W H I T E P A P E R

Peter Flynn,
Business Development Manager, Communications Processors
Texas Instruments

Texas Instruments

Understanding the kaleidoscope of unlicensed spectrum

Overview

These are exciting, if not confounding, times for those trying to comprehend the whirlwind of expansion coming to unlicensed spectrum bands. The simple shared access model employed today in the unlicensed Industrial, Scientific and Medical (ISM) bands will not be a sufficient model when new targeted licensed bands will soon start sharing their bandwidth. And not all bands can be treated equally, at least not from a policy perspective. A wide range of policies and restrictions will be forthcoming which will impact how, where and when these new shared spectrum bands can be used and by whom. This white paper offers a brief overview of the situation and speculates on where it is likely headed. Of course, there are many views on shared spectrum, some more optimistic than others. In fact, one might say that some view the situation through "rose colored glasses," creating a collective kaleidoscope of spectrum options. This white paper attempts to balance the many and varied perspectives on the issues in order to answer the most critical question: What is the bottom line on this kaleidoscope of open spectrum?

Welcome to KAOS – the Kaleidoscope Aura of Open Spectrum!

Why now?

The simple answer to the question of why shared spectrum is appropriate now is that the wireless industry has reached that point where the current ISM bands cannot meet the public's voracious demand for more data and more mobility. The ITU has defined 12 worldwide frequency bands for ISM use, providing a theoretical total of 4.0GHz of bandwidth. Wi-Fi® (802.11xx), which suffers from the greatest congestion, is only using three bands (0.9GHz, 2.4GHz and 5.7GHz) and is limited to 276MHz of bandwidth. A significant and often overlooked application which consumes ISM bandwidth is the wireless cellular service providers which offload significant amounts of their traffic to Wi-Fi access points whenever possible. A study compiled by Cisco found that 45 percent of the global smart phone traffic is offloaded to the ISM bands[1] of unlicensed spectrum. Moreover, the data needs of global mobile phones are expected to exceed 15 Exabyte per month (that's 10 with 17 zeros behind it!) by 2018. Add to this another 50 billion Internet-of-Things (IoT) devices[2] which will likely pop into the ISM bands in the next few years and the additional congestion could threaten data throughput significantly.

Consequently, the groundswell of demand from ISM users and service providers to expand the available unlicensed spectrum bandwidth comes as no surprise. Nor is it startling that with each passing year the chorus gets louder!

But simply allocating more of the spectrum to ISM unlicensed bands is not an easy thing to do. There are no unassigned spectrum bands available to simply add to those already been set aside for ISM. However, much of the licensed spectrum is underutilized. In fact, plenty of licensed spectrum capacity is available as much of it is sitting fallow in many locations. A study by Dennis Roberson[3] of the Illinois Institute of Technology puts the total spectrum utilization at less than 15% in urban areas such as Chicago! (See Figure 1 on the following page.)

So the best option, and the one that is being aggressively pursued by the Federal Communications Commission (FCC), would be to share spectrum when it is not being used, as long as this sharing does not interfere with the current licensed users. Equally important would be the ability to efficiently share spectrum by proactively managing it as a valuable resource. Simply avoiding packet collisions, as the venerable Carrier Sense Multiple Access (CSMA)

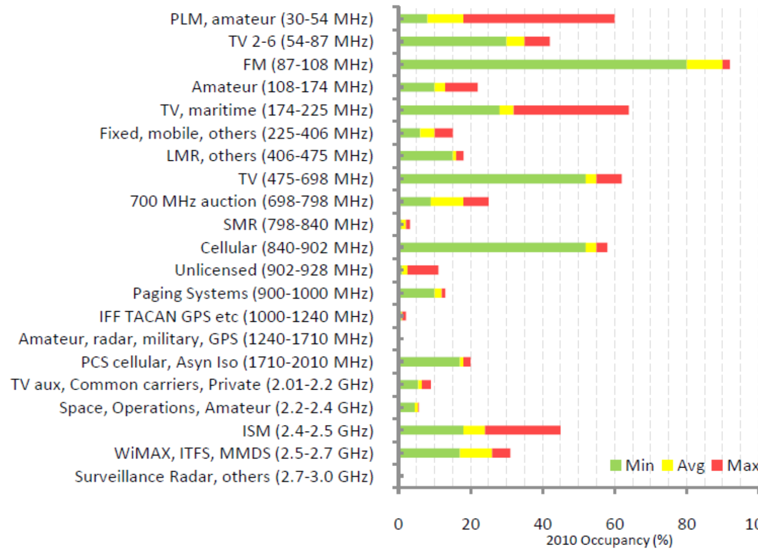

Figure 1: Estimated occupancy by band for 2010 (up to October). Average overall occupancy is 14% for 30–3000 MHz.

protocol has done for years for Wi-Fi (IEEE-802.11), is just not a sufficient model for sharing an access point (AP) with multiple heavy Wi-Fi users.

