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Warehouse Deployment: A Comparative Measurement Study of Commercial Wi-Fi and CBRS Systems

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***Abstract*—In this paper, we analyze the latency, packet drop, and throughput performance of the commercial Wi-Fi and CBRS systems in a dense warehouse deployment. This paper is the first real-time warehouse measurement comparison of the mission-critical application with commercial Wi-Fi and CBRS deployments. The downlink (DL) and uplink (UL) data are transmitted via Transmission Control Protocol (TCP), and User Datagram Protocol (UDP) in the network. The results collected from the realistic implementation demonstrate that as the UL/DL traffic increases in the Wi-Fi network, instability in the system, a significant number of packet drops, and increased latency on the delay-sensitive traffic exist. It is more severe especially in mobility test cases where mobile devices roam from one Wi-Fi Access Point (AP) to another AP. On the other hand, in both static and mobility test cases, the packet drop rate of CBRS is consistently low at the desired target level with TDD frame allocation at Medium Access Control (MAC) scheduling. Also, the Celona Micro-slicing feature in the CBRS network consistently guarantees lower latency across different test conditions.**

I. Introduction

The cellular and Wi-Fi industry is the main source to satisfy the human traffics such as voice, video, and data applications, as the world is moving towards automation with Automated Guided Vehicles (AGVs), robots, drones, etc. The performance metrics such as latency and network throughput are equivalently important in enterprise deployment compared to human traffics. The existing Wi-Fi deployment (Wi-Fi 6 & 6 E with 802.11 ax) is great for indoor environment to meet the demand of mobile users for high data rate applications such as Virtual Reality/Augmented Reality (VR/AR). On the other hand, cellular operators deploy more small cells in 4G Long-Term Evolution (LTE) and 5G New Radio (NR) technologies, mostly outdoor, since the distributed antenna system (DAS) based solution leads to high deployment costs when it comes to local and indoor deployments for enterprises. Furthermore, these traditional cellular deployments usually do not integrate with enterprise local area networks (LAN). The existing traditional approaches such as Wi-Fi and cellular are hard to guarantee or meet the strict requirements of machine-critical use cases as industrial Internet-of-Things (IoT) with the characteristics of automation, smart connected, real-time monitoring, and collaborative control inflicts more strict requirements on latency, throughput, etc. The devices in these enterprises requirements in terms of latency, throughput and packet error rate criteria are completely different from consumer applications.

The other alternate mode of operation is to use Licensed Assisted Access (LAA), or New Radio Unlicensed (NR-U) in the unlicensed system. However, as the load increase, the User Equipment (UE) will experience more contention and collision on the channel, which can lead to more packet drop, higher jitter and latency, i.e., degraded performance in the case of sensitive deployments or mission-critical applications such as automated manufacturing factory and the health-care system. On the other hand, dedicated cellular licensed spectrum deployed in those applications are complex due to expensive custom solutions, completely disparate network, operator controlling everything and cumbersome support model.

The recent release on the locally available clean spectrum, *i.e.,* Citizenship Broadband Radio System (CBRS [1]), gains more attraction for the private deployments in the enterprise and even public scenario such as parking lots because Wi-Fi deployment is not ideal in public when parking lots are few and far between. The whole available bandwidth in the CBRS technology is 150 MHz which consists of 15 channels with 10 MHz per channel. For the initial BS operation, the radio needs to communicate its requirements in terms of transmission power, indoor or outdoor, bandwidth, channel, and operating frequency with the centralized controller known as Spectrum Assisted System (SAS). After the successful spectrum grant response, the BS will be ready to operate on the dedicated channel and frequency.

In this work, we investigate the behavior of the **first real-time warehouse deployments** utilizing two different technologies, such as Wi-Fi and CBRS[1]. Hence, we focus on the impact of the mission-critical application *i.e.,* ping in terms of latency, jitter, packet drop, and throughput with the actual data transmission of TCP and UDP of Uplink (UL) and Downlink (DL). We observe that, as the load (traffic) and the number of users increase in the system, the Wi-Fi is challenged to guarantee the performance compared to the CBRS.

[1]The radio network can be LTE or NR in the enterprise or warehouse deployment. The spectrum used on both technologies is CBRS. For the rest of the document, LTE/5G is referred as CBRS [2].

