Wireless Innovation Forum Top 10 Most Wanted Wireless Innovations

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TERMS, CONDITIONS & NOTICES

Table of Contents

Preface

In 2010, The Wireless Innovation Forum initiated an ongoing project to identify major innovations that would be required to create the foundation of the next generation of wireless devices and systems. These innovations, either technical, business or regulatory, if realized, would address various shortcomings in existing wireless communications from the point of view of the different stakeholders in the wireless industry value chain, including users, radio or platform manufacturers, software and hardware component providers, operators, service providers, and spectrum regulators. These innovations don't necessarily need to result in patents or intellectual property, but would serve to help the community in addressing emerging wireless communications requirements through improved performance of deliverables, reduced total life cost of ownership, and the responsive and rapid deployment of standardized families of products, technologies, and services.

To create this innovation roadmap, the Forum's Committee on Spectrum Innovation sought participation from the different stakeholders to identify perceived or real shortcomings in the wireless domain and to propose innovations that could potentially address these shortcomings. From the input received, the Forum's Advanced Technology Committee selected the following as the revised "Top 10 Innovations" that have the most potential of improving the wireless communications experience (in no particular order):

1. Innovation #1: Artificial Intelligence/Machine Learning for Radios
2. Innovation #2: Dynamic Spectrum Management
3. Innovation #3: Propagation Prediction Techniques for Dynamic Spectrum Sharing and Other Applications
4. Innovation #4: Flexible, Extensible, and Secure Transportation Communication Framework
5. Innovation #5: Advanced Interference Mitigation Techniques
6. Innovation #6: Receiver Performance Interference Thresholds
7. Innovation #7: Low Cost Wide Spectral Range RF Front-End (Multi-decade; Contiguous) (Tx,Rx)
8. Innovation #8: Efficient Techniques to Minimize Power Amplifier Spectral Regrowth in Non-contiguous Spectral Environment
9. Innovation #9: Network Management of Mobile Ad-hoc Networks
10. Innovation #10: Integrated Development and Debug Process for Software-Based Applications in Embedded Heterogeneous Platforms Innovation

In support of the Forum's Strategic Plan, the Advance Technology Committee will maintain this list, adding or subtracting innovations as required to serve the overall needs of the advanced wireless community. The intention of the Forum is to promote this list across the wireless community, and to support research and development activities addressing the targeted innovations both within the Forum membership and in partner organizations.

Wireless Innovation Forum
Top 10 Most Wanted Wireless Innovations

1 Innovation #1: Artificial Intelligence/Machine Learning for Radios

1.1 Executive Summary

With the advent of artificial intelligence and machine learning technologies being broadly applied to many aspects of life, it's only natural for the technology to be applied to radios, as well. There are a number of potential use cases, commercial, civilian and military, some of which are already under investigation. Examples include:

1) The DARPA Spectrum Collaboration Challenge which focuses on the use of machine learning for radios to maximize interference mitigation and spectral usage.
2) Research to enable radios to change or adapt the physical layer in order to increase the effectiveness of transmission while substantially reducing resource utilization and power consumption.
3) Research to enable proactive dynamic spectrum management in order to optimize spectrum utilization and foresee spectrum demand.
4) Programs so that radios can autonomously identify signals of interest, including potential threats.

In order for these scenarios to come to fruition, there are a number of enabling technologies and ecosystems that need to be incubated, nurtured and developed. There is more work needed to be done with regards to both software and hardware. On the software side, one of the greatest challenges is to implement the learning databases, with on-going updates, and then algorithms to make the best decisions using the learning databases. The development of the actual Artificial Intelligence/Machine Learning (AI/ML) algorithms and datasets themselves, form the core of the cognition ability of the radio. On the hardware side, power efficiency, cost per unit, ease for programming and memory requirements all come into play and must be weighted to find the most optimal solution. Different types of processors can be viable choices depending on the specific use cases.

1.2 Application

Developing and deploying autonomous radios capable of AI/ML will benefit a variety of use cases for commercial, civilian and military purposes.

- AI/ML will drive systems for automation and network evolution. Network operators' Operating Expenses (OPEX) can be drastically reduced and customer experience greatly improved as what matters the most gets efficiently delivered.

- AI can be applied to the military, first responders and public safety communities to augment analysis and decision-making capabilities and reaction times both, speeding up learning, and improving their ability to act with discretion, accuracy, and care under uncertain and changing conditions.
- Regulators will have the potential to enable a close to real time and proportionate regulatory regime that identifies and addresses risk while also facilitating far more efficient regulatory compliance.

1.3 Description

AI/ML for radios will be enabled by both hardware and software innovations. For hardware, there is a need for embedded platforms which can support multiple AI/ML use cases and requirements. In terms of processors, the primary choices today for AI/ML processing are Application Specific Integrated Chips (ASIC), (Graphics processing Unit) GPU and Field Programmable Gate Arrays (FPGA). In general, ASIC is the lowest in power efficiency and cost per unit, GPUs are high performance but consume a lot of power, and FPGAs are harder to program but consume less power than GPUs. In addition, memory requirements tend to be high for AI/ML systems in order to store the datasets for training, as well as cognition. And there are also multiple potential form factors desired by different end users, including small standalone devices to rack-mounted units more rugged form factors like VPX. Since there is no single architecture that can support all the disparate requirements of each potential use case, there is a clear opportunity for multiple vendors to compete in AI/ML COTS hardware platforms.

