi-Fi and 5G system to respond to changing application requirements

5G connectivity for reconfiguration purposes, the legged robot can go on with its mission utilizing all of the required camera systems.
- t_3: The legged robot has completed its first task and deactivates the additional camera systems apart from the teleoperation camera stream. The operator indicates a spot better to be reached by the AGV for further exploration.
- t_4: Now the AGV is used for a 360° view, which produces a higher load in the OpenWiFi system. Therefore, the broker mandates the 5G system to reduce its bandwidth to 20 MHz, which is the next smaller bandwidth step the underlying 5G system is able to use, to leave room for the OpenWiFi to increase its bandwidth to 27 MHz which is the maximum the SDR frontend of the system is capable of.
- t_5: Again, the 5G system is done with reconfiguration and enables connectivity again.
- t_6: The AGV operator is done exploring and the 360° camera is stopped.
- t_7: Meanwhile, the legged robot was moved to another position which is again chosen for exploration utilizing a 360° view. This now requires a much higher datarate in the 5G uplink due to a higher resolution camera of the legged robot compared to the AGV. Thus the broker now commands a reduction of the OpenWiFi bandwidth to 10 MHz, allowing the 5G bandwidth to be increased to 50 MHz.
- t_8: The 5G system is reconfigured and the exploration task is started.
- t_9: The mission is finished and both robots are deactivated.

This case study therefore proves the feasibility of the proposed Multi-RAT resource manager approach to efficiently coordinate both systems to serve their dynamically changing UE application requirements.

V. Conclusion & Outlook

In this work, an experimental evaluation of Wi-Fi in private 5G campus network frequency bands has been conducted. It was shown that, using the open source SDR based OpenWiFi stack, especially for low latency use cases, OpenWiFi can be beneficial in licensed frequency bands, but is severely deteriorated in the presence of 5G traffic. Therefore, we introduced a Multi-RAT resource manager concept in order to efficiently assign resources to both technologies as needed.

Further development of the OpenWiFi stack will eventually include IEEE 802.11ax, introducing OFDMA and therefore allow a more deeply integration of both technologies.

Additionally, multi-user analysis of the system as well as the analysis of Multi-RAT devices equipped with both 5G and OpenWiFi is planned, greatly increasing the flexibility of the resource management capabilities of the resource manager system. To further validate the system approach it will be replicated in a simulation environment to enable a comprehensive scalability analysis of the Multi-RAT resource management.

Acknowledgment

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