Towards a Virtual Cellular Network with Variable Grade Spectrum: Challenges and Opportunities*

[Invited Industry Track Paper]

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ABSTRACT

In this paper, we make a case for future wireless networks that will seamlessly exploit many *variable grade* spectrum bands. The transformation we envision will be fueled by a fundamental change in the way networks use spectrum. The mix of spectrum options will include existing exclusively licensed and unlicensed bands and new *shared spectrum bands* where incumbent primary transmitters with interruptible, exclusive access share the band with cooperating (secondary) users. Such bands used in small cell deployments will be key to creating enormous wireless capacity needed to support future traffic demands. The nascent spectrum database technologies will morph into more dynamic spectrum databases and provide essential interference coordination, channel management and monetization. This trend when combined with infrastructure sharing enabled by cloud and SDN technologies will gradually lead to new deployment models. Such network transformation and democratization of spectrum access can fuel innovative business models and new regulatory regimes for wireless networks.

We illustrate the new architecture and component radio, database and security technologies using concrete example of incorporating shared spectrum in a small cell network.

Categories and Subject Descriptors

C.2 [**COMPUTER-COMMUNICATION NETWORKS**]: Network Architecture and Design—*Wireless communication*

Keywords

Shared spectrum, Spectrum databases, High capacity wireless, Future wireless networks

1. OVERVIEW OF THE WIRELESS LANDSCAPE AND KEY TRENDS

The 2010 National Broadband Commission [1] report published by FCC postulated that 1.2 to 1.7 GHz of new spectrum is required to sustain capacity expansion required to meet anticipated growth in wireless data traffic. Even if we discount this estimate, which some consider overzealous and inaccurate, by a factor of 3, still 600 MHz of new spectrum will be required. To that end, two US Government agencies – FCC and NTIA have been tasked to identify 500 MHz of new spectrum to be made available by 2015.

At the current point in the wireless network evolution, two types access networks exist: (1) licensed band cellular networks that are carefully engineered using expensive exclusively licensed spectrum to provide mobile access with national coverage. These are characterized by macro-cells with large coverage area realized using high power (e.g: 40-60 W) basestations. (2) Popular Wi-Fi networks operated in unlicensed spectrum (e.g.: 2.4 GHz, 5.8 GHz, 900 MHz) that provide indoor hot-spot coverage (e.g.: venues, hotels, homes, enterprise) and limited outdoor (e.g.: hot-zone) coverage realized using low power (40 mW-1W) access points. Despite their disparate characteristics, in early days these two access networks were often presented as competing ways to create wireless capacity. However, support of unlicensed and licensed bands on client devices and pressing need to relieve traffic overload in capacity starved cellular data networks caused by unforeseen growth in smart phone use and mobile video has pushed greater integration of these networks. This approach termed "Wi-Fi offloading" has provided some needed congestion relief to cellular networks. However, in many settings, Wi-Fi networks are experiencing congestion and despite continued improvements in Wi-Fi speeds (e.g: 802.11ac), many predict need for more unlicensed spectrum to support greater number of Wi-Fi channels.

As the traffic growth continues unabated, network operators continue to focus on ways improve capacity of their licensed band network. Techniques such as carrier aggregation, MIMO, enhanced inter-cell interference cancellation (eICIC), active antenna arrays (AAA) and increased sectorization are some of the techniques to increase capacity in macro-cells. However, these sophisticated techniques are expected to provide barely factor of 2 (in fact much less in many cases) capacity gains. This is also exacerbated by the fact that data traffic has different characteristics than voice traffic for which macro-cell coverage is suitable. Almost 60% of data traffic is generated indoor or in settings with minimal or no mobility – often termed portable access [4]. The corollary of this is that traffic is spatially clustered and exhibits temporal and spatial hot-spots. This characteristics can be matched perfectly if the coverage of the cell is matched to the spatial cluster size – leading to a concept of "small cells" – indoor femto/pico cells and outdoor metro/micro cells. This suggests a key design principle for future cellular networks:

