Wireless Innovation Forum Top 10 Most Wanted Wireless Innovations

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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. 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 Committee on Spectrum Innovation selected the following as the revised "Top 10 Innovations" that have the most potential of improving the wireless communications experience:

1. Innovation #1: Techniques for Efficient Porting of Waveform Applications Between Embedded Heterogeneous Platforms
2. Innovation #2: Network Management of Mobile Ad-hoc Radios
3. Innovation #3: Receiver Performance Interference Thresholds
4. Innovation #4: Low Cost Wide Spectral Range RF Front-End (Multi-octave Contiguous) (Tx,Rx)
5. Innovation #5: Efficient Techniques to Minimize Power Amplifier Spectral Regrowth in Non-contiguous Spectral Environment
6. Innovation #6: Increase Communications Time on Battery Charge by an Order of Magnitude
7. Innovation #7: Context Aware Cognitive Radio
8. Innovation #8: Interference Mitigation Techniques
9. Innovation #9: Standardized Computer Interpretable Policy Language for Cognitive Radio
10. Innovation #10: Flexible Regulatory Framework for Temporary, Cooperative and Opportunistic Access

In support of the Forum's Strategic Plan, the Committee on Spectrum Innovation 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 advanced 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: Techniques for Efficient Porting of Waveform Applications Between Embedded Heterogeneous Platforms

1.1 Executive Summary

To reduce development time and cost for software defined radios, it is important that the waveform software is written to be "easily" portable from one hardware platform to another hardware platform. SDR development processes today are mostly informal or ill-defined; standards for exchanging information between different steps in processes are not mature; tools do not use standard interchange formats and are not interoperable. An area of emphasis should be on the development of tool interchange standards and the development of end-to-end processes and tools to support the development of SDR applications, components, and platforms.

Software architecture and design paradigms must evolve to integrate the software design model with the physical radio architecture to address platform-specific requirements and differences in the current versus the target radios that impact software porting.

The ability to quickly certify ported waveforms for use on various radio computing platforms also promises to significantly reduce development cost and time to market of software based radios.

1.2 Application

The implementation of software to represent the waveform is often hampered by the fact that the waveform specification is not clearly stated and the target platform is composed of multiple processors, each one interacting with one another differently. Developers need to use multiple tools to achieve their project objectives but lack of standards makes the integration very challenging.

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

1. *Waveform Application Developers:* More efficient waveform porting will enable waveform developers to develop component-based waveform implementations that can be ported to other radio systems. This reduces the waveform development cost.
2. *Radio Developers/Integrators:* As a radio developer/integrator, more efficient waveform porting enables a wider selection of waveforms that may be ported and deployed on their radio systems, within the physical limits of the radio hardware capability.

3. *End Users:* Ultimately, the end user community benefits through lower costs of radios and the waveforms and applications that run on the radio. This applies to both commercial and government users. This end cost benefit is 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.

1.3 Description

One of the benefits of software radios is the ability to reuse parts or all of the software implementation to a different radio hardware platform. However, this is not a trivial problem because SDR 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. In order to achieve this objective, software architecture and design paradigms must evolve to encompass multiple programming languages such as C, C++ and HDL. In addition, design paradigms should 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 systems model of the physical radio architecture to address platform-specific requirements and differences in the current versus the target radios 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 a heterogeneous waveform design. However, in addition to waveform design, the tools must also be capable of modeling the hardware elements of a radio system and be able to represent the constraints and capabilities of the platform in such a form that enables the analysis of a waveform design with respect to the target hardware on which it is to be deployed. This encompasses multiple engineering disciplines including digital design, electrical engineering and software engineering. Furthermore, these disciplines must evolve to operate in a more cohesive and integrated manner that promotes collaborative architecture and design across all engineering disciplines. 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.

Ported waveform software must be certified on the platform to which it is ported. Methods to simplify this process would significantly reduce development cost and time to market and could expand the SDR ecosystem by enabling third-party software to be used across multiple platforms.

2 Innovation #2: Network Management of Mobile Ad-hoc Radios

2.1 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 routers for others. By enabling wireless communications with no available infrastructure, MANET technology creates valuable new capabilities for many applications, but it also poses new challenges for network management.

Although network management is a challenge in any large and complex network, in the context of a MANET neither stable topology nor reliable high-bandwidth links can be assumed to exist. The ability to provide configuration and management of ad-hoc networks has only begun to be recognized as essential to progress of MANET technology and products in this domain. New techniques and thinking are required. This innovation topic seeks to focus interest in developing the essential technologies to provide for network management of ad-hoc networks for defense and commercial applications.

2.2 Applications

The defense, first responder, and public safety communities recognize that in matters of emergencies and in national defense, existing infrastructure can be compromised. So it is essential to these communities that any radio be able to perform the same ad-hoc networking functions as any other radio. While the radios may consist of many different corporate products (heterogeneous hardware), nevertheless the network is able to operate homogeneously without infrastructure.

Recently, the commercial telecommunications sector has recognized that sufficient density of cellular infrastructure to enable adequate service is economically impractical in certain areas of the world. Rather, for those subscribers who are beyond the coverage range of a cell tower, the ability to have an ad-hoc network forward traffic toward nearby cellular infrastructure can be hugely valuable to both the subscriber and to make existing infrastructure more cost effective.