II. Spectrum Characteristics: Wi-Fi and CBRS

This section introduces the primary mechanism of Wi-Fi and cellular technology. We also demonstrate the difference between these two technologies in protocol and mathematical aspects to qualitatively analyze the distributed and centralized properties of the Wi-Fi and Cellular systems, respectively. Please note that the qualitative analysis is also mentioned in the experiment section to justify the results collected from the real Wi-Fi and CBRS deployment setup.

A. Wi-Fi 5GHz Channelization and Access Mechanism

In today's world, the Wi-Fi APs are deployed and operate on both 2.4 and 5 GHz, but typically, there are fewer available spectrums and more interference in 2.4 GHz. Due to the higher availability of spectrum, the Wi-Fi tests in this study were implemented in both the 2.4 and 5 GHz channel. The channelization used by Wi-Fi in 5 GHz, spanning 5.15 GHz to 5.85 GHz [3]. As specified by IEEE 802.11 standard, the Wi-Fi adopts the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), which means that a station can only transmit if the channel is sensed to be idle and the station has not just completed a successful transmission [4]. Otherwise, if the channel is busy during the DCF Interframe Space (DIFS) sensing period or the station is contending after successful transmission, the station persists in monitoring the channel until the channel is sensed idle for a DIFS period. Suppose there are N stations that contends on one channel and transmits with probability τ, then we have the following collision probability:

$$p = 1 - (1-\tau)^{N-1}, \tag{1}$$

where $N-1$ represents that $N-1$ UEs are IDLE and the complementary event represents a collision event. Note that one can also write as follows:

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}, \tag{2}$$

which can be obtained by summed all the stated from the Markov Chain constructed in [4]. Hence, one can utilize numerical techniques such as fixed point iteration to find the corresponding collision and transmission probability. As N increases, *i.e.,* the network is more crowded, it is more likely that more than one station transmit in each times slot, and the successful transmission probability

$$P_s = \frac{N\tau(1-\tau)^{N-1}}{1-(1-\tau)^N} \tag{3}$$

decreases. Hence, it is expected that the throughput decreases and the collision probability increases when the network is more crowded. The theoretical analysis also supports the simulation of average throughput versus the number of APs shown in Table IV.

In order to dive deeper into the packet drop rate because of physical layer, the operating channel spectral efficiency for UEs in Wi-Fi networks [5] is denoted as $\mathbf{C}$ (bit/s/Hz). As $\mathbf{C}$ increases, the rate of each component consuming packets in UL/DL buffer increases given the same successful transmission probability and vice versa. Hence, the packet drop rate resulted from contention-based mechanism can be further magnified by unreliable channel spectral efficiency in Wi-Fi networks.

B. LTE and 5G NR Mechanism

In LTE and 5G NR the radio resources are allocated in a centralized scheduling manner and radio resources allocation is completely different from the Wi-Fi CSMA network. In Wi-Fi, all the clients need to contend for the medium for UL/DL transmission but in LTE and NR all the UEs got allocated radio resources based on the scheduling algorithm in the MAC layer, so there is no contention or inefficient spectrum usage and all resources can be fully utilized to cover UEs due to centralized scheduling approaches of LTE and NR.

Celona channel allocation in 5G is a improvised version of the proportional fairness (PF) algorithm[2]. Denote $x(n)$ the data rate of UE n and $\log(x(n))$ the utility of UE n. From [6], the PF schedule's solution $x(n)$ satisfies

$$\sum_{n\in N} \frac{x(n)-x^*(n)}{x^*(n)} \leq 0, \tag{4}$$

where $x^*(n)$ denotes the optimal PF solution and for any other feasible $x(n)$, the aggregate proportional fairness gain is non-positive. The corresponding PF algorithm [7] has been shown to maximize the network throughput while guaranteeing the asymptotic proportional fairness. The advantage of PF algorithm for scheduling decision is that both of the UL/DL data buffer and the channel spectral efficiency are considered. The UE with higher data rate either due to higher channel spectral efficiency $\mathbf{C}_n$ or higher buffered UL/DL data has higher portion of scheduled resources in resource pool. On the contrary, if the UE has low channel spectral efficiency, the resources allocated is proportionally reduced. In a word, the centralized scheduling decision does not lead to any wasted resource. However, the channel spectral efficiency can reduce the network throughput. PF scheduler algorithm is used in CBRS network for utility maximization formulation. Consider N UEs and $R_t(n)$ denotes the average data rate UE n has received up to time t in a window of T time slots according to

$$R_t(n) = \left(1-\frac{1}{T}\right) R_{t-1}(n) + \frac{1}{T} x_{t-1}(n), \tag{5}$$

where $x_{t-1}(n)$ denoting the actual data rate of UE n at time $t-1$. The PF scheduler allocates resources to user n^* who maximizes the ratio of achievable instantaneous data rate over average received data rate, as shown below:

$$n^* = \arg\max \{P_t(n)\}, \tag{6}$$

where

[2]Due to privacy and confidential reason we are not revealing the actual MAC resource allocation implementation.

