Harvesting Unlicensed and Shared Spectrum: Opportunities and Challenges

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Introduction

The inexorable rise in wireless capacity demand continues to place strains on bandwidth, as we move into a 5G world. On one hand, more and more users are actively using the system, and demanding continuously improved quality of experience. Adding to this is an increasingly diverse array of applications and services, with their own Quality of Service (QoS) requirements. Add in a diversity of terminal devices, and the resultant capacity demand can be expected to push or exceed bandwidth supply even in a 5G world.

Traditionally, wireless technologies have expanded capacity in three ways:

- By adding more spectrum, i.e. increasing supply;
- Via improved spectral efficiency, making better use of the spectrum that is available. This has been done via higher-order modulation schemes (packing more bits into the link), spatial multiplexing (Multiple Input Multiple Output (MIMO) and Multi-User MIMO schemes) and by use of higher spectrum bands ("fatter pipes");
- And via spectrum reuse: dividing the network into smaller and smaller cells, and reusing wireless capacity (the same channels) over and over across a given geographical area. This provides a capacity multiplier effect, and has historically been a major contributor to capacity growth.

Spectrum sharing in unlicensed bands can significantly add to the available pool of wireless bandwidth. Swathes of spectrum are available today in unlicensed bands, governments are releasing new, lightly used bands for spectrum sharing, and new unlicensed bands are being allocated for use in 5G.

This paper discusses opportunities for use of unlicensed bands to augment capacity, several use cases that unlicensed spectrum can support, key challenges that need to be surmounted and solutions to address them.

Growing Scope for Unlicensed Spectrum Usage

Spectrum sharing in unlicensed bands occurs today. Wi-Fi is a good example – multiple Wi-Fi networks and devices coexist in the 2.4 and 5 GHz band today, obeying a well-defined access etiquette. However, unlicensed spectrum usage will grow further as we move into a 5G future. This will be driven by several factors.

1. Unlicensed Spectrum as it Exists Today (in 4G)

Figure 1 below depicts key spectrum bands allocated (in the U.S.), as they exist today. Several unlicensed bands exist – notable among these are the Industrial Scientific and Medical (ISM) bands in 2.4 GHz and 5 GHz. The ISM bands have traditionally been occupied by unlicensed technologies – predominantly by Wi-Fi, although the 2.4 GHz band also hosts technologies such as ZigBee and Bluetooth. Unlicensed LTE operation variants, such as LTE Licensed Assisted Access (LTE-LAA) and MulteFire, are set to operate in the 5 GHz band, in addition to Wi-Fi.

The 60 GHz band supports ultra-high bandwidth, short-range communications, and is considered part of millimeter-wave (mmWave) spectrum. 802.11ad technology (also branded as WiGig) operates in this band today; WirelessHD is another standard that is designed to operate in this band. Both technologies target short-range video products that connect high-definition television (HDTV) sets, Digital Video Recorders (DVRs), set-top boxes, gaming stations and other devices capable of stream uncompressed video over short ranges.