With regards to software, one of the greatest challenges is to implement the learning databases, with on-going updates, and then algorithms to make the best decisions using the learning databases. The development of the actual AI/ML algorithms and datasets themselves, form the core of the cognition ability of the radio. Other software key needs include development related to programming tools and methodologies, libraries and frameworks. Examples include:

1) Tools for programming FPGAs and GPUs which make them easier to program for AI/ML algorithms. There are tools today which support programming languages like OpenCL, which are often used by users starting with GPUs as the key processor. Even FPGAs now support OpenCL and C programming methodologies in order to be easier to program and compete against GPUs.
2) Libraries and frameworks to leverage for quicker development of AI/ML systems. A good example of this is Google's TensorFlow.
3) Then there are the actual AI/ML algorithms and datasets themselves, which form the core of the cognition ability of the radio.

There are plenty of opportunities in the ecosystem for any of these types of innovations that make it easier to develop and deploy radios capable of AI/ML. As the enabling technologies develop and the ecosystem matures, we will see the advent of fully autonomous radios that support a variety of use cases for commercial, civilian and military purposes.

2 Innovation #2: Dynamic Spectrum Management

2.1 Executive Summary

The realization of a fully Dynamic Spectrum Management (DSM) system powered by cognitive network technology and supported by collaborative intelligent radios[1] is considered a future vision for DSM. In the next decade, it is anticipated that the spectrum management ecosystem will experience a paradigm shift by relying extensively on spectrum knowledge (which will leverage the application of data science (e.g. machine learning and data mining) to spectrum and related data) to perform proactive dynamic spectrum management in order to optimize spectrum utilization and foresee spectrum demand. Ultimately, a DSM system will be capable of adapting its prediction and decision-making through machine learning, in order to capture changes and adapt to the RF environment and related spectrum usage parameters.

DSM design paradigms must evolve to demonstrate elements of the paradigm shift by integrating spectrum knowledge as a core function in spectrum management; possibly leading to new and innovative spectrum management strategies and enhancing existing spectrum management strategies. One can envision a long term outcome to spectrum management where a combination of different types of services could dynamically share large portions of pooled spectrum, and further down the road the whole spectrum, in order to maximize spectrum usage efficiency.

2.2 Application

Maximizing spectrum usage efficiency based on knowledge will benefit a broad range of user communities including:

- Network operators can apply a data-driven proactive approach to spectrum access and management, where spectrum shortage and oversupply across different networks can be predicted and managed.
- The military, first responders, and public safety communities can enable quick and meaningful spectrum access based on data-driven decisions, through the provision of relevant spectrum knowledge.
- Regulators can automatically track and act upon unauthorized spectrum usage (automated compliance function) through the use of spectrum knowledge.
- New DSM functions such as flexible licensing, including real-time spectrum monetization with real-time auctions and dynamic spectrum assignment of the licenses,

[1] Paul Tilghman, DARPA, Invited Talk: Spectrum sharing through collaborative autonomy, Sep 25, 2017, VTC Fall 2017 Toronto

could also be considered as part of the DSM evolution going forward and would benefit regulators and brokers.

2.3 Description

The dynamic spectrum management is enabled by several core technologies:

- Advancements in cognitive/intelligent RF radios that allow them to learn and adapt the operational aspects of the radio to their current propagation environment. Cognitive Radios (CR) will operate over multiple frequency bands over a wide frequency range. Lower costs will enable CRs to become ubiquitous.

- Advanced spectrum sensing will be needed to quickly and accurately classify known and unknown sensed RF signals (users) in targeted bands and identify transmission opportunities over a very wide spectrum pool that may host a large number of different wireless services and higher priority services.

- Adaptive antennas that can scan the surrounding environment and adapt directivity and beam patterns to target transmissions.

- Data fusion methods and big-data-analytics for helping with machine learning, prediction and decision-making with appropriate training methods (e.g. Reinforcement Learning).

- Adaptive receivers that can better manage interference and track changes in the RF environment.

Taken together these technologies can enable wireless devices and networks to coordinate access to spectrum among themselves by sharing information on the spectrum environment, prioritizing new spectrum demands (e.g. emergency access), and protecting the priority access of legacy systems (e.g. military radar).

Ultimately, dynamic spectrum management could include local information processing (e.g. machine learning algorithms residing on the cognitive radios), as well as cloud management, to create an ecosystem where the cognitive radios could coexist seamlessly without a need for human intervention / licensing.

3 Innovation #3: Propagation Prediction for Dynamic Spectrum Sharing and Other Applications

3.1 Executive Summary

Propagation prediction is fundamental to spectrum sharing. To enable intensive use of shared spectrum while protecting (but not overprotecting) other users, an evolution in propagation prediction is needed for interference calculations in support of automated frequency assignment. However, due to the high complexity of many sharing environments, currently-available prediction techniques are either too slow (for example, ray tracing models) or too inaccurate (for example, empirical path loss formulas) to support efficient spectrum sharing; possibly leading to overprotection of other users resulting in inefficient use of spectrum.

Several aspects of propagation prediction need improvement:

1. Incorporation of clutter data (buildings and foliage) from rapidly improving geo databases.

2. Improvements in long-distance propagation prediction, which currently sets the size of computed zones within which sharing must be coordinated or even blocked to ensure protection of incumbents.