How to share spectrum efficiently

A quick digression into CSMA (Wi-Fi) will shed some light on the current dilemma. Basic physics restricts wireless communications to just one device at a time; otherwise, interference will impede and possibly cancel simultaneous communications. (Technically, multiple simultaneous broadcasters can occupy a band, but they must be separated by a minimum phase difference to avoid interference. This level of complexity is beyond the scope of this white paper.) The CSMA model requires that a transmitter monitor when other users are communicating in the same band. If a transmission is attempted and a packet collision detected, the transmission is postponed and attempted again later. Simply stated, this is a “Listen Before Talk” protocol. This simple model for sharing the band works well when the probability of collisions is relatively low. This is a valid assumption as long as wireless traffic takes place in “bursts” and very few users simultaneously occupy the same band in the same location. Ten years ago this was the case, given the usage models and applications at the time. But since then, streaming applications, which are not burst-oriented, have become more common, the density of Wi-Fi APs has increased and often overlap, and, of course, the number of users per AP has increased dramatically. All of these factors have conspired to make CSMA’s design premises less viable.[4] Essentially, collision sensing among multiple users sharing the same bandwidth results in significant reduction in overall throughput for all users. This is why Wi-Fi capacity, while often touted as 54MBps, can be as low as 10Mbps on many public AP connections. And, as shown in the following analysis, throughput can quickly degrade by 50 percent with as few as 10 users connected to the same AP.[5] (See Figure 2 on the following page.)

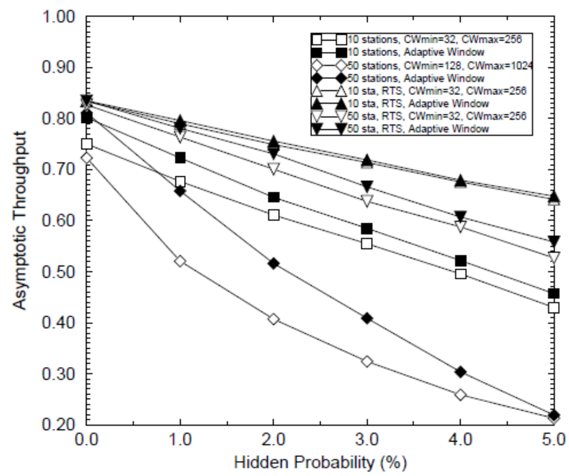

Figure 2: Saturation throughput versus the hidden terminals probability.

Fortunately, protocol models that are more robust with regards to cooperative multiuser sharing of bands have been developed and are being deployed. For example, Time Division Duplex (TDD) assigns a periodic window in time when a user can transmit and receive. During that window, the user has complete control of the spectrum band with no risk of packet collisions. This method is very efficient but it requires close coordination of the time slots by a central base station or communications controller. WiMAX (IEEE-802.16) systems incorporate this methodology as well as some 4G-LTE systems. In 3G/4G cellular systems, a similar spectrum sharing model called Frequency Division Duplex (FDD) is more common.

Recently, other new solutions have emerged. In particular, the FCC is promoting models that dynamically share all of the bands in the entire spectrum by accessing a database of known available spectrum. For example, the International Engineering Task Force’s Protocol to Access White Spaces (PAWS RFC6953)[6] database model is currently providing this function for TV white spaces or unused spectrum in the 75MHz to 600MHz band. A very similar solution, Spectrum Access System (SAS)[7] has been proposed by the FCC for the new 3.5GHz unlicensed spectrum. Basically, in these models the wireless AP or base station queries the spectrum database for available unused spectrum bands in a certain location. Then, the AP or base station would notify the database which band it intends to use and switches its transmitters and receivers to that band before broadcasting. Any devices in the area that are following this model would avoid collisions and interference. This general model is supported by cognitive radios which have the ability to use many different bands and can dynamically switch between bands. IEEE-802.22[8] Wireless Regional Area Network (WRAN) is an example of a standard based on the concept of cognitive radios, which has gained additional industry support through the Whitespace™ Alliance’s[9] Wi-FAR™ standard.

The FCC has added another wrinkle to this notion of database spectrum sharing in the 3.5GHz bands. The FCC has proposed a three-tiered model of users in these bands. Top priority would be given to Incumbent Access (IA) users; the second tier would be devoted to Priority Access (PA) users such as local emergency services; and the third tier would be available to everyone else as General Access (GA) users. Obviously, this general database model for spectrum sharing could be easily applied to other bands as they become available for sharing.