$$P_t(n) = \frac{C_t(n)}{R_t(n)}, \tag{7}$$

where $C_t(n)$ represents the channel spectral efficiency, i.e., the achievable *instantaneous* data rate for user n at time slot t. The scheduler finds the UE with the highest $P_t(n)$ to allocate all RBs in the current time slot t. Then, the user corresponding to the second largest $P_t(n)$ is allocated and so on until there are no resource blocks (RBs) left in current slot.

C. CBRS Spectrum Operation Mode

The CBRS private network utilizes the LTE/NR technology and operates on the 3GPP band 48 of radio frequency spectra from 3.5 GHz to 3.7 GHz (*i.e.,* 150 MHz) for 3 types of users namely: (a) Tier 1: Incumbent Users (e.g. the Navy radar and satellite system) (b) Tier 2: Priority Access License, PAL (e.g., private organizations such as hospitals, universities, factories) (c) Tier 3: General Authorized Access, GAA (e.g., unlicensed users such as phones, tablets, laptops, home routers). Originally, this band was reserved for use by the US Department of Defense, namely US Navy radar systems. However, in 2015, the Federal Communications Commission (FCC) dubbed the 3.5 GHz band the "innovation band" to be opened to new mobile users. The 1st tier incumbent is protected against interference from PAL and GAA users. PALs are awarded to the highest bidders and allow coverage on a county-by-county basis. A single PAL covers a 10 MHz channel within the 3550-3650 MHz band and is assigned in 10-year renewable blocks. PALs must accept interference from Incumbent Access users but are protected from interference from the GAAs, who are last in line to use the spectrum ac ross the 3550-3700 MHz band. Since this tier is of the lowest priority, interference from any other tier or other GAA users is allowed to happen.

III. Wi-Fi and CBRS: Pros and Cons

Both Wi-Fi & CBRS has their own advantage and disadvantage as described.

- **Spectrum Coordination:** In Wi-Fi, the unlicensed spectrum used by multiple technologies with 563 MHz (plus 1.2 GHz coming in 6 GHz bands). This band also supports incumbent protection on 5 & 6 GHz bands. In CBRS, there is a coordinated spectrum allocation between networks which is ensured by SAS. The total bandwidth is 150 MHz, and it is controlled and centralized by incumbent protection by SAS Environmental Sensing Capability (ESC).
- **Coverage Range:** The Wi-Fi has lower transmit power compared to the CBRS. The Wi-Fi noise floor is based on full channel width (for eg, 20+20, 40+40, 80+80 MHz). The noise floor on Orthogonal Frequency Division Multiplex (OFDM) sub-carriers is 15 KHz.
- **Traffic Handling:** In Wi-Fi, the client and APs are in the nature of distributed contention. The dynamic allocation is possible in either direction. On the other hand, in CBRS, the allocation of radio resources in a scheduled manner. It depends on weighted upload and download profiles.
- **Quality of Service:** The statistical prioritization will happen in Wi-Fi due to the contentious nature of the network. This can be improved by an optional RF loop. In CBRS, the deterministic support of QoS due to scheduling and has mandatory RF feedback loop such as Channel Quality Indication (CQI),Signal-to-Interference-plus-Noise Ratio (SINR), etc.
- **Density Handling:** Wi-Fi supports Single Factor OFDMA, & the legacy OFDM is still Prevalent. The co-channel interference in Wi-Fi is blocked due to the nature of CSMA protocol. On the other hand, CBRS supports dual Factor OFDMA (Freq. Time Domains) and co-channel interference is Non-Blocking.
- **Mobility:** The Wi-Fi needs to have the client off-channel scanning, and the client controls the roaming decisions. But CBRS is based on infrastructure-controlled handover decisions, & its precisely timed.