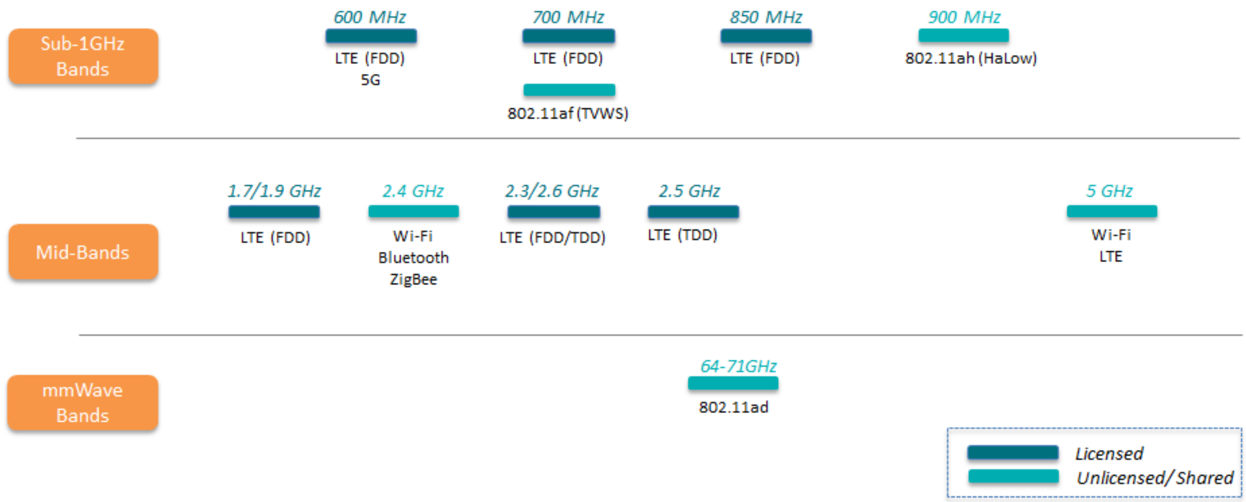

Figure 1: Existing US Spectrum Allocation

2. Greater Scope for Unlicensed Spectrum Use in a 5G World – More Bands, a Readymade Standard

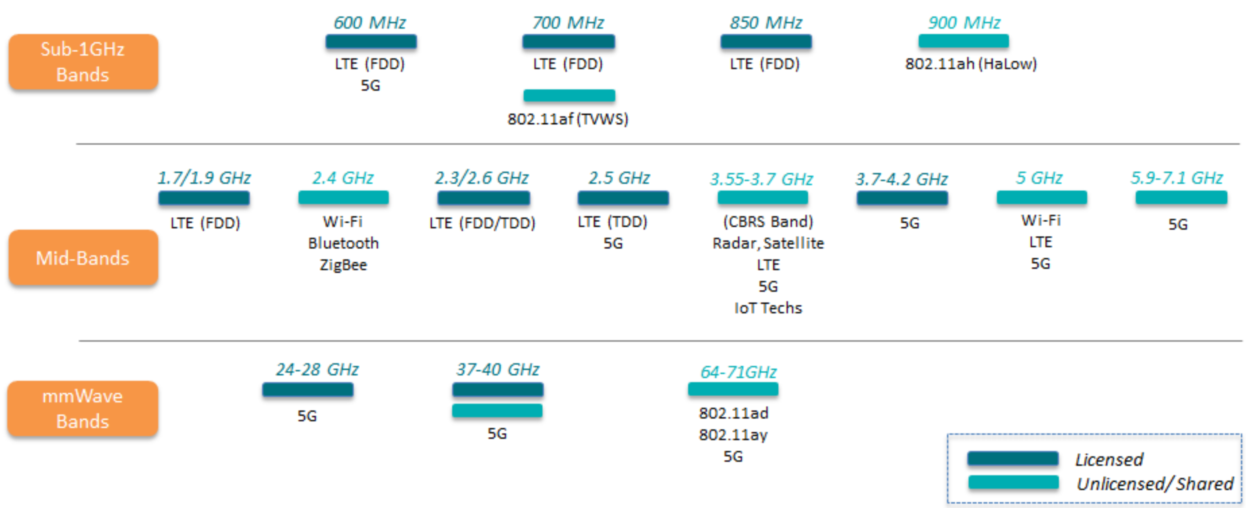

Figure 2: US Spectrum Allocation in a 5G World

As can be seen from Figure 2, the 5G landscape ushers in several additional unlicensed and lightly licensed bands that augment spectrum capacity significantly.

Several additional bands have been allocated for 5G in the U.S. In addition to newly opened-up licensed bands, unlicensed or shared spectrum is available in both mid-bands (between 1 and 6 GHz) and mmWave bands (above 24 GHz). Included in the mid-band range is the 3.5 GHz band opened up by the Federal Communications Commission (FCC) for spectrum sharing – also known as Citizens Broadband

Radio Service (or CBRS). CBRS opens up to 150 MHz of spectrum for lightly licensed and opportunistic use by different technologies – LTE, 5G, IoT technologies and others.

It is worth noting that the 5G New Radio (NR) standard has been designed from the outset to operate in most of these unlicensed bands. We can expect to see 5G networks and devices that are ready from the get-go to leverage unlicensed spectrum more expansively – as opposed to today, where LTE devices and infrastructure have had to be adapted to operate in the 5 GHz and CBRS bands, i.e. as an afterthought.

Figure 2 also indicates that multiple wireless technologies will need to coexist in many of these bands. The 3.5 GHz (CBRS) band is likely to be shared by several technologies. The same is the case with the mmWave 60 GHz band – where 802.11ad, 802.11ay (Wi-Fi's own mmWave technology) and 5G will coexist.

3. 5G Technology Is Unlicensed Spectrum Friendly from the Outset

5G NR incorporates capabilities that lend themselves to efficient unlicensed operation, and should enable 5G to coexist harmoniously with other technologies in the same bands:

- Support of a variety of unlicensed and shared bands by design.
- Band-agility: 5G radios will be able to switch bands nimbly to support specific deployment scenarios and service types.
- 5G NR supports flexible numerology, i.e. physical layer parameters are reconfigurable on the fly to support different operational scenarios and services. For example:
    - Switching from band to band, and reconfiguring to enable optimal operation in the new band;
    - Moving between indoor and outdoor scenarios;
    - Supporting different service types, e.g. applications with latency-critical requirements, high-bandwidth needs, networks with large numbers of devices (e.g. IoT) etc. 5G allows services with different numerologies to be multiplexed within the same carrier (or portion of a carrier).
- 5G NR provides millisecond or sub-millisecond latencies and Gigabit throughputs, which means that a 5G device can switch in and out of a channel in short time, freeing up the channel for use by other devices.
- Network slicing capabilities that allow sharable bandwidth pools to be divvied up and allocated to devices and services in an equitable fashion.

4. Spectrum Sharing Paradigms

Sharing of unlicensed spectrum can be done in multiple ways. Vertical sharing involves a multi-tier structure, where upper tiers have priority over, and are protected from, lower tiers. Examples of vertical sharing models are CBRS and Licensed Shared Access (LSA), where an incumbent system has highest priority access to resources, and lower tiers defer to layers above them (including the incumbent) while trying to access the system. Access to these systems is typically arbitrated by a central database entity.