3. Speeding propagation prediction to enable more dynamic shared spectrum applications.

3.2 Application

The application of improved propagation models is for the evolution of current automated frequency control systems (such as the 3.5 GHz U.S. CBRS Spectrum Access Systems), as well as future systems, such as the 6 GHz AFC (with potential use in many parts of the world), and possible applications in the 3.1-3.55 GHz band being studied for shared use by U.S. regulators. Such models will have applications in many other areas that aren’t even envisioned yet (beyond dynamic frequency sharing, to include network planning), and in all parts of the world.

Currently, incumbent protections are often accomplished with high reliability only by employing propagation models that vastly over-estimate the strength of potentially interfering signals. For example, free space loss is often used as “worst-case,” or models such as Longley-Rice that do not incorporate the effects of clutter may be used, and/or incorporate models of long-distance propagation that are based on very old data that have not been extensively validated. This results in very large coordination or exclusion zones that reduce the efficiency with which shared spectrum can be used. As an example, CBRS exclusion zones in the areas of co-channel fixed-satellite earth stations extend to a radius of 150 km, which equates to a total area of some 70,000 square km, which is bigger than ten of the U.S. states.

Besides improving propagation prediction accuracy, improvements in the speed of propagation prediction may also be useful. The application of this innovation is in database-driven dynamic access to shared spectrum by the nodes of next-generation commercial mobile wireless networks deployed in urban areas. One possible sharing scenario, for example, is an urban 5G deployment in a frequency band whose incumbent users are fixed and located in the surrounding rural area. Spectrum resource assignments to the mobile nodes are controlled by an automated, database-driven decision-making entity protecting the incumbent users from harmful interference. When a mobile network node requiring access to spectrum resources registers or updates its operational parameters (location, transmit power, antenna parameters, etc.), this entity must be able to perform nearly instantaneous calculations of the resulting interference impact on the incumbent users. These calculations must take into account the interference shielding effects of the urban environment, which are due to signal obstruction by obstacles such as buildings. Improved propagation models to more accurately characterize radio signals in small-cell deployments in dense urban environments would benefit service providers to aid them in more effective network deployment which ultimately would benefit consumers (both business and the general public) with improved coverage and quality of service. It would also give the regulators a better understanding of radio propagation characteristics in urban environments that would aid them in their decisions on how best to allocate spectrum so as to use the spectrum most efficiently in these environments.

3.3 Description

For propagation prediction methods to be of value for database-driven dynamic spectrum sharing among mobile radio nodes, they need to be:

1. Sufficiently *accurate* to prevent harmful interference while not being overly conservative with respect to estimating propagation loss on interference paths, which limits spectral utilization efficiency; prediction uncertainty should be dealt with statistically rather than by applying safety margins.

2. Sufficiently *fast* to support spectrum assignments based on the actual locations of mobile nodes; for vehicular nodes, this implies prediction times of less than one second.

The convergence of cloud-based computing with increasingly detailed geo databases is creating a path to achieve both improved accuracy and speed, at least in terms of clutter-aware non-long-distance propagation. Improvement to long-distance propagation will require long-term data acquisition and incorporating those observations into empirical models.

Possible R&D directions for overcoming the limitations of traditional prediction techniques include the use of:

- High-performance cloud computing to accelerate existing prediction methods.

- Radio-frequency sensing data collected from mobile devices in the frequency sharing area, in the same or different frequency bands, supplemented by deterministic-based simulations to determine probability of achieving coverage extent, quality of service indicators etc,

- Maps of buildings, terrain and vegetation, as well as other sources of external data; for example, dynamic maps of vehicular traffic intensity (possibly relevant for signal obstruction) and weather (possibly relevant for millimeter-wave propagation).

- Machine learning techniques for recognizing patterns in past propagation prediction results and their correlation with external data.

- Acquisition of long-term (1-2 years or longer) measurements of long-distance propagation, as a function of multiple factors, including climate, season, polarization, frequency, antenna directivity and tilt, bandwidth, and other factors.

- Incorporation of long-term long-distance loss measurements into new empirical models.

4 Innovation #4: Flexible, Extensible, and Secure Transportation Communication Framework, Architecture, and Management

4.1 Executive Summary

Self-driving cars are anticipated to emerge in the next decade as an everyday technology. Public anticipation of this technology is keen, given the potential to save countless numbers of lives, substantially reduce travel times, and give freedom to those who are unable to drive. While the current view is that cars will have a great deal of autonomy through a vast array of sensors, vehicles will need to coordinate with other vehicles (i.e., signal the need for a lane change), infrastructure (i.e., knowing when a signal will change or a rail crossing will engage), and pedestrians (provide additional safety to pedestrians in addition to visual cues).

While the idea of vehicular communications has been around for some time (such as DSRC, or Dedicated Short Range Communications), it has not been commercially attractive and hence has seen very limited deployment. What has changed is that electronic safety measures have become much more appreciated by the public with the advent of such devices as lane change monitoring, automatic braking, and smart cruise control. New technologies such as low latency communications and machine-to-machine communications are also emerging and supportive of vehicular communications. 3GPP Releases 14 and 15 describe a new technology called cV2x that has promise for integrating vehicular communications into the cellular network. Refinements to cV2x will be forthcoming in Release 16 and likely further refinements will happen in later releases. At the same time, the slow uptake on DSRC has caused the FCC to consider allowing WiFI to operate in the band 5.850-5.925 GHz that had been set aside for vehicular communications.