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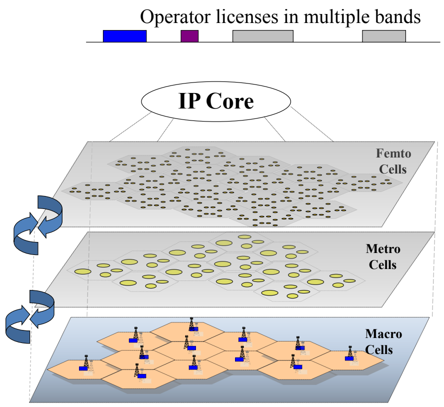
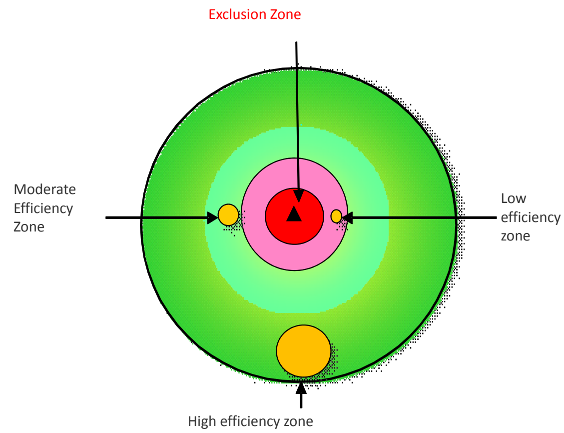


(a) Heterogeneous cellular network



(b) Exclusion zones in shared carrier deployment

Figure 1: Cellular hetnets

> Wide geographical coverage is not as critical as high capacity in small spatial clusters, which suggests expansion of small cells instead of macro-cells as the key trend.

The natural question that arises is what spectrum band should these small cells operate in. If they use the same spectrum as that used in macro-cells they embed in, the client devices require no change in hardware. Such deployments – termed *shared carrier deployments* – require no new spectrum and in principle, no handset changes and are therefore quite attractive. The growth in small cell deployments transform the single tier network with macro-cells into a multi-tier heterogeneous networks – termed *hetnet* (Figure 1) (a) in short.

The hetnet approach in theory provides $O(N)$ growth in capacity for N small cells. However, this has caveats in practice, especially for outdoor metro/micro cells due to co-channel interference across the hetnet tiers. The closer the metro cell is deployed to the macro-cell site, the greater the interference, resulting in coverage areas so small that it does not serve many users and fails to achieve traffic offload. In fact, realistic deployments introduce an exclusion zone around macro-cell site in which metro-cells should not be deployed. Such exclusion zone (Figure 1) (b) can be 30-40 % of the macro-cell coverage and often fall in the traffic hotspot regions.

Using different spectrum bands in each hetnet layer completely eliminates the interference interactions. However, such orthogonal carrier deployments require additional licensed spectrum bands suggesting need for more spectrum for true $O(N)$ capacity scaling and also, corresponding support of these bands in the client devices.

We note that licensed band small cells and unlicensed band access points are both inherently small cells and seamless hand-off from a macro-cell to a diverse licensed band small cell ("hard hand-off") or unlicensed access point ("Wi-Fi offloading or inter-technology hand-off") are fundamentally analogous. This represents a gradual blurring of boundaries between networks that were until recently competing approaches. However, the disparate business models for deploying these networks have made federated authentication and data path anchoring needed for seamless handoff rather challenging in practice. This suggests

> Sustained capacity expansion via integrated hetnet approaches will require support for greater number of spectrum bands in the network and client devices.