With horizontal sharing, all systems sharing the spectrum have the same access priority, and access is typically governed by a well-defined access etiquette. ISM band operation is a good example of horizontal sharing. Multiple Wi-Fi and LTE/5G systems can coexist in 5 GHz, without a central coordinating entity. Hybrid models can incorporate elements of horizontal and vertical sharing.

Unlicensed Spectrum Use Cases

Several interesting use cases exist today, and we can expect to see many more in a 5GG landscape. Use cases entail standalone unlicensed operation, as well as integrated licensed / unlicensed scenarios.

1. Next-Generation Home Wi-Fi System

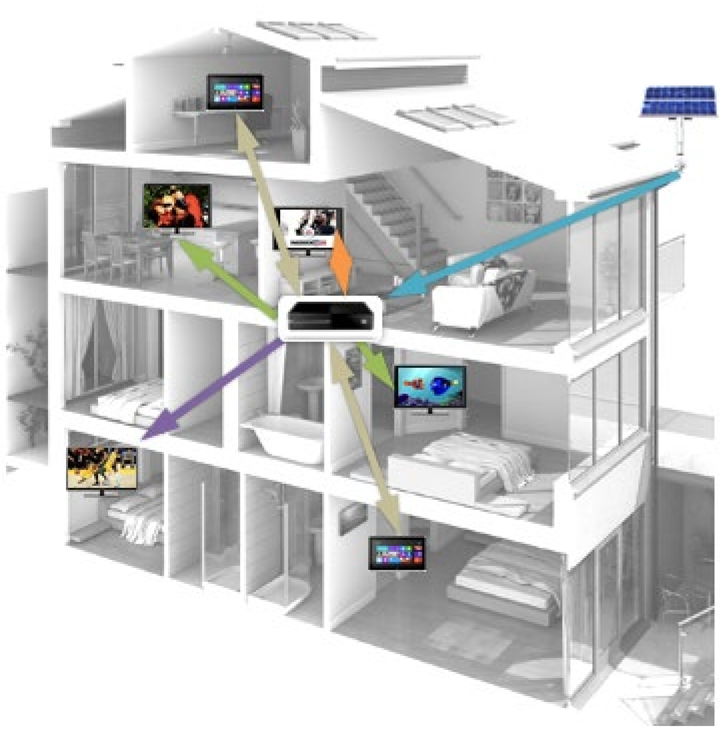

Figure 3: Next-Generation Home Wi-Fi

Next-generation Wi-Fi technologies (802.11ax and 802.11ay) will form the cornerstones of home connectivity and coverage in a 5G world. 802.11ax is Wi-Fi's next jump forward. Apart from providing gigabit bandwidths, 802.11ax is designed to enable more efficient use of bandwidth, and provide higher capacity and interference resistance in dense Wi-Fi deployments. 802.11ax can operate in both 2.4 and 5 GHz bands. It incorporates cellular-like Orthogonal Frequency-Division Multiple Access (OFDMA) and scheduling features, as well as Multi-User MIMO, which enable multiple users to simultaneously use a Wi-Fi channel – supporting a larger number of simultaneous users.

802.11ay is Wi-Fi's next-generation mmWave technology, designed to operate in the 60 GHz band. 802.11ay is ideal for ultra-high bandwidth, short-range communication between devices that carry high-definition video. 802.11ay can be used as an in-room technology in different parts of a home, whereas 802.11ax can provide umbrella coverage across the home and the broadband conduit in and out of the home. 802.11ay's Fast Session Transfer capability can switch a connection between 60 GHz and 2.4 / 5 GHz bands, as the user moves around in the house.

2. Community Wi-Fi Hotspot Network

Community Wi-Fi allows a service provider to craft a crowd-sourced public hotspot network, leveraging unused capacity on existing Wi-Fi infrastructure (e.g. residential and enterprise routers). A service provider can also use this excess capacity to offer retail and roaming services to subscribers of partner operators.

Essentially, each component router in the hotspot network emits two signals – a public signal (public Service Set Identifier or SSID) and a private SSID. The residential user accesses their system using the private SSID, while a roamer uses the public SSID. The two signals are firewalled from one another, so that the respective data connections are secure. Roaming users are only allowed to use the Wi-Fi network capacity that is currently not used by the residential user.

Community Wi-Fi deploys hotspot networks multiple times faster than traditional hotspots, and is expected to evolve to leverage next-generation Wi-Fi and 5G technologies to boost speeds and support greater densification.

3. Licensed – Unlicensed Aggregation

This approach allows a service provider to combine LTE or 5G technology with Wi-Fi to augment capacity. Using LTE/5G and Wi-Fi radios simultaneously on the device and infrastructure ends, it is possible to split a single bearer (or traffic flow) across cellular and Wi-Fi links, based on policy and channel conditions. This allows applications to use both cellular and Wi-Fi links simultaneously, and dynamically move traffic between the two links based on changing radio conditions - providing significant performance gains.

This capability has been standardized by the cellular standards body 3GPP (3rd-Generation Partnership Project) as LTE-LWA (LTE-WLAN Aggregation). A 3GPP study on 5G operation in unlicensed spectrum is looking to do the same with 5G.

4. LTE or 5G Operation Standalone in Unlicensed or Shared Spectrum

This use case entails operating LTE or 5G standalone in an unlicensed or shared spectrum band. Flavors include LTE operating solely in the 5 GHz band (also known as MulteFire), LTE operating in the CBRS (3.5 GHz) band, and 5G NR in any of the allocated unlicensed bands allocated to 5G. This approach combines the performance benefits of LTE with the simplicity of Wi-Fi-like deployments.