Fig. 1: Wi-Fi Indoor Deployment and Floor Plan.

IV. Celons Micro Slicing

Micro Slicing is a powerful technology that allows precise control over resource and service allocation for different groups of delay-critical applications and devices. It offers control and adjustment to numerous service types including data rate, quality, latency, reliability, and network access policies. Fig. 2 shows that the Celona's micro slicing feature allocates users guaranteed portions of the network dedicated to the respective devices and application groups. Every Celona Micro Slicing policy is supervised by the Celona enterprise orchestrator, which allows necessary adjustments instantly. For example, the policy automation with micro slicing will enables the following:

- **APP level service level agreements (SLAs)** for bandwidth, latency and packet error rate as input
- **APP aware provisioning** of the network fabric with individual policies
- **App level key performance indicators (KPI) observability** with AI/ML techniques that learn app behavior over time

The platform records application-oriented SLA and KPI across all devices, granting complete user visibility of the device performance across the spectrum. Celona Micro Slicing has been proposed to accelerate private LTE/5G wireless deployments within the enterprise - and as a result, it allows enterprises to control costs for end users while maintaining higher flexibility and efficiency. Because this technology grants control over network resources, end users are able to avoid occupying unnecessary resources.

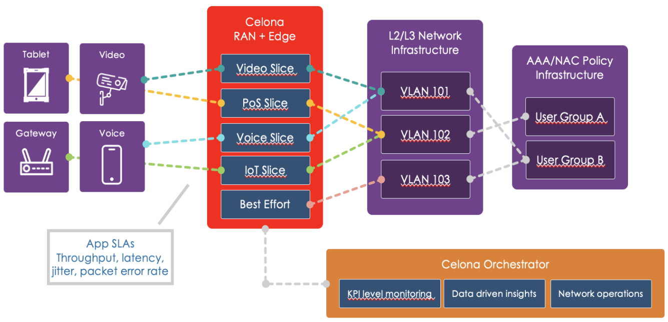


Fig. 2: Celona Micro Slicing Feature.

V. Experiment Environment and Configuration

In this section, we discuss the experiment environment and configuration parameters, and system utilization for the Wi-Fi and CBRS systems. In the warehouse setup, carts (or Fork Lifts) receive direction instruction from DL to collect storage packages and re-store or ship it in the corresponding destination, and report the status back in UL. In some scenario, these carts need to be charged for restoring the battery backup, which leads to high demand in DL and UL.

A. Wi-Fi Environment, Configurations and System Utilization

The setup is shown in Fig. 1, we don't have access to the Wi-Fi network controller so we don't provided any system configuration files. The tools used to understand the Wi-Fi Radio Frequency (RF) footprint are Ekahau Pro, Sidekick, Wi-Fi explorer pro, and wireshark. For indoor, we walked at the consistent speed and most paths where walked in both directions to limit the impact from surveyors body interference. We did both walk test and cart was used at low and high speed at the indoor locations. The Wi-Fi cell edge are recorded as -67 dBm. The seven different SSIDs are present and all are dual band support. The 2.4 GHz Wi-Fi APs are configured on 20 MHz with the possible channels on 1, 6 and 11 and the basic rates are set at 24 Mbps and lowest rate set to 12 Mbps. The Wi-Fi 5 GHz are operating on UNII-1 and UNII-3 so there is no DFS active operation on this band hence it enable the fast handover. All the Wi-Fi 5 GHz APs are configured to the IEEE Wi-Fi 5 standards, with 20 MHz bandwidth.

The high beacon overhead observed on 2.4 GHz which reducing the available bandwidth up to 12% and also due to the amount of co-channel interference and quantity of SSIDs in use, a high base channel utilization was observed. In 2.4 GHz had up to 41% channel utilization with zero users attached and in 5 GHz had up to 18% channel utilization with few users attached.