Let us visit the question of getting new spectrum. In almost all parts of the world, most of sub-6 GHz spectrum is already allocated for commercial or government (e.g: aviation, military) use. With exception of mobile broadband and ISM bands, many useful bands are spatio-temporally underused or unused. Naturally, it is tempting to think that users that use their spectrum less-profitably should be relocated to other bands and freed up spectrum should be re-purposed for mobile broadband. The *Incentive Auction NPRM* launched by FCC to shrink DTV band and release up to 120 MHz is an example of this approach. However, such "clearing" is impractical (e.g: JTRS links used by military in USA), expensive and slow (e.g.: $18 billion over 10-years to relocate 95 MHz of military bands) and fraught with uncertainties (e.g.: DTV band incentive auctions can fail to release any spectrum).

The only viable alternative left is that of "shared use" wherein two types or tiers of devices are allowed to use the band: the primary devices (users) that always have uninterrupted access to the band for their designated mission and the secondary devices (users) that can use the same spectrum bands in space and time when primary is not active. In the event primary needs access, the secondaries must immediately vacate the band. This requirement makes spatio-temporal availability of shared use spectrum statistical in nature.

The recent PCAST report [2] advocates that 1000 MHz of spectrum in 2700-3700MHz should be made available for such *shared use*. Following this recommendation, the recent FCC 3.5 GHz NPRM aims to release up to 150 MHz of spectrum in 3550-3700 MHz band used by multi-function radars and military and naval radars for use in small cells. These trends suggest a key design consideration for future:

> Future wireless networks must support new shared spectrum bands "encumbered" with high priority primary users. The network and client devices using these bands must be agile – i.e. capable of switching to new channels in the event of interruption of in-use channel.

A modern (e.g.: 4G LTE) cellular network consists of three main parts: (1) a radio access network (RAN) composed of basestations of various types (e.g: macro, micro, pico, femto) connected to a (2) packet core network consisting of IP-router based elements such as Service-GW (SGW) and Packet Data Network (PDN) gateway (P-GW) and a (3) control plane infrastructure consisting of authentication, signaling and billing infrastructures with servers such as Home Subscriber Serer (HSS), Mobility Management Entity (MME), AAA etc. The cloud based computing that has already transformed computing, storage and web services, can be applied to cellular networks to get benefits of demand responsive scalability, low CAPEX and OPEX by limiting the need for per-service, per-network or per-operator infrastructure and resulting improved reliability. Similarly, Software Defined Networking (SDN) or Network Function Virtualization (NFV) based on Open Flow paradigm can simplify and scale packet core functions. Another important trend is that of pooling of baseband processing functions in remote locations by exploiting availability of high speed fiber that can transport radio signals in digital I/Q format. Such centralized baseband processing can allow many wireless optimizations such as interference cancellation, joint scheduling across basestations, energy optimizations via sleep scheduling etc. This suggests:

> The cloud and SDN technologies may help reduce costs, improve performance and manageability by encouraging infrastructure sharing.

2. FUTURE WIRELESS NETWORK: A POSITION STATEMENT

This paper makes a case that over the next 10-years the confluence of the aforementioned trends will foster a slow, yet ultimately disruptive new transformation in wireless network architecture, deployment, value chain and business models. In the following, we record the salient changes we foresee.

Operating in wide band, variable grade spectrum: The artificial dichotomy of dedicated licensed band cellular networks and unlicensed band networks will disappear. The new wireless networks will employ mix of *variable grade* spectrum bands – (a) exclusively licensed, single owner, (b) unlicensed with no ownership and (c) shared use bands with one primary owner sharing with many coordinated or uncoordinated secondaries. The grade of the spectrum bands is characterized by *availability* and *quality* (e.g.: number of devices sharing the band, amount of co-channel and adjacent channel interference and propagation characteristics). For example, exclusively licensed bands that have guaranteed availability and have in-band interference protection (via exclusivity of transmission rights) and adjacent band/channel interference protection via stringent filtering requirements represent highest grade of spectrum. On the contrary, shared bands such as radar bands used by high powered fixed (e.g. Fixed Satellite Services (FSS) and mobile radars (e.g.: Naval Radars), public safety spectrum bands can have spatio-temporally variable spectrum availability. When these bands are available, the amount of in-band interference experienced by secondary users depends on the licensing model used. Similarly, dedicated unlicensed bands can have widely varying interference environment though they are guaranteed to be always available.