This model provides particular value to service providers without cellular licenses, e.g. cable operators can deploy LTE small cells to provide outdoor coverage and capacity. It is also suitable for private LTE or 5G networks deployed by enterprises, venues and industrial IoT providers, and can also be used for neutral host deployments that serve multiple operators.

5. Licensed Assisted Unlicensed Access

LTE-LAA (LTE Licensed Assisted Access) augments a service provider's licensed band LTE service by also utilizing the unlicensed 5 GHz band. An anchor licensed carrier (carrying control and data traffic) is combined with an unlicensed carrier that carries data. This approach boosts capacity for an operator with access to licensed spectrum. Unlike the aggregation case discussed previously, the LTE radio actually operates in unlicensed spectrum, and hence must be able to coexist harmoniously with Wi-Fi in the same band. The 3GPP study on 5G operation in unlicensed spectrum is looking to do the same with 5G.

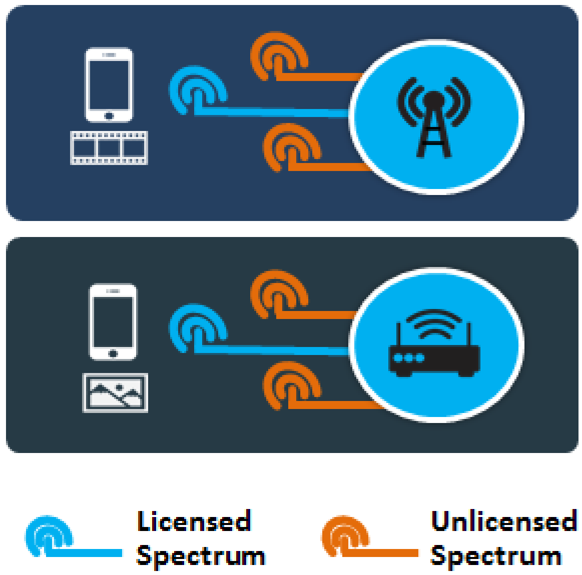

Figure 4: LTE/5G in Licensed + Unlicensed Spectrum

6. Vertical Spectrum Sharing – CBRS

The three-tier Citizens Broadband Radio Service (CBRS) is a well-defined initiative opened up by the FCC to allow lightly licensed and unlicensed use of lightly used spectrum in the 3.55 – 3.7 GHz band. The bandwidth available for sharing is significant – a total of 150 MHz of spectrum is usable when free.

CBRS is a vertical spectrum sharing framework with three access tiers:

- Tier 1 is occupied by incumbents, i.e. military radar, fixed satellite systems
- Tier 2 (Priority Access Layer or PAL) is licensed, and 70 MHz of spectrum is allocated to PAL layers. Up to seven 10 MHz channels can be allocated per "census tract" (about the size of a small town) and awarded to the highest bidders for three-year periods. Tier 2 users can access channels that are not in use by Tier 1 users
- Tier 3 is General Authorized Access (GAA), where no license is required – and is open to opportunistic use. GAA users can access channels that are not in use by Tier 1 or PAL users.

Enforcement of access rules and arbitration of spectrum access is done by a Spectrum Access System (SAS) database. The fact that PAL licenses will be granted for smaller geographical areas (census tracts) than traditional cellular licenses makes these licenses much more affordable for smaller players. This, in fact, is one of the FCC's goals with CBRS – to stimulate wireless innovation and competition, and encourage smaller players.