The business model for vehicular communications is becoming more attractive for governments and commercial companies. Increasing traffic flow without building new roads or lanes is attractive to governments that need low-cost solutions to traffic congestion. New business areas and revenue and access to high volume data customers and the ability to integrate vehicular communications into the cellular infrastructure is attractive to service providers. Car manufactures are able to entice new car buyers with new technologies that promise safety and convenience.

Yet, there are hurdles to realization of vehicular communications. The regulatory environment is in flux regarding the spectrum availability for vehicular communications. Should or will one standard exist for the vehicular communications band? If not, how will various standards co-exist in the band especially when safety applications are supported? What will be the impact of WiFi in adjacent bands or even co-channel with vehicular communications? How can technology improvements progress when not all vehicles may not have the latest technology?

4.2 Application

How will this technology make an impact?

Creating this Framework will allow for a quicker, smoother, and more risk adverse deployment of vehicular communications. The framework will also facilitate a competitive business environment, minimize regulatory decisions, and facilitate rapid progress in improving vehicular communication technology.

4.3 Description

What is needed to support vehicular communications is the formulation of a flexible, extensible, and secure transportation communications framework. Such a framework will enable a competitive ecosystem of service providers, manufacturers, and deployment services to collaborate and develop best deployment practices. This framework needs a common language, technical expectations, security mechanisms, and open interfaces. The framework developed must be able to live through the life of a car, spanning 20 years or more and hence should evolve with time along with the applications it supports. It needs to be compatible with the regulatory framework of various nations yet be customizable for the specific needs of a nation or region within a nation. Such a framework will require SDR innovations beyond what is available today, primarily because of latency concerns. Something analogous to a Software Communication Architecture (SCA) is needed. However, end-to-end response time of 1ms or less will be needed and will become the key technical driver in designing the architecture and implementing of the vehicular communication system.

Spectrum awareness is a key technology in supporting this framework. It is important for co-existence of dissimilar standards and it is important in the build out of the technology to know when and where communication resources are available and the nature of the interference in that area. Given that safety systems will depend on the availability of spectrum appropriate security measures need to be define, including physical layer security to avoid jamming or spoofing attacks.

The policy regards to spectrum for the use in vehicular communications is still in flux, but for now it appears that the FCC will take a hands-off approach and let market forces decide what standards will be deployed in this band and its adjacent channels. This has far reaching implications.

Many component technologies are necessary to fulfill the promise of a unifying framework. Key technology areas and their needs are listed below.

1. **SDR**
    - Architecture that is common and can grow with time
    - Very low latency architecture and realizations which may imply considering importance and the age of information in setting processing priorities.

- Low power systems that can support vehicular to pedestrian communications
- Interference rejection techniques
- Ability to coordinate with cellular and new bands
- Very dense deployment of nodes
- Secure at all-layers, including physical layer

2. **Spectrum management**
   - Determine and distribute what standards are used where
   - Determine potential for adjacent channel interference and mitigation techniques
   - Low latency spectrum information distribution (beyond what CBRS can do)
   - Monitor small cells and low-level signal levels over large areas

3. **Deployment processes**
   - Simple to deploy by unskilled workers
   - Adaptable to changes in the RF and physical environment
   - Assessment of how well the system performs at various sites and continued monitoring of its performance
   - Reduce sensitivity of performance to different vehicular platforms

5 Innovation #5: Advanced Interference Mitigation Techniques

5.1 Executive Summary

Improved mechanisms are required to reduce intrusive and destructive interference to communications signals and circuits. Improved and applied interference mitigation and cancellation techniques may be utilized to improve quality of service, range, spectrum efficiency and spectrum re-use if properly implemented. Interference reduction and mitigation techniques continue to mature for a subset of communications systems including military and some commercial applications. Development of interference rejection systems that are realizable in consumer communications devices including broadband consumer handsets and base sites, land mobile narrowband and broadband systems including public safety and mission critical applications, and other cost and size-conscious systems are needed.

5.2 Applications

Interference can take multiple forms. Some common forms are 1) intentional jamming, as often occurs in military communications or as a denial of service attack to existing systems, 2) unintentional or non-intentional interference, often resulting from misuse of equipment (wrong frequency settings including operation outside of authorized bands, exceeding necessary or licensed power levels, etc.), equipment failure / degradation, or emission spillover from OOBE in other bands, or 3) collisions of like waveforms such as those that occur in unscheduled or collision-sensed environments (ex: Wi-Fi), and 4) dissimilar or disparate waveforms vying for use of identical spectrum allocations such as in ISM, unlicensed, and lightly licensed bands. In all cases, the resulting interference acts to decrease the signal to interference plus noise ratio at the receiving end of the communications path and, if of sufficient level, will act to degrade quality of service or deny service entirely. This can range from impaired or obliterated voice quality degraded data fidelity, or complete denial of data throughput.

5.3 Description

Innovations are sought that deal with how Software Defined Radio (SDR) and/or Cognitive Radio (CR) might alter the system design tradeoffs either to enable better rejection of interference without the exponential cost growth associated with more traditional solutions. Such innovations might include, but not limited to, the ones listed below. It is realized that many of these techniques are already used in some advanced communications systems, but not used in others because of design tradeoffs such as the implementation cost of such techniques would be prohibitive for many applications or other factors necessary for their deployment. It is recognized that CR techniques, whereby the frequency plans could be modified to operate in non-interfering bands, might be a solution but spectrum availability or operating frequency range of the radio may be cost prohibitive. Significant cost/implement size of current techniques as well as new techniques are being sought. Examples of potential research categories applicable to interference mitigation are given below.