The main challenge is how to engineer the wireless network using mix of such spectrum bands to deliver performance that rivals performance of a network with equivalent amount of exclusively licensed spectrum.

Moving control in the Cloud via dynamic databases for coordination: The FCC rules in the context of DTV whitespace introduced a key architectural innovation in the form of a spectrum database (called TV Database (TVDB)). It was conceived as a compromise which sacrificed some spectrum usage efficiency to avoid complexity of distributed sensing based schemes for secondary use of DTV VHF and UHF band. This database (DB) approach, initially aimed at quickly bootstrapping secondary use ecosystem, will become a dominant architectural innovation for future. It can be further expanded to federal spectrum bands and in fact can be shown to be essential to guarantee security of primary occupancy information, scalable secondary use and reliable primary protection. However, DB functions in case of primary bands with more complex use patterns will become more dynamic and challenging to realize. Such a DB also resembles the centralized Self Organizing Network (SON) servers currently being developed for hetnets deployed in licensed cellular bands. In the long term, these various DB functions will converge into a single entity that manages various licensed and shared spectrum bands across multiple vendors, operators and primary users. The DB will also implement various spectrum access models – such as exclusive licensing, light licensing and unlicensed with a fine spatio-temporal granularity. By associating a market model (e.g: fixed priced transactions, real-time auctions) to first two methods of access, DB can create a real-time market for spectrum access or wireless capacity realized using such spectrum. In short, the spectrum DB will become heart of wireless network and its associated value chain.

Infrastructure sharing Though large scale small cell deployment is essential for capacity expansion, the economics of small cell deployment is challenging if every operator has to deploy its own small cells. The dominant components of cost will be the cell site and the backhaul required to connect small cell to the network. The cost of cell sites can be amortized across operators if small cells that support multiple frequency bands and multiple standards (e.g.: 3G / 4G) become feasible.

The wireline fiber based backhaul though ideal may not be available in exact location of small cell deployment and may be operated by different wireline operators. This may necessitate wireless backhaul solutions to ease deployments and reduce costs. However, since small cells are often deployed in clutter at 8-15 feet of height, such wireless backhaul must support near or non-line-of-sight (nLOS/NLOS) backhaul which needs sub-6 GHz spectrum that is in short supply. These constraints may encourage site and backhaul capacity to be shared. Specifically, SDN (Open Flow) technologies that offer centralized control of packet data paths can be key to realize such sharing in backhaul and wireless access.

Regulatory transformation: Here the analogy we can consider is that stock market trading. The human stock brokers shouting out stock sales on a exchange floor have given way to automated trading by algorithms that employ intelligence gathering tools that sniff all online information sources. Much the same way, FCC and its regulatory processes represent stock brokers of the old world. Increasingly spectrum management will be automated and fueled by "RF intelligence sources in the network" and centralized in the dynamic DBs. In such a future, role of FCC and NTIA will be redefined to DB-assisted enforcement of spectrum usage such as access fairness, collusion detection, market manipulation and RF compliance to spectrum lease.

Business model transformation: Current wireless network is a vertically integrated business where all aspects of wireless service offering – acquisition of licensed spectrum, deployment of network, marketing and management of customer facing service are integrated into a single entity. However, forces of sharing and virtualization can gradually transform this. Specifically, the business of spectrum DBs can be just "infrastructure service" instantiated on a cloud with real-time guarantees. Similarly, the entire control path of cellular networks – that deals with subscriber authentication, session tracking and billing can be virtualized into a Cloud business. Small cell RF-frontend deployment and management can be an independent business. Instantiation of customer services of variable QoS on such infrastructure can be another independent business. Much the same as Amazon Cloud services can be leveraged by vendors for web presence of their business without owning a server or a piece of software, wireless services can be commoditized.