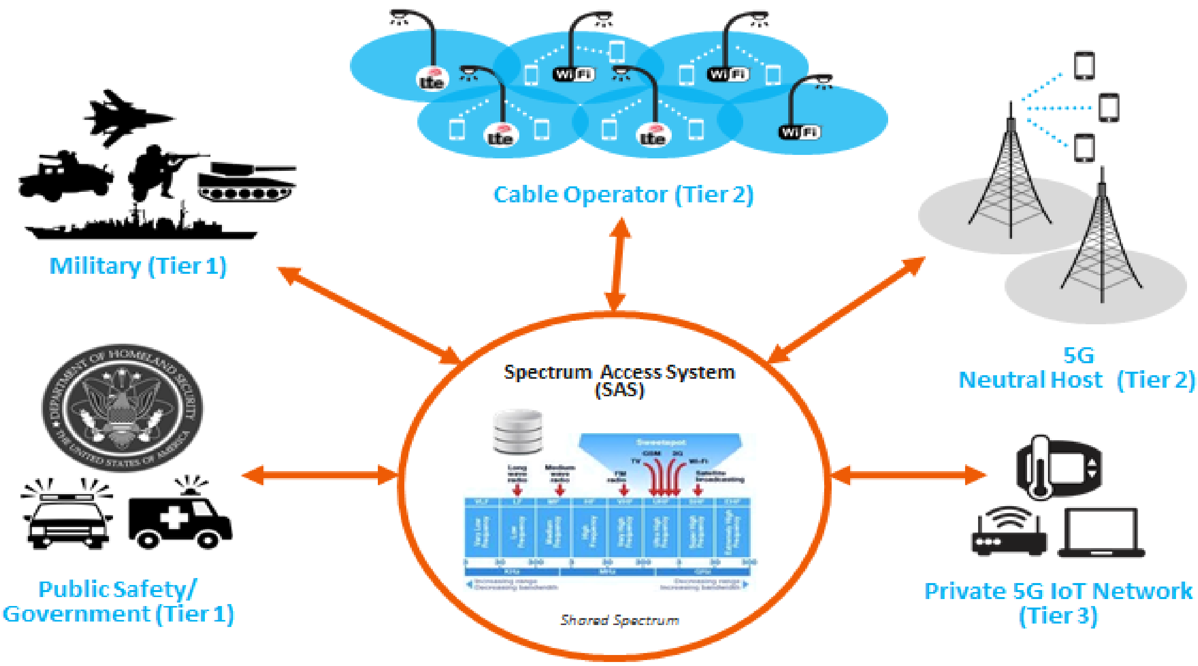

Figure 5: CBRS Framework and Use Cases

Figure 5 shows exemplary use cases that CBRS can support. Players without licensed spectrum like cable MSOs are good examples of Tier 2 licensees. A cable co. can leverage PAL licenses to provide outdoor service using small cells, as an example. The propagation characteristics of 3.5 GHz make it highly suitable for small cell operation. Enterprises and venue owners can acquire PAL licenses and create private LTE or 5G networks. Industrial IoT is a good example of a Tier 3 service. It is worth noting that PAL users can add to their Tier 2 allocation by accessing the system at Tier 3 when possible.

Unlicensed Spectrum - Performance Challenges

As multiple technologies start to use unlicensed bands and deployments densify, congestion and interference become significant issues. This is driven by multiple factors:

- Multiple technologies occupying the same spectrum bands. We already see this within the 2.4 GHz band, where Wi-Fi, Bluetooth and ZigBee operate. The 5 GHz band is set to see LTE operate in it, in addition to Wi-Fi, with perhaps 5G NR in the future as well. The CBRS band is likely to see diverse technologies having to coexist in it.
- Dense deployments will add to the problem. In an area with a large number of devices deployed close to one another, there can be severe contention for radio resources.
- Multiple service providers delivering service in the same areas add to the densification issue.

What this brings about is congestion and potential interference. When a large number of devices, and multiple technologies, contend for the same radio resources, channel access wait times go up, and performance metrics get affected. Latency and jitter go up, throughput reduces, and QoS gets affected.

The other performance variable that needs to be managed is coverage. While the higher frequency bands (e.g. mmWave) support high bandwidths, it is typically at the expense of propagation range. Poor coverage (as a result of a device experiencing low signal strength) results in low throughputs, high error rates and high latencies.

These issues are observable with Wi-Fi deployments today, and will affect other technologies attempting to coexist in various unlicensed bands.

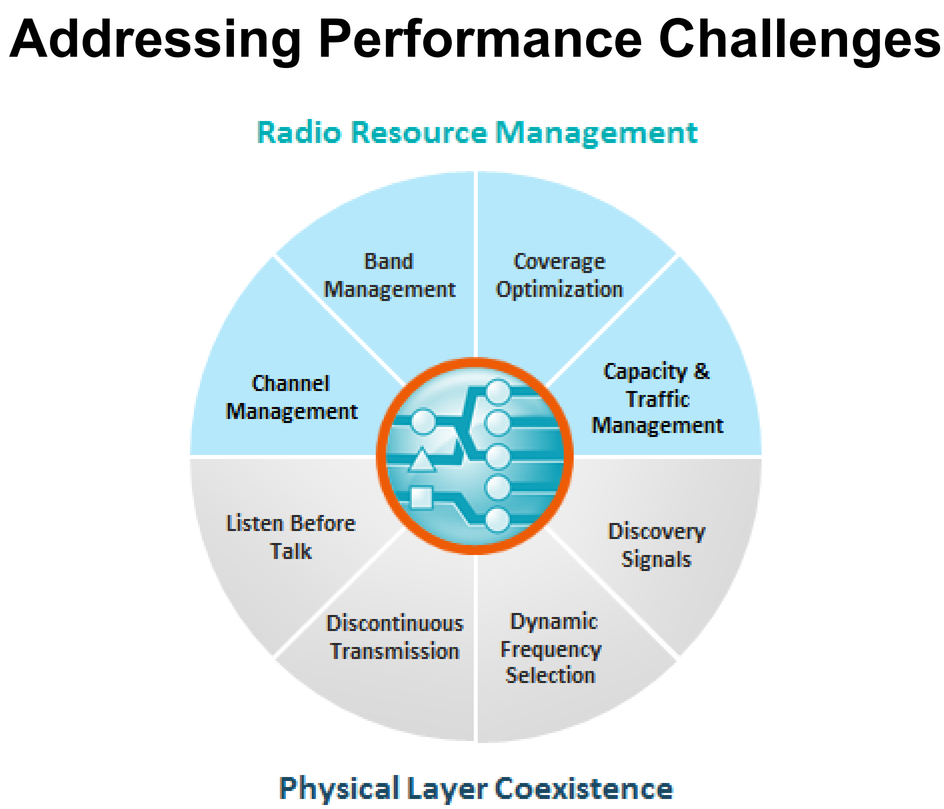

Figure 6: Addressing Performance Issues at Two Levels

Issues have to be addressed at two levels – via physical layer coexistence mechanisms as well as Radio Resource Management (RRM) schemes. With Wi-Fi, physical layer mechanisms like Listen Before Talk (LBT) have been used to prevent devices from stomping on one another via simultaneous transmissions in the same channel. LBT, Discontinuous Transmission and other Physical layer techniques have been adopted by LTE-LAA, which aims to operate in unlicensed bands.

