Accelerating 5G QoE via Public-Private Spectrum Sharing

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ABSTRACT

Fifth generation wireless systems (5G) must achieve high user Quality of Experience (QoE) in order to compete for market share. Each candidate 5G wireless radio frequency (RF) band offers advantages such as longer range or higher data rate than 2G, 3G, and 4G, but no single band or air interface standard by itself fully achieves ubiquitous levels of QoE for the complete range of wireless access devices. Spectrum clearing cannot keep pace with user demand, so public-private spectrum sharing is emerging as an affordable, near-term method of increasing radio access network (RAN) capacities for content delivery. This paper presents a fresh look at QoE; spectrum scarcity; public uses that underutilize candidate 5G radio frequency (RF) spectrum; and emerging public-private radio interference management frameworks that enable near-term spectrum sharing, with positive consequences for 5G price, performance, and total user QoE.

INTRODUCTION

Clearing radio spectrum from an allocated but underutilized usage to repurpose the spectrum band to another usage often requires many years to accomplish. For example, the transition from analog television (TV) to digital TV, public safety, and cellular telephony is taking more than a decade. The bands that are easy to clear have been cleared, so the next round of spectrum clearance genders significant resistance from incumbents. The explosion of data rates offered by smart phones is overwhelming allocated 2G-3G-4G spectrum, rendering spectrum clearing and infrastructure build out unable to keep pace with demand. Furthermore, 5G networks require gigabit per second (Gbps) data rates for new generations of increasingly computationally intelligent — increasingly cognitive [1] — fixed, nomadic, and mobile devices. The explosion of devices includes smarter phones, tablets, laptops, entertainment centers, vehicles, roads, pipelines, buildings, and other equipment that will connect to increasingly distributed and diverse 5G Internet Protocol (IP) networks.

Data rate has been the key metric for wireless quality of service (QoS) in the past, but past may not be prolog. Wireless devices like smart phones access multiple types of networks: in 2007 the original iPhone paired 2G with consumer-owned WiFi® wireless local area networks (WLAN); the Google Android pairs 3G for voice with 4G for Internet access. The smart phone thus has become the wearable hub by which users integrate multiple wireless access technologies into fixed and mobile personal information experience, the point where consumers measure QoE. In the 5G era, integrating diverse spectrum access bands and air interfaces into a single experience may achieve high QoE at times with lower QoS than competitors, as the iPhone did in 2007.

OVERVIEW

Therefore, this article begins with a review of QoE as the fundamental driver for 5G networking markets and technologies. It then introduces spectrum sharing in a context of constraints imposed by the laws of physics and device cost. A closer look at radio interference management then yields a spectrum reuse ontology from which alternative 5G architectures for spectrum sharing are considered. The architecture level possibilities support the conclusion that 5G spectrum sharing will introduce affordable near term products and services to address the explosion of smart phone traffic and myriad new wireless applications in a way that directly addresses the diverse needs for high QoE. This article thus shows how spectrum sharing between public and commercial usage renders affordable the current exponential increases in traffic that challenge 3G-4G to meet user QoE market realities, without compromising QoE of military and public safety users. This arrangement is termed public-private spectrum sharing.

QUANTIFYING QUALITY OF EXPERIENCE (QOE)

QoE metrics attempt to characterize the match between user needs and content as delivered. Timeliness of delivery is an aspect of QoE that is supported by high data rate, but QoS is a means to an end. For high QoE that goal is high Mean

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Opinion Score (MOS) [2]. QoE should measure the timeliness of content delivery with respect to user needs for timeliness in a given application. For example, the delivery of content in 50 milliseconds that an application expects to receive in 150 ms may result from high QoS, but may degrade QoE, e.g. because some on-line gaming applications protect users having Internet Protocol (IP) pings of greater than 100 ms by making them immune to attack, while those with short ping responses literally suffer and die when hit by a projectile during the next 100 ms. In addition to detracting from QoE in such apps, inappropriately high QoS may waste gigabit per second 5G wireless link bandwidth compared to a lower QoS 100 ms ping. Thus, given many types of applications dependence, more QoS does not always make for higher QoE, but key determinants of wireless QoE that have become widely recognized include:

Radio engineering rules of thumb for spectrum sharing are based on the laws of physics and device pragmatics that limit the data rate between devices of comparable size, weight, power, and complexity into a general pattern of log-log data rate as a function of carrier frequency.

1) **WLAN Generates QoE:** Most (>70%) wireless Internet content is generated or consumed at home or at work via nomadic devices (laptops, smart phones, etc.) via WLAN, typically owned by the business or consumer; high QoE requires WLAN product price points; lack of interference management renders WLAN QoE low under heavy loads.

2) **Location:** User expectations, hence QoE, differ per application and per context of use, but wireless devices and networks have difficulty determining context, such as specific user location, particularly with increasingly constraining privacy laws.