- Development and use of active cancellation techniques where a-priori knowledge of the interfering system can be utilized to an advantage to partially cancel the undesired, interfering signal, thus improving the figure of merit of the desired communications channel for a given communications path. Cost-effective, solutions that can be integrated for incorporation into consumer and professional narrow and broadband equipment is required.
- Enhanced Uplink and Downlink power control throughout the communications system, using only enough power to maintain communications at prescribed levels of acceptability. In particular, development of enhanced open-loop control systems that sense the radio environment, requests for re-transmission, and predictive path analysis to minimise power on channel, necessary bandwidth, and other scalable features of the transmission system based on local environmental observations. Furthermore, and in example, for low priority communications paths, the power could even be set for degraded voice quality relative to the paths with the highest priority to reduce interference to critical systems. Closed-loop, scheduled systems such as LTE take advantage of power control today. Unlicensed, opportunistic systems, in general, do not. Development of incorporated open-loop control systems into non-homogeneous systems will substantially mitigate interference and allow more efficient use of available spectrum.
- Advanced, adaptive beam-forming techniques to maximize antenna gain in the direction of the communications path and minimize gain in the interference direction. Null-steering techniques should also be utilized to actively protect critical link paths. The latter technique could be extremely valuable in the 6-7GHz band to protect critical PtP links. Additional spectrum allocations are also anticipated to exhibit similar limitations.
- Adaptable data rate to the minimum throughput rate needed for the communication and/or according to priority of the operator. This may be implemented in several forms. In example, the use of slower data rates spread over a wider channel or running bursts of

larger constellations on a given channel if the channel will support it. Scheduled systems take advantage of spectral, temporal, and modified waveform techniques today. Further development of algorithms for implementation of these techniques using learned knowledge of the channel for independent, autonomous users of spectrum is required to improve spectrum efficiency and quality of service among the various users of opportunistic, unlicensed, and shared spectrum.

- Adaptive receive filtering to provide better rejection of the interference balanced against possible sensitivity degradation and / or signal quality factors such as BER, etc. This would include greater reliance upon error correction within the receiver to offset degraded performance due to information truncation and the resulting effect upon demodulation such as constellation decision points. Adaptive truncation of bandwidth, coupled with shared or learned intelligence of factors affecting the current channel and surrounding spectrum, further augmented by modified waveforms including modulation constellation depth and signalling cadence can substantially improve integrity of communications for channels that experience interference.
- Adapting the communications system to survive using learned knowledge of the temporal and/or spectral cadence of interfering signals. Interference often exhibits characteristics that can be learned. This learned knowledge of the interfering signal can then be utilized to improve the overall resiliency of communications. Examples of unintentional sources are 1) Interference from sources such as power conversion, 2) Efficient lighting, and 3) Wired data signalling systems. Techniques of this nature are particularly important for avoidance of chirped interference signalling.

6 Innovation #6: Receiver Performance Interference Thresholds

6.1 Executive Summary

The growing movement to encourage spectrum sharing will be a significant enabler for novel radio communication solutions. However, existing spectrum users have a reasonable expectation that their systems operation will not be impaired by new in-band and adjacent band users. Historically, this has been managed through a variety of standards and regulations primarily focused on transmitter parameters, sometimes with unexpected consequences. The Forum believes that the entire range of both transmitter and receiver characteristics must become an integral part of spectrum regulation and management. Specifically, focus should be added to both defining the expectation of interference based on receiver performance in each band and informing regulatory decisions based on that expectation. This latter includes understanding the current and expected roadmap for receiver technology advances. Focusing on receiver performance and associated interference thresholds, can bring much benefit in terms of spectrum efficiency through such definition and regulation while at the same time reducing risk for new market and new technology entrants.

6.2 Application

Applications for this innovation include enabling spectrum sharing systems in existing bands through the identification of the critical receiver parameters required to minimize adjacent channel interference. These applications are tied to an understanding of the capabilities of current and future receiver front end technologies, which in turn define the standards required to support spectrum regulations. They can also be used to drive improvements in receiver performance to increase access to spectrum over time.

6.3 Description

The critical receiver parameters required in order to enable spectrum sharing systems in existing bands must be developed looking at a historical view of how receiver performance has impacted spectrum regulation. Potential examples from the U.S. include the 800MHz Public Safety rebanding and LightSquared terrestrial LTE at 1.5GHz. These issues continue to be raised as evidence by the December, 2017 Federal Communications Commission (FCC) workshop and panel discussion on 800MHz issues relating to Power on Ground increases in the Cellular A/B bands (US), plus the re-purposed Specialized Mobile Radio (SMR) band, also at 800MHz (now carrying Code Division Multiple Access (CDMA) plus a 5+5 MHz LTE signal) is front and center.[2] The potential of increased interference to narrow-band public safety and Private Land Mobile Radio Service (PLMRS) narrowband radios systems as a result has led to Telecommunications Industry Association (TIA) beginning discussions on standardized testing and reporting of blocking dynamic range and other issues specific to the 800 MHz allocations[3]. Issues of this nature are not limited to the US: Canada also has an active Consultation on this plus additional spectrum allocation (Reference). Various spectrum occupants - new and incumbent - within the communications realm will continue to be at crossroads as other allocations, such as L-band near Global Positioning System (GPS) and Earth to Space and Space to Earth in the 1.5/1.6 GHz bands also remain contentious. Furthermore, spectrum sharing in the C-band, 6/7GHz, and Ka bands also present potentially difficult environments for receivers to operate within.