At Fontech, our observations with Wi-Fi have indicated the critical need for Radio Resource Management (RRM) to resolve congestion and coverage issues. Techniques for intelligent allocation of channels, steering of client devices to a less congested band, power control and client steering become critical in making the system work well in contentious environments. RRM plays a proactive, preventative role – it preempts congestion and coverage from becoming issues, via smart allocation of radio resources. RRM is complementary to physical layer schemes, which arbitrate access to resolve issues with the use of the resources.

The remainder of the document describes the results of tests conducted with Wi-Fi that characterized the positive impacts of RRM in resolving performance issues. Three categories of RRM functions are described here: dynamic channel management, band steering and client steering. While these results are for Wi-Fi, they are relevant to multi-technology coexistence scenarios in different unlicensed bands.

1. Setup

The tests were conducted in collaboration with a prominent North American cable operator, in a college dormitory environment. This was a field trial with a live Wi-Fi network, with Fontech's cloud-based RRM solution managing 100 dorms and 75 Wi-Fi Access Points (APs) – a dense deployment scenario. The system was run for two weeks with RRM functionality switched off, and for the subsequent weeks with RRM enabled – to obtain a clear performance comparison. The Wi-Fi network experienced real-life usage by students through the entire period.

2. Dynamic Channel Management

Dynamic channel management algorithms mitigate channel congestion and interference. They detect developing congestion; if congestion builds up to a configurable threshold level, the algorithms select a less congested channel and switch the AP and its clients over to the selected channel. The goal here is to maintain good service quality, by not allowing key service quality metrics to degrade to poor levels.

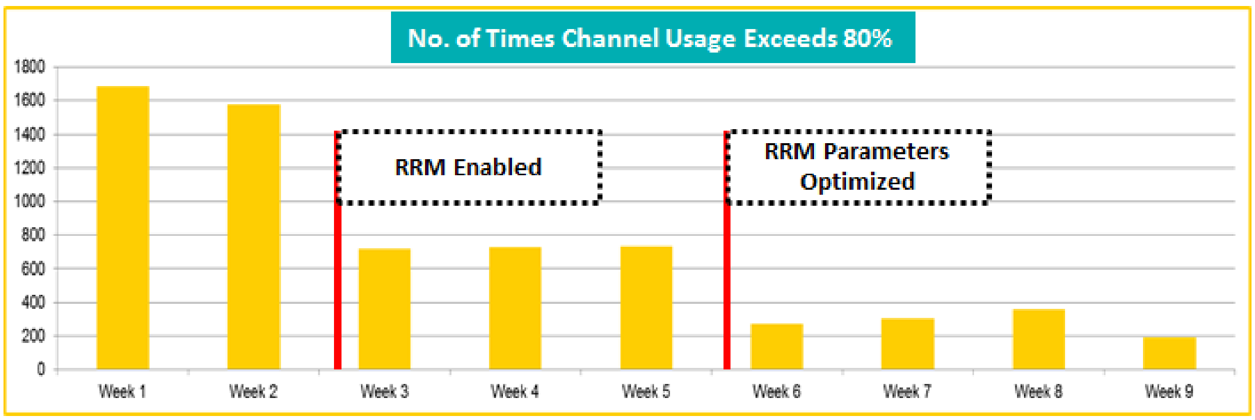

Figure 7: Reduced Congestion Spikes with RRM

Figure 7 shows the first set of results. The monitoring system counted the number of congestion spikes (i.e. the number of times the channel usage level exceeded 80% for any Wi-Fi channel) per week. (Channel usage indicates the percentage of time a channel has been busy processing traffic). When RRM was off (the first two weeks), the number of spikes was very high – reaching over 1600 in Week 1. When RRM was enabled, congestion reduced appreciably – the number of spikes dropped by more than 50%. When RRM thresholds were further optimized (prior to Week 6), the number of spikes dropped to a fraction of what it had been without RRM.

Figure 8 depicts the number of occurrences of persistent congestion within the system. With RRM disabled, this number was high. Week 1 had 1,133 events – each of these was a congestion event that warranted a channel change. However, with RRM disabled, no channel change occurred, congestion conditions persisted and the events kept recurring. When RRM was enabled (Week 3), the number of congestion events dropped to negligible levels. This was because when channels got congested, RRM changed channels quickly and alleviated congestion, preventing recurrences of these events. Only 2 APs experienced any kind of congestion during the latter period.