3) **Advertising** generates a majority of Internet content, most of which changes slowly, not requiring 5G data rates and thus may be pushed off-peak for anticipatory caching in future nomadic devices to reduce demand peaks, mitigating 5G build out for given QoE.

4) **High Speed Vehicular Mobility:** Connectivity while mobile at high speed remains key to high QoE; content for high QoE while highly mobile differs from other contexts.

5) **Urban Mobility:** Urban mobility on foot and via public transportation has QoE more like home or work than like high speed vehicular mobility.

6) **Military and Public Safety** render critical services to society, so their usage of spectrum must preserve mission-critical QoE without compromising governmental responsibilities; rarely quantified as QoE, governmental QoE must be measured and preserved for effective spectrum sharing.

These QoE determinants shape 5G markets. In addition to interactive multiparty gaming, wireless Internet applications now embrace diverse content including machine to machine (M2M) data, music, texting, digital photography, video clips, multicast video streams, and even the occasional voice conversation. The optimization of QoE with respect to QoS is widely recognized as NP-complete, computationally impractical. With over 100 peer reviewed technical papers on QoE in the IEEE in 2013 alone, quantifying QoS versus QoE is attracting much attention, but remains in its early stages. Commercial acceptance of QoE includes recognized maps among MOS, QoE, and QoS, particularly for video content delivery, but as yet there is no broad consensus on how best to measure QoE for a given class of applications, much less in the general case.

These trends are driving service providers toward 5G small cells for urban infrastructure and toward TV white space (TVWS) for broadband Internet penetration of rural markets. Wireless is competing for high QoE with digital subscriber lines (DSL) in suburban settings, while terrestrial wireless competes for high QoE with satellite services in suburban and rural markets. Constraints on achieving QoE appear in the physical limits and rules of thumb of radio systems engineering that set context for spectrum sharing.

LONG ESTABLISHED RULES OF THUMB FOR WIRELESS DATA RATES

Radio engineering rules of thumb for spectrum sharing are based on the laws of physics and device pragmatics that limit the data rate between devices of comparable size, weight, power, and complexity into a general pattern of log-log data rate as a function of carrier frequency, as illustrated in Fig. 1. The log-log pattern occurs because of a radio rule of thumb that affordable spectrum access typically is about plus or minus 10% of carrier frequency. For example, the FM broadcast bands occupy spectrum between 88 and 108 MHz, or 20 MHz, +/- 10% of a central frequency of 100 MHz demonstrating the +/- 10% rule. As carrier frequencies increase into the tens of GHz, > 1 GHz of bandwidth becomes available to affordable devices. Spectrum access translates into channels and bandwidth, which translates directly into per subscriber data rate. However, as shown in the figure, with current technology gigabit per second data rates are affordable only over a few tens of meters at reasonable size, weight, power, and cost.

The log-log diagonal of Fig. 1 includes the spectrum subspace of the original iPhone, which in 2007 integrated 2G and WiFi®, for market dominating QoE in a 3G market. In this example, WiFi's 50 Mbps over a range of tens of meters displaced 3G femtocells as the consumer choice because of low cost and high availability. Thus, driven by the six QoE determinants given above, the domain indicated for 5G in Fig. 1 includes at the lower end the TVWS bands, where radio waves of low frequencies reach rural subscribers in wooded terrain much better than those of the higher carrier frequencies. The 5G domain of course also includes the 3G-4G mobile cellular telephony bands. Higher 5G frequencies include the 28 GHz band, where tests were conducted recently outdoors in New York City [3]; and the 60 GHz bands, where short range Gbps performance indoors also has been demonstrated.

Implied in the figure are the many incumbents in the envisioned 5G domain. Incumbents include millimeter wave backhaul, civilian and military radar systems, and satellite communications with large antennas and high power in the bands above 3 GHz. Since spectrum clearing is impractical even in low density federal bands,