TABLE I: Deployment Parameters

Parameter	Value
Experiment Environment	Indoor
Number of indoor Wi-Fi APs	103
Number of indoor CBRS APs	22
Wi-Fi and CBRS AP Placement	Roof Ceiling
Wi-Fi Operating Frequency	2.4 and 5 GHz
CBRS Operating Frequency	3.55 to 3.7 GHz
Mobile devices used	Samsung S21 and Google Pixel
Enabled Celona Micro slicing	Yes
Enabled Wi-Fi QoS	Yes

B. CBRS Environment and Configuration

The CBRS deployment and the connection setup as shown in Fig. 3 and 4. The frequency planning was constructed based on Celona Self Organizing Network (SON) algorithm to set the optimal EARFCN and transmission power to reduce the co-channel interference. The Physical Cell ID (PCI) allocation algorithm allocates different PCI for each CBRS AP so there will not be any PCI collision or confusion problem. In this test setup, we used ROHDE & SCHWARZ autonomous mobile network scanner with external Single Input Single Output (SISO) antenna module to collect the radio signals in terms of PCI, EARFCN, RSRP, RSRQ and SINR. The samsung galaxy S21+ device is used with Qualipoc setting to collect all PHY, MAC and Application layer information. The walk and drive test is performed similar to the Wi-Fi experiment, a custom route developed for the location in the manner that would replicate the real world movements through the indoor warehouse building. The collected radio metrics was analyzed using industry standard post processing software. Table. I shows the number of Wi-Fi and CBRS AP nodes are used to cover the same region of the indoor warehouse.

C. Traffic Environment: TCP, UDP Iperf and Ping Application

In our experiment, we use two different nature of QoS application such as iperf and ping. For the Wi-Fi network, we got permission to install the iperf server on the controller edge to avoid any other additional overhead delay on the backhaul network. Similarly for CBRS AP, the DL and UL iperf traffic goes through our own deployed server (in the Celona 5GC edge). Both the DL and UL traffic is TCP, we load the network by enabling multiple TCP connections (*i.e.,* 60 parallel streams) over the iperf to mimic the behaviour of high demand. This emulates the scenarios from 25 to 30 UE scenarios with 1 DL 1 UL or 2 DL 2 UL devices. We also run the experiment on UDP with smaller packet size less than 1 MB *i.e.,* 1000 Kbps to mimic the behaviour of short bursts. The ping packets are transmitted in the interval of 10 ms and the time to live is 64 hops with the ICMP packet mode. The timeout duration of the ping packet in the experiment is 1000 ms. The experiment procedures are as follows.

- Ping for 60 seconds at 10ms

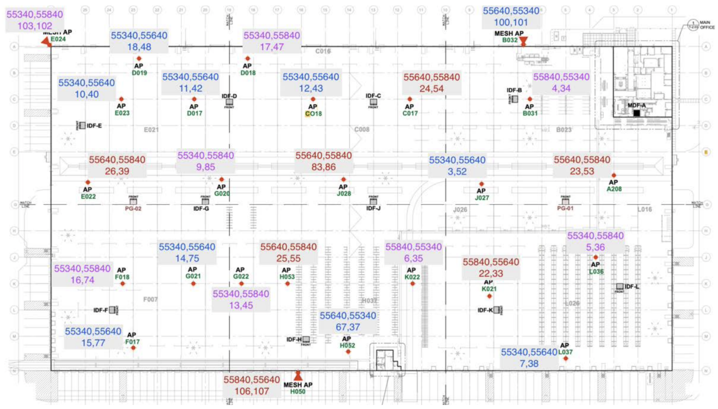


Fig. 3: CBRS Indoor Deployment and Floor Plan.

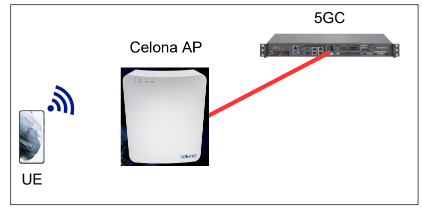


Fig. 4: Celona Setup

- Ping for 60 seconds at 10ms, then Start Iperf3 TCP UL for 60 seconds
- Ping for 60 seconds at 10ms, Start Iperf3 TCP DL for 60 seconds
- Ping for 60 seconds at 10ms, Parallel Iperf3 TCP UL and DL for 60 seconds
- Ping for 60 seconds at 10ms, Start Iperf with UDP 1 Mbps bandwidth

It is noteworthy that multiple types of traffic can happen in practice such as heavy UL traffic, heavy DL traffic, and dynamic and small packet transmission. These traffic can also happen at the same time for various scenarios.