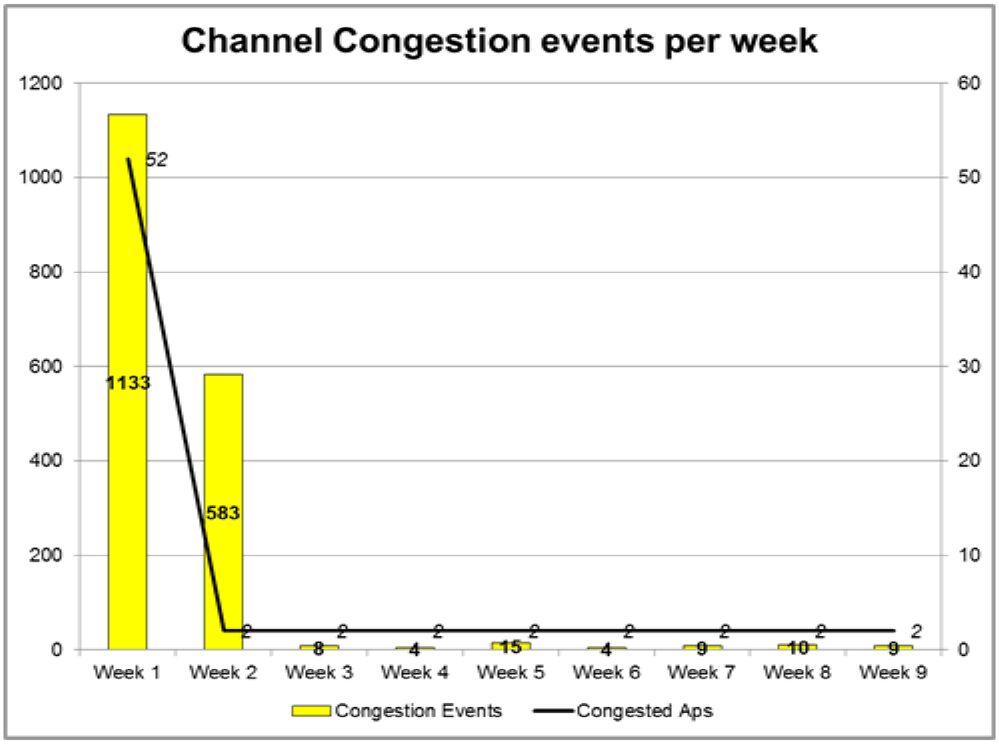

Figure 8: Dramatically Reduced Number of Congestion Events with RRM

3. Band Steering for Bandwidth Optimization

Band steering moves associated clients to a different radio/frequency band to improve quality of experience. When an AP's radio is overloaded, band steering functionality moves client devices to another radio to mitigate the congestion scenario. Band steering can move client devices from mmWave bands to lower-frequency spectrum if coverage is an issue. Band steering can also steer clients with good coverage (strong signal strengths) automatically to the 5 GHz band to provide them much higher bandwidth. Figure 9 below illustrates the effects of this bandwidth optimization capability.

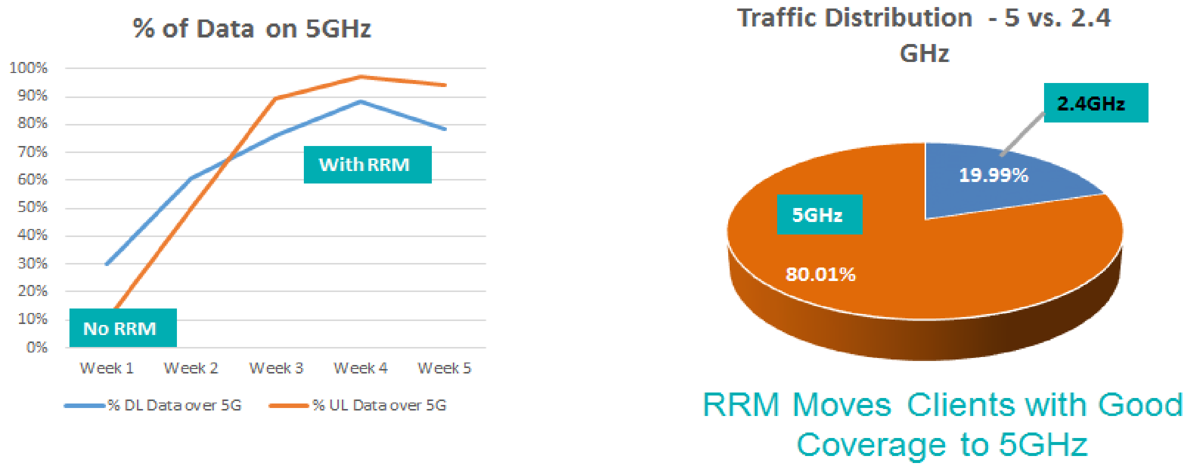

Figure 9: Bandwidth Optimization with Band Steering

The right-hand side of Figure 9 shows average traffic distribution between 2.4 and 5 GHz bands, during the period with RRM enabled. Over 80% of traffic stayed on 5 GHz. The algorithm keeps clients on 5 GHz, as long as signal strength is strong. The left side of the figure shows a "with / without RRM" comparison. The percentage of data on 5 GHz increased significantly after RRM was enabled. Our measurements indicated that overall throughput jumped by over 100% as a result of clients being steered to 5 GHz.