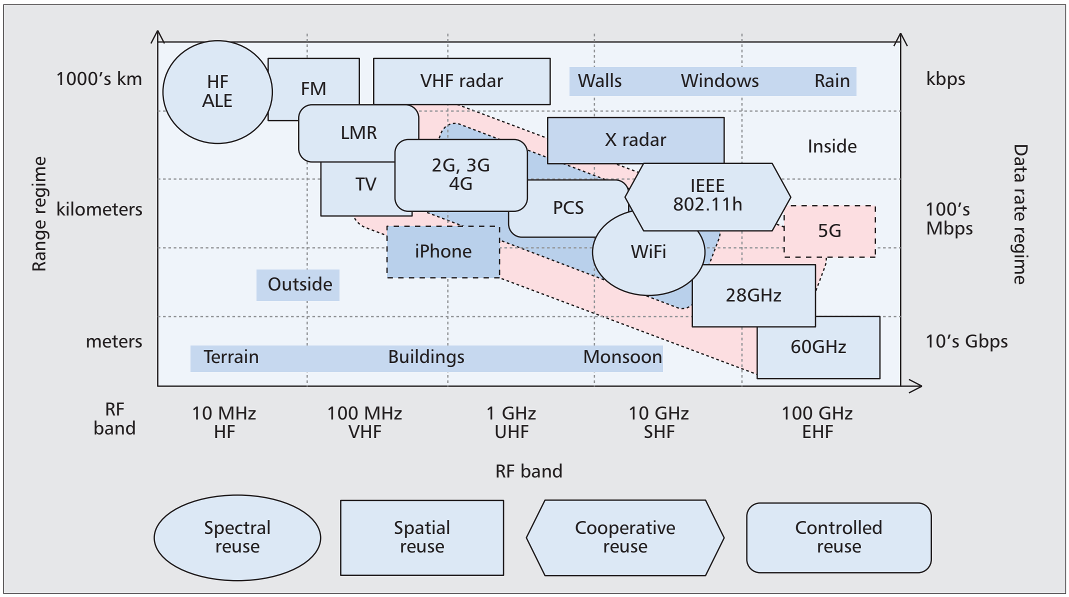


Figure 1. Log-log relationship of data rate vs. radio frequency for affordable devices.

Spectrum sharing may occur between an incumbent commercial usage and a secondary commercial usage, with TV White Space as a current example of commercial-commercial spectrum sharing that is acting as a foundation for public-private spectrum sharing in the USA.

such as satellite ground stations, spectrum sharing with such incumbent systems must be seriously considered. Effective sharing of such spectrum should meet the commercial demand in ways that leverage and respect the six QoE determinants listed above.

Current 4G technology provides a strong foundation for spectrum sharing. Carrier aggregation (CA), for example, in 3GPP 4G Long Term Evolution (LTE) offers the ability to achieve higher data rates by increasing the transmission bandwidths greater than what can be supported by a single RF carrier or channel. Spectrum availability is a key issue for LTE, and in many locations only small bands are available. Therefore the 3GPP specifications support CA over more than one band of spectrum (interband CA). Inter-band CA requires the use of multiple transceivers in the User Equipment (UE) with additional complexities resulting from intermodulation and cross modulation of multiple transceivers. Both CA and other advanced techniques such as coordinated multipoint (CoMP) for the cell edge are designed to use spectrum that has very similar propagation characteristics (homogenous spectrum).

5G systems, on the other hand, will combine multiple PHY, MAC, RAN, mobility management, and IP core technologies across multiple bands that have different propagation characteristics and access rules (inhomogeneous spectrum). As shown in the 5G domain of Fig. 1, spectrum quantity and inhomogeneity increases with spectrum sharing.

QUANTUM LEAP IN US REGULATORY POLICY

In part because of the incipient success of TVWS regulatory policy, spectrum sharing became the policy of the US government by Presidential Memorandum on 14 June 2013, [4]. Since spectrum clearing is expensive for incumbents and takes decades for auction and build-out, governments and regulatory bodies are embracing policy innovations like spectrum sharing to enable advancements in technology, and not heavily regulated environments, to shape the 5G competitive landscape. Thus, this article summarizes the status and prognosis for public-private spectrum sharing as a regulatory framework for accelerating 5G QoE into global markets.

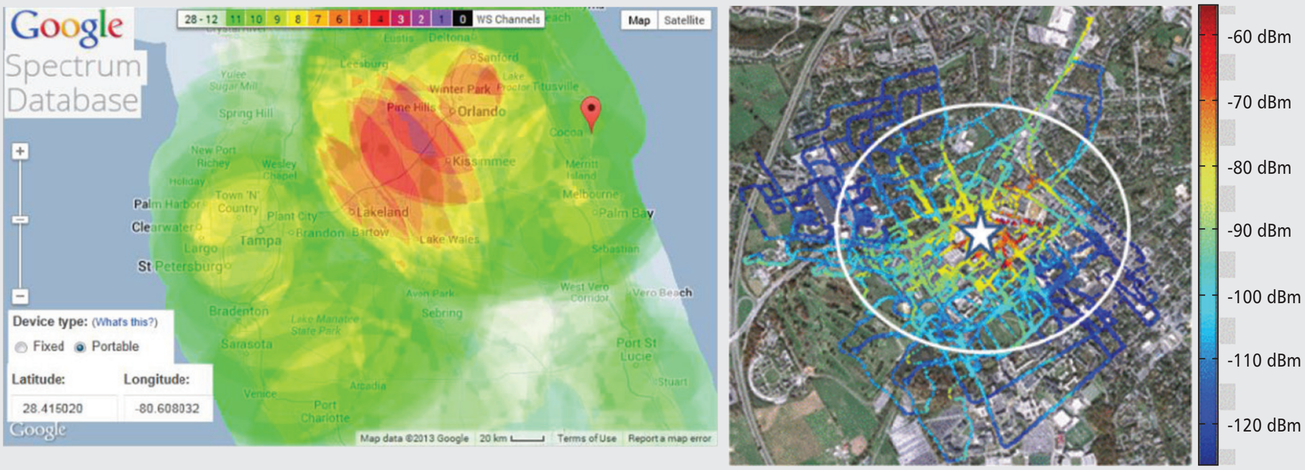
SPECTRUM SHARING

Spectrum sharing between commercial and government usage occurs when a commercial radio access network (RAN) or UE uses a spectrum band allocated for government usage, i.e. in a place, time, and RF channel that the government is not using at that time, subject to agreement by the government that such usage is allowed.