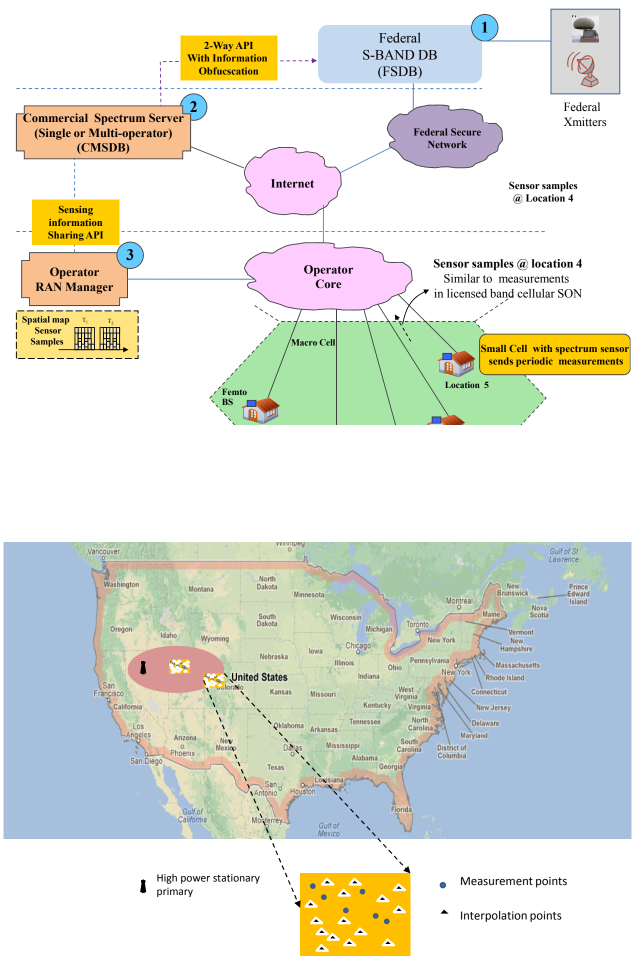
The reduced emphasis on national coverage and emphasis on capacity instead of coverage realized using small cells and shared spectrum enables city and regional level operators to emerge. In fact, if the deployment of small cells, backhaul and DB based coordination are offered as commoditized services and subscriber authentication and billing become cloud services, small cells network can have microscopic scope – as small as a mall, airport or a building and such networks can go organically into a "stitched quilt" of a network.

The above does not suggest that the world as we know will overnight transform. Much the same way in real world we have public parks, house backyards and country clubs meeting needs of different people at different times and social status, mix of business models that provide various differentiators will emerge.

Need for an exclusive license: The question "do you need a exclusive license to operate a wireless network?" is rather provocative. The license is a tool to guarantee "certainty" – certainty in terms of interference environment, for business investment and guarantees in return of investment (ROI) and ultimately a level of service guarantee that can be quantified in simple monetizable plans a customer can understand. Interference certainty simplifies design of network and client devices, reduces cost of RF, baseband and network components and makes capacity calculations feasible. The certainty of investment return was key when expectation of deploying networks with national coverage was basis of wireless network business. These needs may not be necessarily valid going forward. A small cell network can be narrow in its spatial footprint –covering a city and such networks in disparate locations can be tied via roaming databases. Also, the licenses of future can be smaller in temporal and spatial scope and exclusivity of ownership limited to that small scope. In fact, advances in interference cancellation may allow multiple but limited number of operators to co-exist in a license scope – leading to non-exclusive, light licenses. Despite these advances, realizing performance similar to that of a exclusively licensed spectrum in a network with only *shared use* and unlicensed bands may have practical limitations. To compensate loss of a shared use channel or deterioration of an unlicensed band requires significant alternative bands and cost of channel switching may impair performance. As such we believe licenses – albeit with smaller spatio-temporal scope ("decimated licenses") and "controlled non-exclusivity" will be essential even in future to provide guarantees for high performance users and base level of service for all. By associating a monetary transaction and controlling the number of concurrent licenses via spectrum DB to such light licenses, the small cells can be provided arbitrary interference protection.