The critical receiver parameters can be used to define harmful interference thresholds to establish new spectrum use conditions, as introduced in the white paper prepared by the FCC Technological Advisory Committee entitled "Interference limits policy – the use of harm claim thresholds to improve the interference tolerance of wireless systems[4].

The current and expected receiver performance criteria for existing systems must then be evaluated for effective protection. This requires a survey of existing systems across the government, public safety, satellite, and commercial markets. A roadmap of receiver performance then needs to be developed, as well as an evaluation of the potential impact of evolving communication systems on incumbent solutions.

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[2] https://www.fcc.gov/news-events/events/2017/11/public-forum-800-mhz-spectrum-sharing Public Forum on 800 MHz Spectrum Sharing

[3] http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf11333.html Consultation on the Spectrum Outlook 2018 to 2022

[4] http://transition.fcc.gov/bureaus/oet/tac/tacdocs/WhitePaperTACInterferenceLimitsv1.0.pdf

7 Innovation #7: Low Cost Wide Spectral Range RF Front-End (Multi-decade; Contiguous) (Tx,Rx)

7.1 Executive Summary

Small, low cost transmitter and receiver front-ends are critical to enable viable wireless solutions in spectrum that is being opened by regulatory bodies to improve spectrum utilization and meet the broadband needs of their citizens. Generally, receiver front-ends are available that continuously operate from 100MHz (or below) to 6GHz today. Front-end technology that allows for either very high blocking dynamic range and / or pre-filtering is still lacking. The definition of High Dynamic Range is vaguely defined and varies. Example: Subscriber equipment may be termed as high dynamic range when 95-100dB blocking dynamic range is exceeded; Base station / infrastructure equipment may be termed HDR when >110dB is met or exceeded. At present, most transceivers continue to utilize a “Velcro” approach towards hardware design. Velcro designs utilize added components external to the core chip set such as duplexers, additional PA devices, switches, and other components to add additional bands of interest to a transceiver or to fulfill circuitry that does not currently offer cost effective incorporation into present-day chip sets or produce required performance even if it could be integrated into the chip set. Present-day transceivers that offer high performance across multiple bands continue to utilize numerous duplexers, selectable filters, and multiple Low Noise Amplifiers (LNA) sections; all external to the core chip set. As the upper limit continues to push towards 40GHz, or higher, another approach is required. Considering 3GPP bands now reach down to 400MHz, the RF performance requirement will soon extend to 2 decades and beyond. It is desirable to make available front-ends that cover extended frequency range; easily two-plus decade RF Front Ends; contiguous, while retaining necessary performance criteria such as tunable selectivity, blocking dynamic range, IM performance, noise figure, and phase noise floor. Out of Band Emissions, frequency stability and tolerance, and low phase noise are some of the critical criteria of the transmitter section of the desired wide band or wide tuning range RF front-end.

In cellular chipsets, the method to achieve wide spectral range tune-ability has turned to having a multitude of receiver chains (and associated filtering) for the many bands of interest. A focused review of how to apply these approaches to continuously operable systems would be a new path forward.

7.2 Application

This innovation supports applications that require an RF front-end, capable of transmitting and receiving over a very wide spectral range. For example, front-end implementations capable of operating within TV Whitespace allocations in a continuously-tuned fashion. Designs must include operation over all TV channels, regardless of world region, while retaining the ability to operate in the presence of strong adjacent and alternate TV transmitters. An additional example would be a continuously-tuned front-end that could take advantage of licensed broadband / LTE services as well as unlicensed, lightly-licensed, and leased spectrum. Such a device might conceivably operate from below 400MHz through 40GHz or higher. An upper limit of 6GHz is easily justified today.

7.3 Qualifiers

The innovation includes transmit and receive subsystems, should be low cost and small in physical size, with acceptable power consumption, multi-octave operation, and high linearity on receive and transmit. In addition to "extreme tune-ability", the need for a multitude of transceivers to support Multiple-Input-Multiple-Output (MIMO) systems across continuous, tunable spectrum will further increase the complexity of these systems. Therefore, this topic remains critical and has expanded in scope since first considered.

7.4 Description

Regulatory bodies around the world are looking for opportunities to improve spectrum utilization and provide more broadband service for their constituencies. Often, the spectrum "white-spaces" that are becoming available are not contiguous and are located in harsh RF environments. Noted above is TV whitespace where there could be one or more unoccupied 6MHz channels across the broadcast television allocation. Guard band spectrum found between service allocations is also applicable[5]. A viable product solution using this spectrum needs to be producible at low cost, operate over this broad frequency range because the unoccupied channels vary by geographical area, and have a receiver that can tolerate a high power TV broadcast signal on adjacent or alternate channels. Design of receivers involve high linearity front ends coupled with tunable pre-selection or its equivalence. For reference information, see section 6 on TVWS in "Public Safety Interference Environment – Raising Receiver Performance Requirements" http://groups.winnforum.org/p/cm/ld/fid=88, December 3, 2009, Session 3.2)

Another example is that of opportunistic and as-needed broadband spectrum access. Devices are generally designed to operate on several pre-determined bands. These bands are generally described within 3rd Generation Partnership Project (3GPP) documents and are standardized. In general, devices are regionalized; they are populated to operate on regional bands with sufficient overlap so that some world-wide access is guaranteed. Private networks, extensions of public carrier networks, and device to device communications may utilize additional spectrum, such as database driven licensing at 3.5GHz and unlicensed spectrum at 5GHz, to accomplish one or more of these goals. Additional spectrum will also likely be identified that can be used for similar needs or to further augment capacity through discontiguous bonding. To that end, front-ends of the future should evolve towards continuous spectrum use ability. Substantial challenges must be overcome to ensure that performance criteria, noted above, are sufficiently met.