Spectrum sharing requires radio resource and mobility management techniques across both homogeneous and inhomogeneous spectrum, which increases system complexity and cost. The benefits of the increased complexity include enhanced spectrum utilization and adaptation, ensuring that the most appropriate spectrum and technology is used for a given service to enhance the likelihood of high QoE. However, the six QoE determinants listed above can be mutually contradictory as a function of user, application, content type, location, mobility, time, and other context generating the current flurry of research cited above.

SPECTRUM SHARING WITH TELEVISION (TV) AND RADAR

Spectrum sharing may occur between an incumbent commercial usage and a secondary commercial usage, with TV White Space (TVWS) as a current example of commercial-commercial spectrum sharing that is acting as a foundation for public-private spectrum sharing in the USA. Television broadcasters have benefitted from location-based licensing via geographic partitioning to limit interference among TV stations.



(a)

(b)

Figure 2. Spatial sharing of unused television (TV) channels and incumbent radar bands: a) Google® TVWS spectrum database; and b) radar band propagation measurements.

TVWS is location-based spectrum sharing, the use of white space between licensed TV broadcast towers for other commercial purposes, such as rural broadband. US TVWS databases, illustrated in Fig. 2a, identify geographic areas of low broadcast coverage and thus of high TVWS availability. TVWS opted for larger spatial exclusion zones instead of the potentially smaller zones that could result if regulators had required that TVWS devices be capable of sensing the incumbent signals.

Large exclusion zones of the TVWS database reduce the probability of unintended interference by these new devices. However, measurements in the field often conflict with the expectations generated by the database alone. Recent test deployments of TVWS devices near Sacramento, CA, USA included much higher levels of noise and less occupancy per channel than projected from the database, in part because of inaccurate radio propagation modeling.

Propagation modeling and interference oversimplifications can detract from spectrum sharing in the higher radio frequency bands. Consider, for example, spectrum sharing in the US 3550–3650 MHz band (termed Citizens Broadband Service, CBS). The Notice of Proposed Rule Making (NPRM) of the US Federal Communications Commission (FCC) regarding commercial spectrum sharing with incumbent naval radar and fixed satellite systems in the 3550 MHz band is exemplary of US federal actions on spectrum sharing. The 2012 NPRM used simplified propagation and interference models to identify exclusion zones that essentially eliminated usage along the coasts of the US, eliminating approximately 60% of the US population from sharing CBS spectrum. In response, Federated Wireless (formerly Allied Communications) analyzed measurements taken by Virginia Polytechnic Institute of 3395 MHz received signal strength intensity (RSSI) in Blacksburg, VA (Fig. 2b). The majority of a signal propagating from the central star of Fig. 2b is less than –80dBm RSSI outside of a 1 km radius. This corresponds to a fourth-law radiation pattern (best fit proportional to $1/r^{3.8}$). Such a limited propagation characterizes the 3550 MHz band in suburban settings reflecting the majority of the population areas restricted by the coastal exclusion zones of the NPRM. Such RSSI measurements could be acquired by smart phones. A secure, enhanced TVWS-type geospatial database generates an additional 216 Terabits per second of capacity without harmful interference to the incumbent radar for 24 times the capacity of the original FCC proposal. Thus, measurements and realistic interference models enhance the public interest and improve the spectrum sharing efficiency [5].

INTERFERENCE CONTROL

Figure 3 illustrates key interference control challenges of spectrum sharing. Finite-time radar and communications signals occupy theoretically infinite radio spectrum, generating measurable out of band interference, not all of which is converted to heat by filtering. High gain antennas of Fig. 3, like the millimeter wave backhaul incumbent transmitter A1, distribute energy beyond the intended backhaul receiver, A2. This causes interference with a distant in-band small cell B, depicted by the red zone AB. Power typically is not controlled at A1 once the backhaul link is established. As small cells proliferate, previously harmless effects like wind loading on transmitter A1 can increase interference by pointing its pencil beam further into the cell.