VI. Experiment Result Discussion

A. Wi-Fi and CBRS Heat Maps

Fig. 5(a) shows the heat map of the Wi-Fi coverage in the warehouse scenario. Most of the coverage are in the range of -65 to -75 dBm. Similarly, Fig. 5(b) shows the RSRP heatmap of CBRS system and 60% of the coverage are in the good throughput region. From the heatmap it is obvious that there is *no coverage hole* on both Wi-Fi and CBRS system. Hence, the RF planning is designed well to cover the entire warehouse. On the other hand, the number of indoor Wi-Fi AP deployed is 103 that is higher than the number of indoor CBRS AP *i.e.,* 22 to cover the same region as shown in Table. I. Please note that 103 and 22 are the minimum numbers of Wi-Fi AP and CBRS that could cover the warehouse, respectively. This leads to more reuse of same channel in Wi-Fi and which leads to more contention and collision on the unlicensed medium.

B. Static Unloaded Scenario

1) CBRS: In this subsection, we investigate the radio resource allocation of CBRS MAC. Fig. 6(a) shows the ping traffic on the CBRS spectrum. If there is no other traffic over the air and only ping transmission happens in the interval of 10 ms. The ping latency we observe in the range of 30 to 40 ms, this is due to the LTE frame protocol stack overhead but there is no much fluctuation on the packets and the jitter (*i.e,* the difference in latency between packet flow from one client to another) is in the order of 10 ms. Similary, when we add the UL and DL traffic after 60 ms transmission of ping traffic as shown in Fig. 6(b). We observe the UL throughput of close to approximately 24 Mbps on 20 MHz bandwidth[3]; this is because of one layer with no carrier aggregation. On the downlink, the CBRS can reach up to a maximum of 140 Mbps[4] with 20 + 20 MHz carrier aggregation. We see some degradation or increase in ping latency during UL and DL transmission, but it is in the range of $<$ 100 ms. Also, the fixed TDD UL and DL frame format with celona micro-slicing have benefits in terms of allocating the radio resource by reserving the slot for UL and DL transmission compared to the contention-based.

2) Wi-Fi: Fig. 6 (c) shows the Wi-Fi ping traffic in the unloaded scenario. We see more fluctuation in the transmission, even in the unloaded scenario. Fig. 6 (d) shows the ping and UL + DL transmission in the Wi-Fi network. The ping traffic gets more unstable when UL and DL start to transmit. The throughput performance of UL and DL are the same, and it is degraded due to contention on the medium. This is due to the Wi-Fi APs operation on only 20 MHz channel. Though there are Wi-Fi APs deployed on the 5 GHz band, which is capable of supporting 20, 40, 80, and 160 MHz, the warehouse Wi-Fi network planned to have more dedicated narrow channels instead of more overlap wider channels. Moreover, in 5 GHz, the transmission power is fixed irrespective of the bandwidth, but it is different in the recent 6 GHz spectrum band. This leads to large range coverage, and there are more Wi-Fi APs deployed, which leads to more contention and collision on the medium.

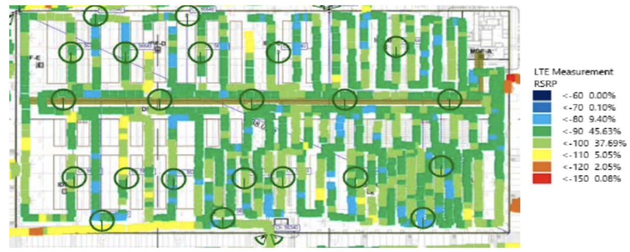
C. Static Loaded Scenario

1) CBRS: In this subsection, we load the network with one more additional UEs on the same channel conditions and connect to the network with UL and DL transmission. Fig. 7 (a) shows the CBRS with only ping for the initial 60 seconds,

[3]Depends on the good channel condition it can go up to max. of UL one layer 40 to 50 Mbps

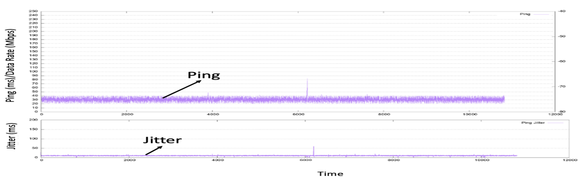
[4]Depends on good channel condition it can go up to max. of DL 180 Mbps