Controlling market disruption: Cellular networks today represent critical infrastructure with economic impact in excess of \$1.6 trillion (\$ 1trillion revenue, \$550 B taxes, fees, 8.5 million jobs). The technology innovations have potential to create disruptive business models and strain cellular network operators whose revenues are already constrained due to slow growth in ARPU. It may be essential to craft regulation with two conflicting goals: (1) ensure incumbent interests are protected and enhanced and (2) new competition can be encouraged. For example, though in theory Dynamic DBs in its full potential can implement exclusive licenses, regulation need not bring existing licensed bands under such umbrella until technology and market mechanisms are designed and proven to be resilient. Similarly, for sharing to be feasible in many mission critical, sensitive spectrum bands, proof of primary protection and useful secondary capacity need to be demonstrated over sustained time period. This suggests conservative policy mechanisms that are relaxed over time leading to a slow evolution.

3. WHITECELLS: A CANDIDATE ARCHITECTURE FOR EVOLUTION



(b) Spatial interpolation technology

Figure 2: Split dynamic database, whitecells and DREAM

In the following, we propose a new architecture called *White-Cells* (Figure 2) [3, 5] that helps realize some aspects of the evolution outlined above. In the cellular instantiation of this architecture, LTE RANs are augmented with new type of small cells called *whitecell* which support multi-band access operating in two types of bands: traditional licensed cellular and shared spectrum bands such as 2-4 GHz S-band radar bands and DTV whitespace bands in 470-700 MHz. Each whitecell also has a built-in wideband receive-only spectrum sensor that can rapidly scan all cellular and shared bands to characterize locally perceived spectrum activity. In the non-cellular version, whitecell only supports unlicensed and shared spectrum bands where interference protection can be obtained via obtaining shared spectrum band leases that are exclusive or near-exclusive. The salient aspects of our architecture are discussed in the following.

Split Database: Our architecture, instantiated for S-band, sists of a *Split Database* with two component DBs:

(1) Federal S-band DB (FSDB), likely managed by defer government establishment that securely handles all informatio primary and their spatio-temporal behavior. It is designed policies and security mechanisms to provide a obfuscated, s tically impregnable access to primary channel availability. It only entity that can control which federal band channels (e.g band) channels are available for secondary use and also, can municate with Federal transmitters (e.g.: radars) to alter the rameters for enhanced co-existence.

(2) Commercial Multi-vendor S-band DB (CMSDB): is a da that controls the commercial LTE RANs of single or multipl vice providers, enabled with whitecells. Our model supports tiple CMSDBs similar to current TVDBs but does not need to communicate with each other as channel availability gran always common to all and each DB is free to decide how the allocated to secondary devices under its control. The split a tecture also absolves FSDB to track secondary user populatio instead limits it to large spatial summaries and a few contact p in the form of CMSDBs. This makes our approach very sca and also, maintains a strong wall of separation between con cial RANs and sensitive information about federal missions and transmitters. The CMSDB can be further broken into two layers: (1) the database layer that (a) receives spectrum demands and radio environment mapping (REM) data, (b) uses it to makes channel allocations, and (c) provides transaction or auction mechanism for awarding the leases, (2) a RAN manager (RANMAN) that coordinates the channel acquisition, configuration and release for the whitecells and uses the wideband spectrum sensors in them to collect REM measurements. In a cellular version of whitecells, RANMAN can be operator specific, where as in non-cellular scenarios, RANMAN can be implemented as a separate business.