As 5G markets cause small cells to proliferate, the out of band energy that has been acceptable in the past will aggregate nonlinearly, introducing increased interference levels into spatially coincident spectrum bands such as the 4G sector antenna at C in Fig. 3. Gbps small cell data rates use GHz clocks that radiate energy into the 4G towers and devices, aggregating to cause measurable interference. Although spectrum masks reduce adjacent channel interference, low cost devices may lack the high performance analog filters that more fully suppress out of band energy. Hence, market-friendly devices tend to radiate measurable interference into other radio frequency bands. Such devices contribute to urban noise that typically is 30 dB greater than thermal noise, the lowest physical limit of radio interference. Increased video content in the Internet of Things (IoT) may offer machine to machine (M2M) communications as a large consumer of 5G spectrum. The accumulation of millions of such individually small RF effects motivates a focus on control of interference for 5G and more aggressively managed spectrum sharing. Since 5G may include combinations of many different bands, some allocated, some shared, and some aggressively controlled, the next section examines the advantages and disadvantages of different spectrum sharing alternatives in spectrum reuse ontology.

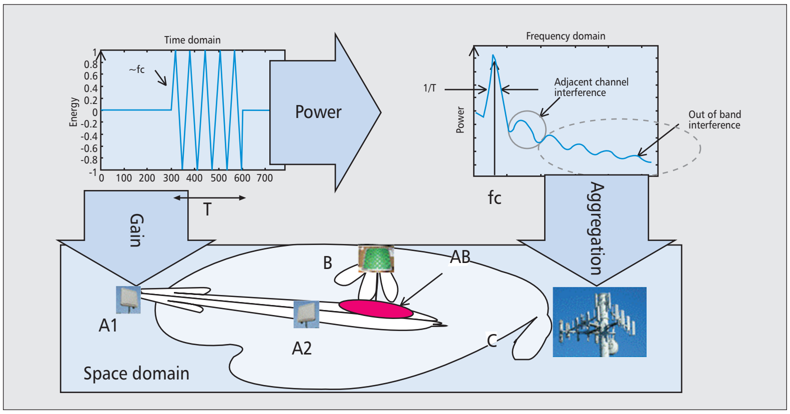


Figure 3. Space-time-frequency domains of spectrum sharing.

SPECTRUM REUSE ONTOLOGY

All radio spectrum is reused in some way: much of the potential information capacity is shared among alternate primary users or among primary and secondary users. Historically, regulatory authorities have managed spectrum by organizing it into bands with specified usage (e.g. fixed, land mobile, etc.); channels within bands (e.g. for emergency notification); and legally binding usage mandates, both nationally and via international agreements. Reuse paradigms are summarized in the ontology of Table 1. Frequency reuse, for example, employs carrier frequency as the primary reuse parameter with output power limitations and transmission masks completing the reuse paradigm. Access protocols provide real time reuse via frequency division multiple access (FDMA); interference acceptance also occurs with ultra wide band (UWB), e.g. short pulses of low power with energy spread instantaneously between 2 and 10 GHz.

Spatial reuse employs geographic location as the key parameter via controlled radiation patterns. (e.g. AM, FM, TV broadcast, and satellite ground systems). Temporal reuse employs time as the key parameter, using time slots with access protocols for time division multiple access (TDMA), e.g. GSM. Etiquette-based temporal reuse occurs in IEEE 802.11h radar sharing, where communications ceases for 30 minutes after radar has been detected in the 5.9 GHz band. Code space reuse employs approximately orthogonal pseudorandom spreading sequences for code division multiple access (CDMA) of 3G