(a) *Wi-Fi RSSI*

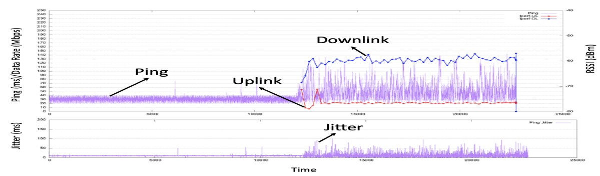


(b) *CBRS RSRP*

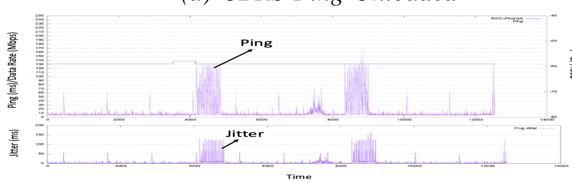
Fig. 5: *Wi-Fi and CBRS Heat Maps*



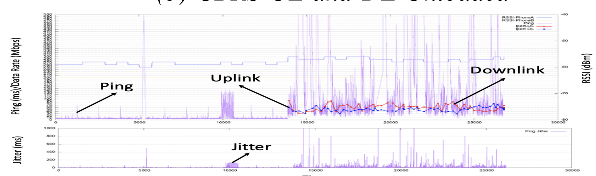
(a) *CBRS Ping Unloaded*



(b) *CBRS UL and DL Unloaded*

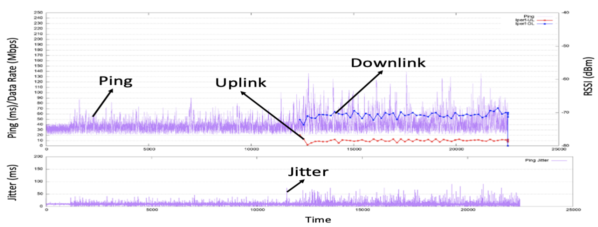


(c) *Wi-Fi Ping Unloaded*

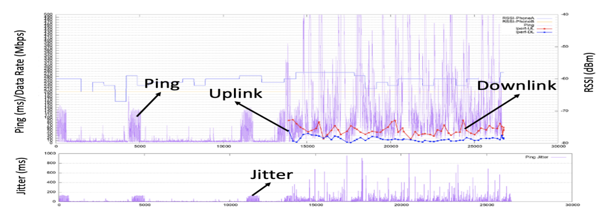


(d) *Wi-Fi UL and DL Unloaded*

Fig. 6: *Static: CBRS & Wi-Fi Unloaded Ping, UL and DL Scenario*

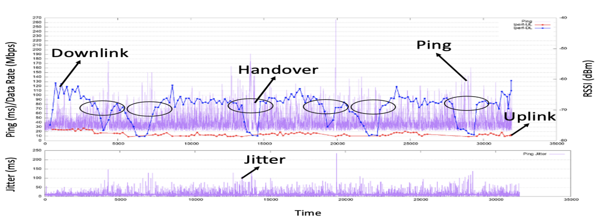


(a) *CBRS UL and DL Loaded*

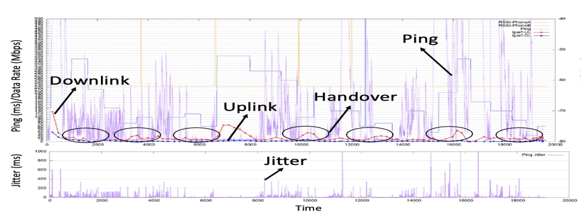


(b) *Wi-Fi UL and DL Loaded*

Fig. 7: *Static: CBRS & Wi-Fi Loaded Ping, UL and DL Scenario*



(a) *CBRS UL and DL Loaded*

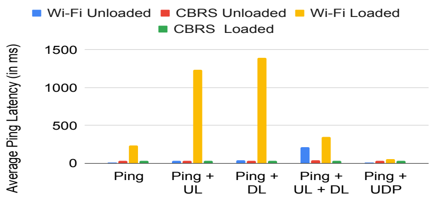


(b) *Wi-Fi UL and DL Loaded*

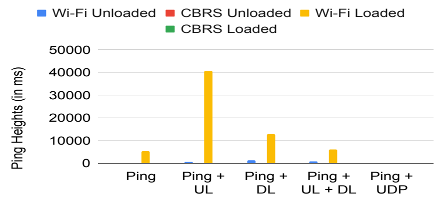
Fig. 8: *Mobility: CBRS & Wi-Fi Loaded Ping, UL and DL Scenario*

and then after 60 seconds, two devices are connected to the same CBRS PCI. The DL and UL throughput is reduced to half *i.e.,* DL: 70 Mbps per UE device and UL: 12 Mbps per UE device. This shows the benefits the scheduling with TDD slots, and the radio resources are fairly shared among the two UEs.