Tracking and Controlling secondary user population: The mission critical nature of S-band federal transmitters, requires that all secondary use be expressly interruptible in the event mission parameters (e.g.: geographical scope of primary band use, tolerated interference etc.) are altered. This requires that unlike TVDB, the database in S-band should register and track secondary device characteristics (e.g.: location, TRX characteristics etc.) and activity (e.g: coverage region, secondary throughput) and also, maintain low latency logical channel of communication with it. This task is performed by the CMSDB+RANMAN layer, which is analogous to Small Cell Controller servers in current cellular deployments. This DB maintains a live secure TCP flow with each whitecell and commands channel allocation, de-allocations, sensing operations and collects sensing information. For example, in the event of a channel de-allocation, a message flows along the path: FSDB $\rightarrow$ CMSDB $\rightarrow$ whitecells $\rightarrow$ (broadcast message *Move to cellular channel*) to end-user devices (e.g: phones). Such message exchanges can be accomplished easily under 2-second duration.

Dynamic Radio Environment Activity Mapping (DREAM) aims at accurately tracking radio environment impact of primary and secondary device transmissions and ultimately assisting schemes (e.g.: channel allocation) for better co-existence. Based on knowledge of primary activity received from FSDB, the CMSDB schedules the whitecell sensors to collect dynamic secondary and primary user activity in S-band in 2 steps: *Step 1:* CMSDB dictates all secondary transmission to be shifted to cellular band to allow sensors only capture primary activity. *Step 2:* all sensors collect aggregate primary and secondary activity. These location tagged measurements are processed at each cell to create spatial and temporal summaries e.g. to estimate duty cycle of primary, max-min-median energy, propagation loss range and uploaded to the CMSDB. These summaries can be used to better estimate the coverage of primary transmitters (e.g: service contours/coverage of radars) which are "exclusion zones" where secondary use can be precluded. They can be supplied to the FSDB to enable it to add enough spatio-temporal randomness to channel availability grants. Such randomness aims to increase statistical hardness of inferring primary behavior based on channel grant pattern observed at a single secondary user. These summaries will also be used (a) in CMSDB for allocation of available channels to secondary devices and (b) in whitecells to introduce randomness in packet-level scheduling of secondary packets transmitted in secondary use channel.

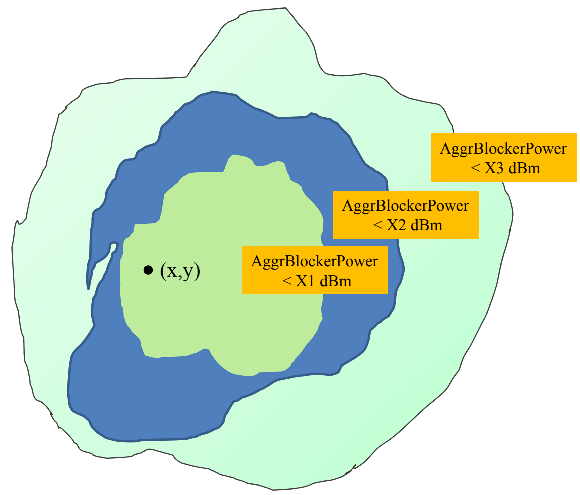


Figure 3: Admissible Region Contours (ARC)

Admissible Region Contours (ARC): This innovation uses DREAM and is aimed at aiding optimum channel allocation and achieving better co-existence of secondary devices in S-band, by better tracking impact of primary devices on secondaries. The main objective of TVDBs is to provide primary protection and they are not mandated to provide any additional information to secondaries on impact of primaries on their channel use. In contrast, DREAM capability can easily track channel quality impact of primaries. If the CMSDB knows the receiver characteristics, it can estimate how much adjacent channel splatter from radar primaries and adjacent channel transmissions from secondaries increase interference in the desired channel. This aggregate interference varies from location to location and for a given receiver sensitivity and filter characteristics, it upper bounds the achievable maximum data rate. This idea can be captured in what we call Admissible Region Contours (ARC) (Figure 3) (similar to topographical contours in geographical maps and in fact, more dynamic version of protection contours in TVDBs) constructed such that each contour has an associated with it a maximum signal blocker power P_{blk} (in dB scale). All points on or inside this contour experience at least P_{blk} power. These contours when correlated with location of secondary device can help predict best case in-band interference and correspondingly, TDD receive performance and thus help better allocate channels. These contours change infrequently in the context DTV whitespace but require much more dynamically updates in S-band. For example, in case of naval radars mounted on cruisers, as the radar rotates, the primary energy received in the direction of targets and side lobes varies with rotation and the exclusion zone itself moves.