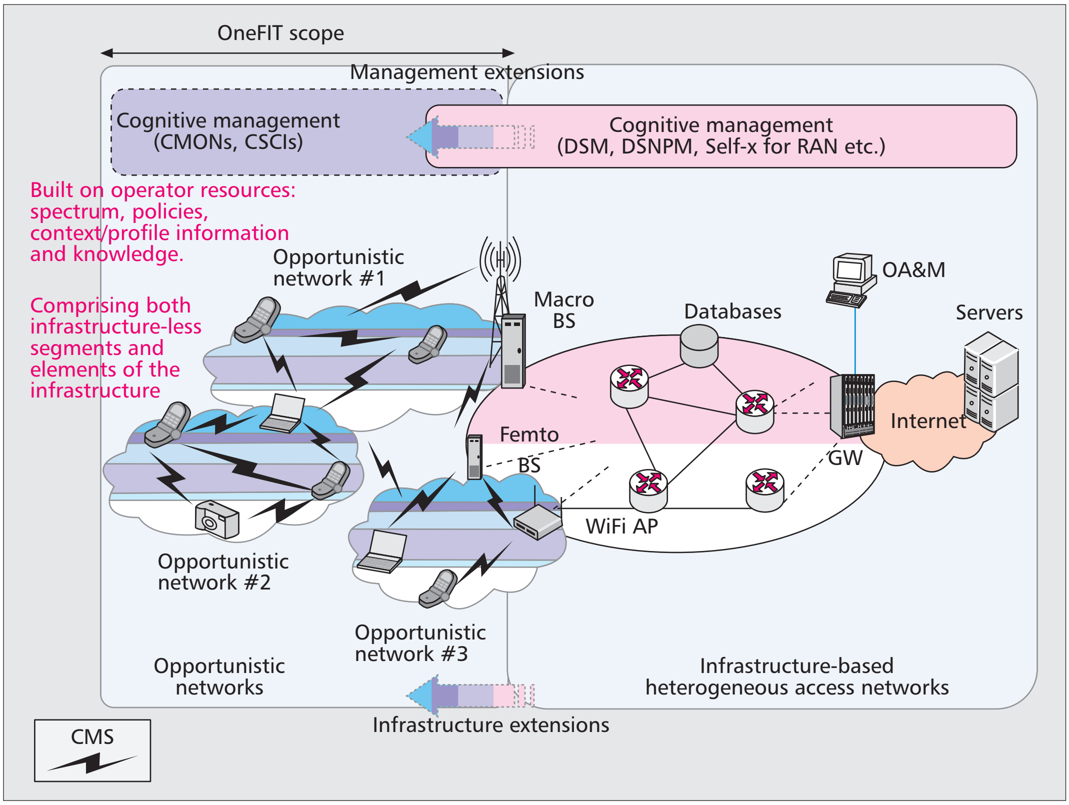


Figure 4. OneFIT builds on operator resources for incremental evolution.

Type	Reuse Domain	Reuse Parameters	Reuse Protocol	Illustrative Examples
1	Frequency	Usage, power, and transmission mask	Band-specific	Regulatory band plans
1.1	Frequency	fc, bandwidth	FDMA	AMPS 1G, LMR
1.2	Frequency	Bandwidth, power	Accept interference	UWB
2.1	Space	Location, antenna radiation patterns	Location-based permission	AM, FM, TV broadcast satellite ground stations
2.2	Space	Radiated power	Channel selection	ISM Bands (WiFi), DECT
3.1	Time (fine scale)	Time slot	TDMA	GSM 2G
3.2	Time (coarse scale)	Primary user signature(s)	Etiquette	IEEE 802.11h (radar)
4	Code space	Short, long sequences	CDMA	3G
Hybrid	Space-time-frequency	Radio resource blocks (RB), power	PHY-MAC radio access protocol	LTE OFDM, OFDMA PHY-MAC

Table 1. Spectrum reuse ontology.

systems. Hybrid reuse combines frequency, space, and time parameters via time-frequency resource blocks, e.g. in 4G physical (PHY) and media access control (MAC) protocols. 5G should evolve new hybrid combinations of these reuse techniques for spectrum sharing, combining cognitive radio technologies and geolocation database techniques for novel spectrum sharing architectures suggested by the following.

ALTERNATIVE ARCHITECTURES FOR 5G SPECTRUM SHARING

The European Community's OneFIT ICT7 program [6] describes an LTE-centric candidate architecture applicable to spectrum sharing. OneFIT includes hybrid control with a signaling channel termed Control Channels for the Cooperation of Cognitive Management Systems (C4MS) that could evolve 5G from 4G LTE as illustrated in Fig. 4. OneFIT integrates licensed spectrum with opportunistic networks, which, although not mentioned specifically in OneFIT, may include shared spectrum via the cognitive management plane.

Extending the OneFIT cognitive management plane to inhomogeneous and shared spectrum yields an important new expanse of integrative 5G architectures that follow the iPhone to integrate short range, high data rate, consumer-available unlicensed RAPs with the longer range, mobility friendly mid band LTE infrastructure. Evolution may include opportunistic access to TVWS and millimeter wave bands for the 5G domain of Fig. 1.

Huawei Technologies recently showed that the power efficiency of 4G networks can be improved by 20% to 50% by separating the control function from the high speed data transport function [5]. Combining Huawei's function separation with OneFIT's cognitive plane and with control of unlicensed GB/s radio access points to reduce overall cost yields Fig. 5. Such visionary architectures may increase infrastructure capacity by a factor of 10 to 1000 depending on standardization, regulatory, and market developments.

The architecture of Fig. 5 suggests LTE-compliant control signaling via an updated Mobility Management Entity (MME) for opportunistic and collaboratively controlled shared spectrum small cells. The diverse mix of spectrum sharing RAPs and UE devices may include WiFi, TVWS, 28/60 GHz, the 3350 MHz radar band in the US, etc. The US 3350 MHz band is particularly relevant to 5G urban small cells and to enhanced consumer owned WLAN. Current FCC filings envision three possible CBS tiers of access: incumbents with the highest priority; a priority access license (PAL) tier for 4G-like access; and a general authorized access (GAA) lower tier that accepts interference comparable to WiFi. Such a CBS band may integrate commercial cellular and WLAN usage in a dynamic mix. 4G systems based on exclusive reservation of spectrum have encouraged large, expensive, long-term licenses with a lack of build-out that many term spectrum hoarding, ultimately inhibiting the high spectrum utilization that high QoE requires.

The future MME needed for Fig. 5 would be responsible to a government entity such as a Federal Spectrum Access System (SAS) for opening, renting, and closing spectrum in accordance with governmental needs. A shared spectrum MME may orchestrate self-organizing shared spectrum RANs to future-proof service providers against market variations including market uptake, the pace of standards bodies, and profit risk of single-source infrastructure suppliers.