Where is the spectrum coming from?

As mentioned previously, there are no free bands of spectrum, just a lot of underutilized bands. Utilization can be measured in many different ways. For the sake of simplicity, this white paper only addresses spatio-temporal utilization[10]; that is, spectrum utilization at a given location and time.

Based on this information it is tempting to simply propose relocating incumbent users in an underutilized band to another low-traffic band so that the bandwidth is utilized more efficiently. The problem with this approach is that it is hugely expensive to relocate users from one band to another. In addition, doing so could take over a decade or longer to complete. Of course, the installed base of equipment currently operating in a certain spectrum band is what would drive these cost and time factors. All of the equipment currently occupying a band would need to be replaced and all applications updated to the band where the applications are moving. The National Telecommunications and Information Administration (NTIA) concluded that clearing just one 95MHz band by relocating existing Federal users to other parts of the spectrum would take 10 years and cost some $18 billion.[11]

Clearly, the cost in terms of time and money is too great to play musical chairs with spectrum allocations. Instead, the preferred alternative would be to rely on technology to improve the management of underutilized spectrum and thereby free up capacity in these bands. With new technology, this can be done without impacting the existing licensed users in these bands.

In 2012 the President's Council of Advisors on Science and Technology (PCAST) issued a report which recommended the sharing of underutilized spectrum and identified many bands currently dedicated to federal users which could be shared.[12]

Table 1. Federal and shared bands under investigation for shared use

Federal and shared spectrum bands under investigation

Frequency Band (MHz)	Amount (Megahertz)	Current allocation/usage (Federal, Non-Federal, Shared)
406.1–420**	13.9	Federal
1300–1390**	90	Federal
1675–1710*	35	Federal/Non-Federal shared
1755–1780*	25	Federal
1780–1850	70	Federal
2200–2290	90	Federal
2700–2900**	200	Federal
2900–3100	200	Federal/Non-Federal shared
3100–3500	400	Federal/Non-Federal shared
3500–3650*	150	Federal
4200–4400** (4200–4220 & 4380–4400)*	200	Federal/Non-Federal shared Federal/Non-Federal shared
Total	**1,473.9**	

The FCC has been aggressively working with industry and other governmental agencies to devise cooperative models for sharing spectrum. The FCC's focus is on six bands (1300, 1755, 2200, 2900 and 3500 MHz as well as multiple 5GHz bands[13]), potentially making as much as 700MHz of spectrum available to unlicensed bands. But, as stated earlier, not all spectrum bands can be treated equally. The incumbent users in these bands – mostly federal agencies but also Doppler radar and satellite communications – will require assurances that they will not experience significant interference from unlicensed users. And each band has its own incumbent use case scenario, which may vary by location, time, power level and interference sensitivity.

Clearly, managing any newly shared spectrum band will not be trivial considering all of the diverse requirements. Basing solutions on the notion that spectrum is a valuable resource which must be managed judiciously will be essential because the application of any model must be variable over time, capacity and location.

What this means for end users and equipment suppliers

End users, of course, simply want more bandwidth – anywhere and at any time – for their mobile devices. But providing the equipment that can dynamically access multiple bands, accommodate a range of various management policies and adapt to the available spectrum in a certain location is quite challenging. Add to these factors the complication that global spectrum sharing would require that bands align across all countries around the world. As a result, very few of bands would be available for sharing. For a daunting look at the challenge of global spectrum alignment, the FCC has provided the following table:

http://transition.fcc.gov/oet/spectrum/table/fcctable.pdf

Clearly, APs and base stations will need to be very flexible and dynamic in their ability to quickly and efficiently select available bands while minimizing cost and overhead. No doubt this can be done, because, in fact, some solutions are already available. Adding these capabilities to mobile end user devices will surely increase the power, size and cost of devices. So the key question, as always, will be determining the value of all of this to the end user and then developing a solution that is supported by a viable business case. Once the value is clearly perceived in the marketplace as greater than the cost, the solution will be embraced.

Of course, integrating these band-adaptive capabilities into mobile end-user devices is pointless unless and until a clear plan has been devised for deploying the wireless network infrastructure that would support the new bands and band-sharing policies. Consequently, the initial challenge will be to bring APs to the market which can leverage the capacity of these bands as part of a wireless backhaul infrastructure solution. For example, these shared bands could become a point-to-point (PtP) last-mile backhaul solution for small cell deployments and machine-to-machine (M2M) applications, including smart grid, and oil and gas industry applications.