However, within the exclusion zones, the received energy can periodically change with a duty cycle and the ARCs change accordingly. The trade off of ARC update frequency, channel capacity variation and allocation performance dictates how fast ARCs should be computed.

Spatial interpolation technology: As the density of small cells increases, if the sensing is implemented naively where all cells perform sensing in all bands, inordinate amount of data may be generated towards the CMSDB. Since, the CMSDB knows the location, terrain, and transmit and receive characteristics of secondary devices, a spatial interpolation technique can use REM values at a limited subset of locations to predict values at other locations. If the set used for prediction is changed over time, it allows randomizing or scheduling the set of small cells which perform sensing, thus reducing the load on each cell.

Integrated channel switching and aggregation: The shared spectrum channels can be interrupted and unlicensed spectrum can deteriorate due to increased interference and therefore, capability to dynamically switch channels at RF level and transfer packet traffic over multiple channels in an aggregated fashion to achieve high capacity is critical. Such integration has been considered in current networks for mobility hand-offs across multi-technology networks and is extended to whitecells. However, channel bonding across disparate wireless interfaces is still not a mature technology and needs careful design. Layer-1 carrier aggregation mechanisms emerging in 802.11ac and LTE-Adv standards are baseband specific. An alternate approach could use inverse fair queueing based mechanisms that aggregate layer-2/layer-3 packet flows over multiple radio interfaces each using a different band. Though such an approach may be inferior in latency performance, it is baseband agnostic and can be far easier to implement in software in OS kernels used in access points and client devices.

Whitecell hardware and corresponding client devices need use of RF front ends and antennas that can operate in multiple bands – often wideband, such as 150 MHz wide in 3550 MHz band. The feasibility of building network and client devices that can operate in wider swaths of spectrum bands is the key enabler for whitecells. Even with today's technology, the A/D conversion and subsequent digital signal processing can be increasingly made wide-band tunable over 0 to 6 GHz and handle up to 40 MHz channels. However, building analog front ends that can tune over such wide-band under software control, meet adjacent channel splatter constraints across entire 6-GHz band for transmit and handle large blocker signals in nearby bands on the receive path appears elusive. In the near term, band specific filters leveraging promising switched filter banks can be used for cost effective design.

4. EPILOGUE

Our vision of future wireless networks presents new challenges and opportunities for equipment vendors, network operators and wireless industry on the whole.

To realize our vision, new generation of products – wide-band basestations, NLOS high capacity backhaul, virtualized control plane and packet core elements, spectrum databases, and network analytics will be necessary. As a leading supplier of 3G/4G networks world-wide and a recognized innovator, Alcatel-Lucent/ Bell Labs continues to be a pioneer in these technologies.

For incumbent operators, the network evolution we outlined can help reduce their "sunken costs" and help cost-effectively increase network capacity by reducing the capital expenditure. Over the course of evolution as vertically integrated operator business change to horizontal business, the operators can diversify into the new business.

The gradual flattening of network business also opens door for new competition to emerge. Such new organically growing networks though will not be a replacement for operator managed networks with clear pre- or post-paid monetization models and well defined service offerings. However, increased competition and "capacity where you need it most of the time" nature of these networks makes them very attractive for end-users.

Small cell networks in shared spectrum also will be relevant for rural broadband and fixed wireless to augment wireline infrastructure in many parts of the world.

In summary, we believe that innovation in wireless networking should now shift its focus from improving existing fixed band cellular or Wi-Fi networks to incorporating seamlessly multiple variable grade wide bands and in process unleash new wave of research and business opportunities.

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