A C4MS-like standard could be adopted by an evolved WLAN community for mutual coordination and self-organization and for more aggressive shared spectrum interference control. Another key ingredient of shared spectrum integration would be an open architecture for minimizing drive testing (MDT), an extension of

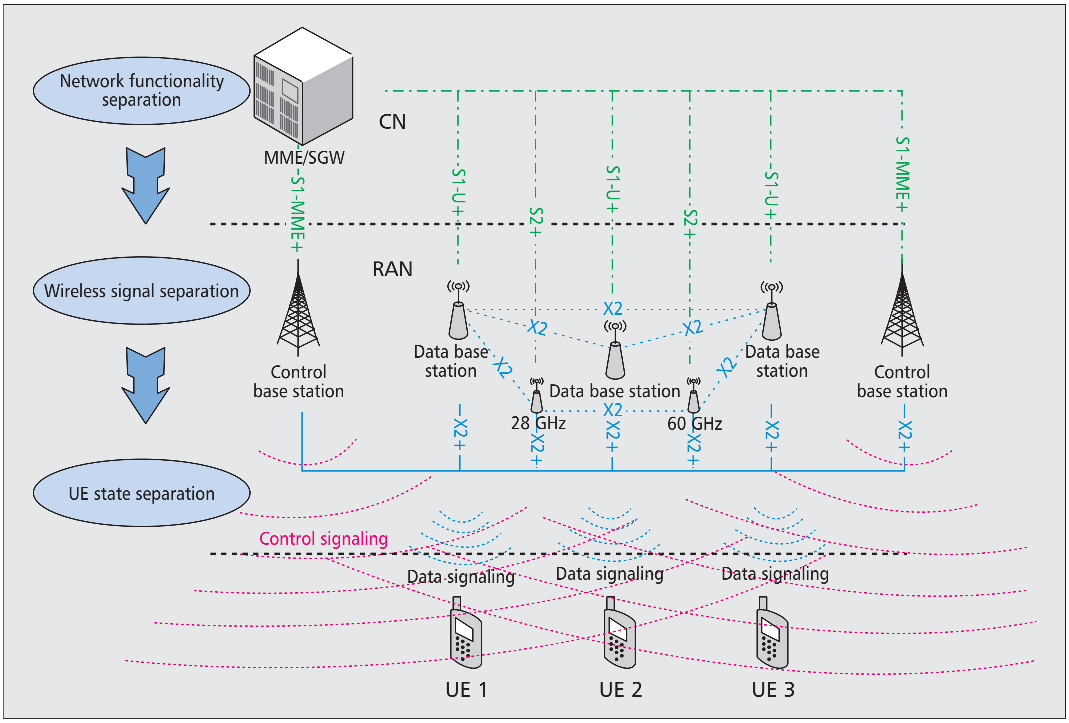


Figure 5. Function separation between control and data enables experience integration at low cost.

Possibly the most aggressive 5G spectrum sharing architecture thus far considered by policy makers is that of multifunction RF. Within the decade, it should be feasible to realize radar functions in cellular communications infrastructure networks.

LTE UE capability to measure and report channel state information to the host network. 5G spectrum sharing also requires the protection of government usage, including protecting the national security interests of federal users. Thus, 5G spectrum sharing necessarily entails tighter integration of federal incumbents with the next generation of cellular wireless standards, notably LTE and WLAN standards.

MULTIFUNCTION RADIO INFRASTRUCTURE ARCHITECTURE

Possibly the most aggressive 5G spectrum sharing architecture thus far considered by policy makers is that of multifunction RF. Within the decade, it should be feasible to realize radar functions in cellular communications infrastructure networks as illustrated in Fig. 6.

Multifunction RF would integrate public and private services across radar and adjacent communications bands into a single integrated broadband multifunction spectrum allocation. Associated infrastructure provides an agile mix of public-private communications, radar, and navigation-related services, as illustrated in Fig. 6a. The technologies enabling the vision include cognitive radar [7] of Fig. 6b. Cognitive radar and cognitive radio yield a multifunction RF architecture framework to accelerate innovation, reduce costs, and invite productization. Safety, however, becomes more complex with multifunction RF. Should commercial users of military radar bands expect to be attacked electronically as if they were "the enemy?" This is not a silly question. In the US scheme, an "alarm signal" has been proposed to alert all commercial users to vacate the band until the Federal SAS specifically approves using the band again. Thus, well-behaved commercial users would not be "attacked". However, some devices may not 'get the word.' Using commercial equipment in a military band may well cause an emission to be attacked electronically or a device to be attacked physically in some unusual situations, so technology and regulation must address even such improbable use cases.