As mentioned previously, equipment and devices which are able to cooperatively negotiate access to a wide range of bands and quickly select the optimal band are referred to as cognitive radio devices. These devices may also need to adapt to the different power levels in various countries as well as the many protocols supported within each band. Developing this high degree of flexibility can be challenging and invariably leads down the path toward software-defined radios (SDR) because of this technology's inherent flexibility.

What is the end game?

What can be expected down the road in terms of building out the infrastructure and developing the next generation of smart mobile devices to meet the imminent tidal wave of demand?

Ultimately, many experts expect that the broad wireless marketplace will evolve more toward business models based on dynamic use cases. This will come in many forms, including the following: pay-for-access models currently employed by cellular service providers; the content providers' pay-for-capacity or "fast lane" model; and a more sophisticated pay-for-use model where the value of wireless access is determined by the competitive demand of end users who dynamically decide when they want to buy access to the wireless infrastructure based on the market price at a certain time and in a certain location.

This last model was proposed as part of the PCAST report in 2012 and it is slowly gaining momentum. Basically, it places the value determination with consumers. For example, users would share available bandwidth with thousands of others at a stadium during a sporting event where the online streaming of instant replays could create a very competitive localized marketplace. According to this line of reasoning, providing adequate service in such a situation would come at a greater cost to service providers, so the price of wireless access to users should increase proportionally with the demand. Two hours after the game, when everyone has gone home, little demand for that same bandwidth capacity will remain in the area of the stadium so the price of access would drop significantly. The dynamic-demand-cost model evolves to one that is very similar to paying higher tolls on a freeway during rush hour as compared to paying lower tolls during off-peak travel hours. The intent of such models would be to enable the determination of value to be driven by consumers with each purchase decision they make. In turn, the value of a service will drive the funding of new capacity to meet any growing user demand.

The key point here is nothing is free when it comes to shared spectrum. There must be an economic model supporting the deployment of infrastructure based upon the value established by users. In addition, no single economic model will be the solution in every region. Multiple economic models will be employed to accomplish the goal of ubiquitous and global wireless broadband access.

How do we get there?

Wireless processors are available today which can implement the latest protocols and cognitive radio functionality to achieve the goal of shared unlicensed spectrum. Full SDR solutions are now a reality. For example, TI's TCI6631K2L system-on-a-chip (SoC) integrates two ARM® processor cores with four TMS320C66x DSP cores with a fully configurable Digital Radio Front End (DRFE) and more than a dozen radio and packet accelerators. This SoC can interface directly with TI's AFE7500 integrated Analog Front End (AFE) via JESD204B. This two-chip combination can form the basis for multiple radio solutions from 400MHz to 4GHz with off-the-shelf SDR implementations for LTE, LTE-U, WiMAX, Wi-FAR as well as proprietary solutions.

Moreover, databases are available today for implementing PAWS and SAS functionality so that underutilized bands can be proactively and efficiently shared among unlicensed users.

Since the requisite technology and consumer demand exist, one can only wonder what is preventing the effective sharing of underutilized spectrum.

First, global leadership and collaboration is needed to agree on the bands to be shared and commit to a timeline for the required policies and regulations. This could be tricky because spectrum bands do not align globally; protection of incumbent users is needed and clear-cut economic incentives to drive policy makers in the same direction have not emerged.

Second, without a clear policy on the bands to be shared and models on which to base a business case, device manufacturers will not have incentive to invest in developing solutions for expanding the infrastructure. And without the infrastructure, mobile device manufacturers will not burden their devices with capabilities for accessing bands that may be inaccessible.

All stakeholders need to come together to achieve success in this endeavor, but it won't happen overnight. The feasibility of sharing underutilized spectrum should first be demonstrated in several bands. Then the marketplace will drive further expansion. Shared unlicensed spectrum will have a huge impact on broadband data services around the world. The technology exists to solve the problem. Now, global policy consensus must be built.

Stay tuned. This "KAOS" will be truly dazzling!

References

[1] http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.pdf

[2] http://www.cisco.com/web/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf

[3] http://www.ece.iit.edu/~taher/dyspan11.pdf

[4] http://en.wikipedia.org/wiki/Hidden_node_problem

[5] http://www-sop.inria.fr/members/Sara.Alouf/Stage/bianchi1996.pdf

[6] https://datatracker.ietf.org/doc/rfc6953/

[7] http://spectrumworkshop.uservoice.com/

[8] http://www.ieee802.org/22/

[9] http://www.whitespacealliance.org/

[10] http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6478159

[11] http://www.ntia.doc.gov/report/2012/assessment-viability-accommodating-wireless-broadband-1755-1850-mhz-band

[12] http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf

[13] http://www.fcc.gov/document/5-ghz-u-nii-ro

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265