8 Innovation #8: Efficient Techniques to Minimize Power Amplifier Spectral Regrowth in Non-contiguous Spectral Environment

8.1 Executive Summary

This innovation references techniques including algorithms, software, hardware, and/or mixed techniques that significantly reduce spectral re-growth when multiple transmit signals operating in non-contiguous allocations, are passed through a non-ideal transmitter. All transmitter topologies

[5] https://www.fcc.gov/wireless/bureau-divisions/mobility-division/700-mhz-guard-bands

exhibit non-linear response in varying degrees. Discontiguous placement of carriers exasperates the problem as Out of Band Emissions (OOBE) requirements must be met along multiple boundaries to insure spectrum purity. This innovation addresses the need for improved techniques implementation of RF amplifier systems that will allow multiple fallow portions of spectrum to be virtually utilized as a single, continuous channel.

8.2 Application

In many secondary spectrum deployment scenarios, it will be difficult to locate contiguous wideband spectrum due to the interspersed nature of primary users. Thus to achieve sufficient communications bandwidth for high data rate applications, it will be necessary to combine together multiple smaller pieces of contiguous spectrum which would ideally be transmitted from a single transmitter. In such a scenario, it is vital that the primary user signals are protected from interference.

8.3 Description

Simply filtering or nulling the transmitted signal energy in the intermediate subbands at baseband will not provide sufficient protection to the primary users due to transmitter nonlinearities leading to spectral regrowth in the primary users' spectrum of operation. Likewise, while narrower bandwidth signals can be used that eliminate the possibility of spectral overlap, this narrow bandwidth is often insufficient to carry the user payload. Similarly, significantly increasing guardbands can improve primary user protection, but this is highly inefficient use of spectrum. Ideally techniques should mitigate this spectral regrowth in unused bands in transmissions over non-contiguous spectrum without increasing guardbands to achieve suppression that yields at least -70 dBm signal level in protected bands.

8.4 Qualifiers

Single band (e.g., TV bands) is acceptable. Multiple transceiver chains to multiple antennas are not desirable for this topic. Technology of interest may consist of software, hardware, or hybrid solutions. Many different techniques have been proposed, including predistortion and subcarrier manipulation techniques, but these techniques individually normally achieve suppression at levels below the 70 dB required in many allocations. Furthermore, while regulatory requirements may currently be met with existing solutions, solutions should anticipate these requirements to become more stringent in the future. It is clear that current masks do not fully protect adjacent channel services; one such argument is put forward by Iridium warning of potential interference from adjacent allocations used by Terrestrial L-Band LTE systems. Similar potential issues will come to light in other bands such as 3.7-4.2Ghz and 6-7GHz. Furthermore, the potential of zero-guard-band allocations for broadband use adjacent to other services reinforces the need for stricter OOBE requirements. Continued development of linearization techniques (pre-distortion and feedback to name 2), amplifiers with increased power efficiency and reduced spectral re-growth, along with wider supported channel bandwidth and frequency range are necessary. Regulatory standards do not, and cannot, long term, remain fixed and many current PA designs simply meet current requirements with little margin.

9 Innovation #9: Network Management of Mobile Ad-hoc Networks (MANET)

9.1 Executive Summary

A MANET is a Mobile Ad-hoc Network which does not require network infrastructure or centralized administration. Mobile hosts in a given area dynamically connect to each other and form a network, transmitting and receiving data not only for their consumption but also acting as relays and routers for others. By enabling wireless communications with no available infrastructure, MANET technology creates valuable new capabilities for many applications, Existing network management solutions are limited, typically focused on providing network management capabilities to only a small subset of homogeneous MANET system.

Since deployed systems may consist of many different networks supplied by different corporations, it is essential that the network management be able to operate across these heterogeneous solutions. This innovation topic seeks to focus interest in developing the essential technologies to provide for network management of heterogeneous ad-hoc networks for defense and commercial applications.

9.2 Application

Management of a wireless ad-hoc network can be used in many ways. Network management can be used to enable real-time optimization of the allocation of network services, to manage network stability, priority, to cope with connectivity issues and to adjust various radio and network performance parameters as required by current users or applications. Network management can also be used in a non-real-time sense to enhance the radio network behavior, either in anticipation of expected traffic properties or based on experience of traffic and system behavior in a geographic region.

The defense, first responder, and public safety communities recognize that in matters of emergencies and in national defense, existing infrastructure can be compromised. It is essential that radio network communications can be maintained in the absence of a dedicated, purpose built infrastructure. In such situations, we can foresee multiple MANET networks coexisting.

To allow for quick and efficient deployment it is essential to provide an application for configuration and management of the multiple networks in order to obtain a single operating view. Solutions to this innovation would greatly help tying together disparate networks to be managed as a single network.