When spectrum allocated for radar services is shared by communication networks, the communication bandwidth can be significantly increased. In addition, increasing the number of radar nodes to one per cell tower could increase quality of a candidate radar function such as weather or airspace surveillance. When temporally sparse events occur, such as Hurricane Sandy in 2012, multifunction infrastructure could allocate more radio resources to monitor the event in a finer scale to provide more reliable and accurate information. In addition to existing services, multifunction RF can introduce new services, such as ground vehicle and object detection and tracking. Because of the ubiquity of cellular infrastructure, such capability can be beneficial to public safety and border control. It can also generate a new business sector similar to current geolocation services, and provide opportunities for service providers and device makers. Research results motivating such an architecture include the use of IEEE 802.11 as a radar, which is a demonstration of how communications signals can be used for radar functions at the same time as communicating [8].

Recent advances in Multiple Input Multiple Output (MIMO), cognitive radio with Dynamic Spectrum Access (DSA), along with cognitive radar extend spectrum sharing to Total RF detection, ranging, and communicating. Security will be a key challenge [9] as will enterprise systems engineering and related legal and safety issues. Concepts have been developed for joint

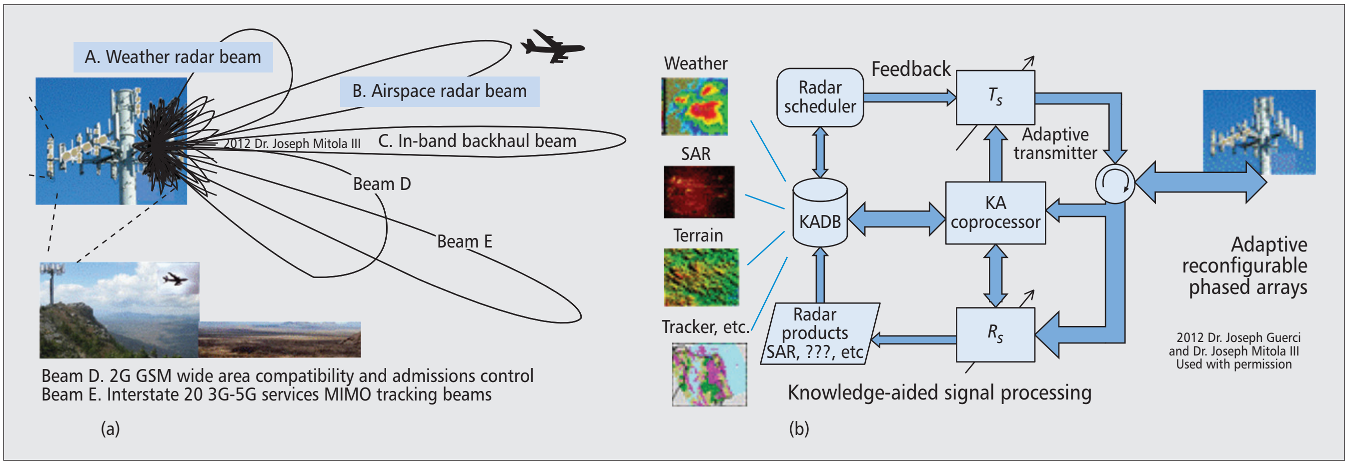


Figure 6. Multifunction radio infrastructure spectrum sharing architecture: a) Multifunction radio system concept; b) cognitive radar architecture.

radar and communications architectures [10, 11] including ultra wideband short range radar and vehicle to vehicle applications, for a relatively strong base of related research.

CONCLUSION

The iPhone disrupted many plans for consumer acceptance of 3G and 4G femtocells as the preferred home wireless network by delivering high QoE, initially with barely tolerable 2G QoS. It is widely understood that with de facto statistical multiplexing of packets and device economies of scale, TCP/IP ultimately became superior to the Synchronous Digital Hierarchy (SDH) for core telephony networks including LTE. If past is prolog, the Internet and cognitive device spectrum sharing technologies offer 5G devices with Gbps data rates and the Internet's massive economies of scale. Spectrum sharing architectures may integrate low cost, unlicensed high data rate radio access points with longer range lower data rate LTE or LTE-like networks, perhaps migrating the mid band macro-cells toward primarily a control network while shared bands deliver Gbps data rates over short ranges in homes, businesses, and small cells. The pervasive nature and complexity of shared spectrum interference generation motivated an ontological perspective on spectrum sharing in the context of degrees of control of spectrum reuse. Meeting the 5G radio spectrum shortage may be facilitated by considering all types of spectrum reuse as sharing, enabling the efficient sharing of federal spectrum for commercial usage of underutilized radio spectrum bands. The focus of this article on public-private spectrum sharing for high QoE may complement the historical QoS focus to bring the gigabits per second of 5G to home, office, and leisure life quickly and efficiently.

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BIOGRAPHIES

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Meeting the 5G radio spectrum shortage may be facilitated by considering all types of spectrum reuse as sharing, enabling the efficient sharing of federal spectrum for commercial usage of underutilized radio spectrum bands.