4. Client Steering (Device Mobility) for Coverage Optimization

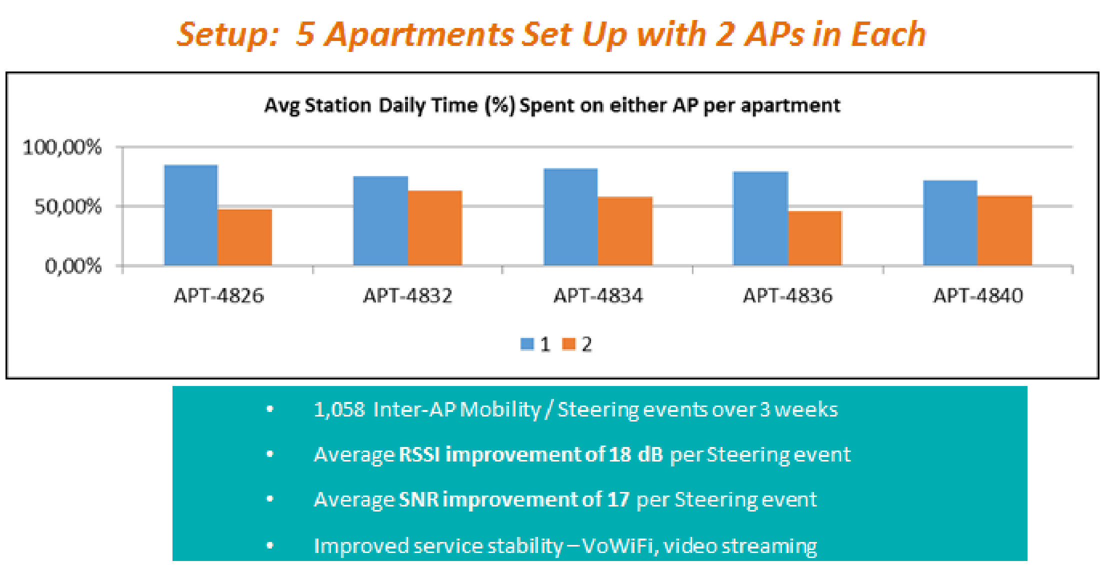

Figure 10: Inter-AP Client Steering to Optimize Coverage

The goal of client steering is to steer a client with poor coverage (e.g. low signal strength) to a better AP or radio. If the client is on 2.4 GHz and drifts out to a region with poor coverage, client steering steers it to a better AP (in a multi-AP deployment). If the client is on 5 GHz and starts to experience poor coverage, it gets steered to the same AP's 2.4 GHz radio, or to another AP (if the network includes multiple APs). The aim is to provide the device a consistently good QoS as it moves around.

Within the dorm field trial, 5 two-level apartments were set up with 2 APs in each. Figure 10 shows the average time (%) spent by client devices on the two APs in each apartment. Clients moved around appreciably between APs in each apartment. Over 1,000 client steers were recorded. An average signal strength improvement of 18 dB was achieved per steering event; Signal-to-Noise ratio (SNR) improved by 17 on average per steering event. The data indicates that client steering improved coverage dramatically.

Conclusions

Unlicensed spectrum usage is expected to proliferate appreciably in the near future. In a 5G world, unlicensed spectrum will not just be the domain of unlicensed technologies like Wi-Fi. We can expect to see diverse technologies – licensed and unlicensed – operating in this space. A lot more spectrum will be available for unlicensed use – new bands allocated to 5G, as well as shared bands such as CBRS.

In addition, 5G NR technology has been designed from the outset to be spectrum sharing friendly. 5G NR is highly band-agile, and supports flexible reconfigurability to optimize itself for diverse bands, deployment scenarios and service types. Unlicensed operation is likely to be the building block for several interesting uses cases – next-generation Home and Community Wi-Fi, Licensed / Unlicensed integration, private LTE / 5G networks, neutral host models and vertical spectrum sharing scenarios.

Considering all factors – more bands, unlicensed-friendly technology, use cases – it is easy to see that unlicensed spectrum use is likely to grow significantly in the coming years. But this does not come without issues. Coexistence of multiple technologies in these bands, high usage and dense deployments will create performance issues – congestion, interference etc. – unless access to the spectrum is coordinated cohesively.

Hence, the use of RRM techniques will become critical. Optimization schemes such as dynamic channel management, band steering and client steering can help mitigate congestion and coverage issues, and optimize service quality. This paper illustrates impacts RRM can have in this regard.

Abbreviations

3GPP	3rd Generation Partnership Project
5G	5th Generation
AP	Access Point
CBRS	Citizens Broadband Radio Service
DVR	Digital Video Recorder
FCC	Federal Communications Commission
GAA	General Authorized Access
HDTV	High-definition television
IoT	Internet of Things
ISM	Industrial, Scientific and Medical (band)

LBT	Listen Before Talk
LTE	Long Term Evolution
LTE-LAA	LTE Licensed Assisted Access
LTE-LWA	LTE WLAN Aggregation
LSA	Licensed Shared Access
MIMO	Multiple Input Multiple Output
mmWave	Millimeter-wave
MSO	Multiple System Operator
NR	New Radio
PAL	Priority Access Layer
QoS	Quality of Service
RRM	Radio Resource Management
RSSI	Received Signal Strength Indicator
SAS	Spectrum Access System
SCTE	Society of Cable Telecommunications Engineers
SNR	Signal-to-Noise Ratio
SON	Self-Organizing Networks

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