9.3 Description

Designing MANETs which are highly mobile and rapidly deployable requires a means to perform distributed Network Management. Commonly network management can include adequate Management Information Base (MIB) elements that allow tracking of radios and gateways to wired infrastructure or to other networks, as well as means to provide real-time or non-real-time

optimization. Network Management Systems allow limited exchanges to maintain bandwidth efficiency and support real time operations through service provisioning across the network. The challenge is to maintain the usage of bandwidth across the network while keeping network overhead as minimal as possible so that the applications can have maximum bandwidth utility of the network especially as the networks get larger.
The required innovation is the development of standardized Network Management techniques for distributed MANETs. To be considered are MIBs, Simple Network Management Protocol (SNMP) structures, signaling protocols, and knowledge representations that allow the network to locally self-optimize or to be remotely optimized via an operator to enable the industry to implement standardized tools, software, and information representations, and to update network behavior and performance. Such signaling exchanges represent overhead to the user network traffic, and as such it is important to minimize the total overhead introduced by Network Management Tools.

10 Innovation #10: Integrated Development and Debug Process for Software-Based Applications on Embedded Heterogeneous Platforms

10.1 Executive Summary

Software Defined Systems (SDS) are a dominant portion of the communications eco-chain due to their increased flexibility in addressing evolving requirements and multi-mission profiles. General purpose hardware devices can now be specialized via software-based algorithms (including firmware) to execute multiple defined tasks. With the rapid advances in technology, it is, however, imperative to reduce software development cost while maintaining the highest overall system performance as the software is ported from one platform to another.

Standards-based approaches are essential to facilitate the integration of software and firmware with hardware, and are even more important when the hardware platform is likely to change over time, due to technology refresh and insertion, or the move to a completely different platform (e.g., a national waveform needing to be ported on multiple vendor systems).

The Software Communications Architecture (SCA) has been created to facilitate portability of software between different hardware platforms, by standardizing the infrastructure code needed to install, configure, and interconnect software components over heterogeneous systems. However, the SCA does not address the development of the waveforms, such as the signal processing for the physical layer, which needs to be able to execute on different processor types (GPPs, FPGAs, GPUs) and operating systems.

SDS software development processes today are mostly informal or ad hoc, as defined by the company developing the waveform. They can even vary depending on the architecture, processor types and operating systems chosen for a particular design. Software architectures and design paradigms must evolve to integrate the software design model with the physical hardware architecture to address platform-specific requirements and differences in the current versus the target systems that impact software porting. Having a single system-level tool for the development and debugging of waveforms that can support any heterogeneous processor architecture would be a significant innovation.

10.2 Application

The implementation of software and firmware to represent the signal processing application is often hampered by the fact that the application specification is not clearly stated and the target platform can be heterogeneous and distributed, i.e., composed of multiple operating systems and multiple processors located on different boards and connected via multiple inter-process communication (IPC) protocols. The interaction between the different platform components is often specific to the operating environment. In order to develop power and cost effective waveforms, developers generally need to use multiple development tool flows from different companies, (i.e., Intel, Xilinx, Mentor, Cadence, etc.) which often comes at a cost to waveform portability. Prototyping and debugging waveforms across these multiple tool flows is extremely difficult.

The benefits of achieving greater software portability between heterogeneous platforms will benefit a broad range of user communities including:

1. *Application Developers:* More efficient signal processing application porting will enable developers to implement component-based applications that can be ported to other software defined systems. This reduces the application development cost.
2. *Platform Developers/System Integrators:* As a platform developer/system integrator, more efficient porting processes enables a wider selection of applications that may be ported and deployed on their systems, within the physical limits of the hardware capability.
3. *End Users:* Ultimately, the end user community benefits through lower system costs, or greater capabilities (e.g., more applications on the same platform). This applies to both commercial and government users. This end cost benefit can be realized because one of the side effects of more efficient software is a more product-based development, resulting in wider range of products and a more competitive environment.

10.3 Description

One of the benefits of SDS is the ability to reuse parts or all of the software implementation to a different hardware platform. However, this is not a trivial problem because SDS platforms often contain multiple processors of different types, e.g. General Purpose Processor (GPP), Digital Signal Processor (DSP), Field Programmable Gate Array (FPGA), as well as evolving processor architectures together with other reconfigurable components and devices.

To reduce development time and cost, it is important that the software written be “easily” portable from platform to platform, and across different processor types. In addition, design paradigms can allow for multiple design approaches such as multi-threaded applications on GPP or concurrent state machine designs for an FPGA.

Design paradigms should also integrate the software model with a system model of the physical system hardware architecture to address platform-specific requirements and differences in the current versus the target platforms that impact software porting. There are several key elements that are required to realize this innovation. These encompass the range of technology, engineering disciplines, systems engineering practices and process, common representation standards, and intra-company process changes.

New technology is required to enhance and extend the expressiveness of current design and modeling tools to encompass the complete system design process. In addition to the application design, the tool or set of tools must also be capable of modeling the hardware elements of a target platform and be able to represent the constraints and capabilities of the platform in such a way that enables the analysis of an application design with respect to the target hardware on which it is to be deployed. This is a fundamental difference in mindset from most current practices and processes which are typically hardware focused through the systems discipline with the software engineering aspect typically not joining the process until after the hardware architecture has been largely decided.