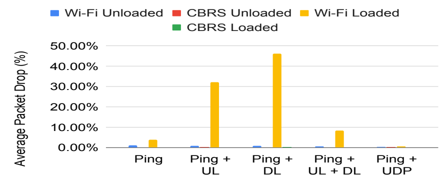
2) Wi-Fi: Fig. 7 (b) shows the Wi-Fi loaded scenario with the additional UE, which is similar to the CBRS loaded setup.



(a) Avg. Ping Latency



(b) Max. Ping Heights



(c) Avg. Ping Drop

Fig. 9: *Static Loaded and Unloaded Scenario*

We ensure the UEs are in good channel condition in terms of RSSI and connected to the same SSID MAC address. When the UL and DL traffic is loaded after 60 seconds, we notice there is more fluctuation compared to the unloaded Wi-Fi scenario. This leads to high latency in the order of 500 ms. Also, the DL and UL throughput are not shared with fairness because of more contention and collision among the Wi-Fi clients. This can lead to more buffer overflow due to less access to the medium which is different from the CBRS system.

D. Mobility Loaded Scenario

In this scenario, we used a cart to do real AGVs mobility in 25 Km/h and the floor plan is demonstrated in Fig. 3 and connection setup as shown in Fig. 4. This is a fast indoor scenario with the TCP application running on the UEs for both CBRS and Wi-Fi experiments. We observed maximum 149 ms latency in the CBRS and greater than 500 ms latency in the Wi-Fi system. During the time of handover from the serving PCI to target PCI in CBRS there is noticeable decrease in throughput from 120 Mbps to 20 Mbps and resume back to max throughput after successful handover. Fig. 8 (a) shows the performance in the CBRS system, where all the three traffic ping, DL and UL starts at the same time. The interesting part is that the DL and UL throughput is stable, although performance degradation does exist during the handover phase between one PCI to another PCI for CBRS. Fig. 8 (b) shows the performance of the Wi-Fi system, where the ping, UL, and DL are not stable with the high ping latency, and some zero throughput's on UL and DL transmission. This is because the Wi-Fi handover is initiated by clients without having the full knowledge of the RF and making the break-and-make decision. On the other hand, in CBRS, the handover is managed by infrastructure; hence the make-and-break decision leads to seamless transmission with not much degradation in the performance.

E. Analysis on Ping and Packet Drop

Fig. 9(a) shows the average ping latency on the Wi-Fi and CBRS systems. In these results, we demonstrate ping-only traffic, ping + TCP UL, ping + TCP DL, ping + TCP UL + TCP DL, ping + UDP DL + UDP UL. The ping packets are in the interval of 10 ms. As there is a mix of TCP iperf UL and DL, the ping average latency suffers greater than 500 ms in the Wi-Fi system. On the other hand, the CBRS latency is guaranteed for critical applications like ping. When we try to send the UDP packets with a minimum size of < 1 MB, the Wi-Fi system is able to guarantee the latency. Fig. 9(b) shows the maximum ping heights achieved on both Wi-Fi and CBRS systems. When there is a ping + UL transmission, note that there is a higher packet drop rate in Wi-Fi compared to the CBRS as shown in Fig. 9(c). But interestingly we noticed, the impact with ping + UL + DL is low compared to ping + UL and ping + DL, this is because UL and DL has very low throughput similar to Fig. 8 (b) and the ping + UL + DL is almost the same as ping-only traffic, i.e., the necessary channel contention is much lower than ping + DL or ping + UL. Wi-Fi QoS enabled feature supports the ping traffic with less latency and packet drop.

VII. Conclusion

This paper showcases the first measurement study of commerical Wi-Fi and CBRS systems in which we observe CBRS technology provides robust indoor coverage with a low density of nodes or base stations to solve the roaming issues on the Forklift or AGVs. CBRS provides seamless mobility with consistent throughput and low latency for indoor use cases. Mission-critical applications can run reliably over CBRS compared to Wi-Fi. The CBRS networks provide demonstrable economic and technical benefits.

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