It is also anticipated that much of the “internet of things” (IoT) and “machine to machine” (M2M) technology now in development will make extensive use of ad-hoc network techniques to provide for connectivity.

2.3 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.

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.

Development of standardized Network Management techniques, 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 are required 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. Consequently, it is essential for wireless network management to include a great deal of attention to minimizing the corresponding overhead traffic demand. Given that the ability to manage the network often arises when the network is already under a heavy traffic burden, efficient techniques are particularly important.

Important domains for technical breakthroughs include the ability to show scalability to ad-hoc network sizes well beyond 1000 nodes, the ability to adapt regions of the network through adapting network behavior to cope with local traffic properties and Quality of Service (QoS) demands, and the ability to efficiently distribute traffic load so as to not overly tax individual nodes. The ability to understand and effectively utilize node resources such as available prime power or Multiple Input/Multiple Output (MIMO), and the ability to manage nodes that are advantaged (good links) or disadvantaged (poor links) are also important domains for network management methods and standards. The ability to adapt data rates, MAC protocols, and cyber protection mechanisms are also essential new domains to be addressed via wireless standards.

3 Innovation #3: Receiver Performance Interference Thresholds

3.1 Executive Summary

The growing movement to encourage spectrum sharing will be a significant enabler for both "cognitive" and "non-cognitive" radio systems. 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 long term 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.

3.2 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 or co-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.

3.3 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 US include the 800MHz Public Safety rebanding and LightSquared terrestrial LTE at 1.5GHz. This can be used to define harm 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[1].

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.

4 Innovation #4: Low Cost Wide Spectral Range RF Front-End (Multi-octave Contiguous) (Tx,Rx)

4.1 Executive Summary

Small, low cost transmit 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, such front-ends are limited in tunable range. It is desirable to make available front-ends that cover extended frequency range; easily in excess of one decade, 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.

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

4.2 Application

This innovation supports applications that require an RF front-end, capable of transmitting and receiving over a very wide spectral range. For example, a front-end capable of operating in TV Whitespace in a continuously-tuned fashion. This includes operation over all TV channels, 2-51 (54-698MHz), 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 4GHz or higher. An upper limit of 6GHz is easily justified today.

4.3 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.

4.4 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 from 54-698MHz. Such whitespace would be shouldered by strong adjacent or alternate TV transmitters. 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 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 shared use-cases contemplated 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.

5 Innovation #5: Efficient Techniques to Minimize Power Amplifier Spectral Regrowth in Non-contiguous Spectral Environment

5.1 Executive Summary

This innovation is for techniques (algorithms, software, hardware, or mixed technique) that significantly reduce spectral regrowth (target of -70 dBc) when a wideband (>= 20 MHz), but non-contiguous, signal is passed through a nonlinear transmitter.

5.2 Application

In many secondary spectrum deployment scenarios, it will be difficult to find contiguous wideband spectrum due to 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.

5.3 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' bands. Likewise, while narrower bandwidth signals can be used that eliminate the possibility of spectral overlap, this narrow bandwidth is often insufficient. 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 -70 dBc signal level in protected bands.

5.4 Qualifiers

Single band (e.g., TV bands) is acceptable. Multiple transceiver chains to multiple antennas are not desirable for this topic. Technology of interest can be a software, hardware, or mixed signal solution. Many different techniques have been proposed, including predistortion and subcarrier manipulation techniques, but these techniques individually normally achieve suppression at least 30 dB. This is significantly less than the 70 dB required in most bands.

6 Innovation #6: Increase Communications Time on Battery Charge by an Order of Magnitude

6.1 Executive Summary

The use of battery powered communications devices requires the user to carry either extra batteries or have frequent access to battery recharging facilities. For some user scenarios it imposes a significant burden to carry additional batteries since the user must operate without access to battery charging facilities for extended periods of time. These users constantly have to trade the frequency of communications and what they communicate with its impact upon battery life. Battery life is generally quantified in hours given a ratio of a talk time and idle time; or percent transmit, percent receive, percent idle.

6.2 Application

For military, mobile users, firefighters and other emergency responders in remote areas and other unserved areas the extension of communications time on a battery charge by an order of magnitude would reduce the amount of batteries they would need to carry as well as allow them to communicate more frequently. For those users in remote areas for extended periods of time, the users must make tradeoffs between food, water, and other mission essential equipment and the amount of batteries that will be needed to power their communications devices.

6.3 Description

There are many different technical approaches to increasing the communications time on a battery charge such as reducing processor power consumption, increasing power amplifier efficiencies, signal processing techniques, improving battery chemistry and other techniques or technologies to get more energy per kg. New opportunity spaces include providing the radio with ability to understand the user's performance requirements regarding various types of traffic and how that traffic relates to the overall mission objectives and the ability to switch amongst modes in response. The ability to achieve battery life enhancements may involve tradeoffs with various types of constraints in terms of size and weight.

7 Innovation #7: Context Aware Cognitive Radio

7.1 Executive Summary

Methods, tools, architectures, and languages need to be developed to enable cognitive radios to incorporate contextual reasoning into their decision processes. By adapting to dynamic contexts, cognitive radio algorithms can be automatically matched to changing conditions, wireless network performance can be significantly improved, end user experience enhanced, and network management time and costs reduced.

7.2 Applications

By incorporating context awareness into cognitive radio processes, the following will be feasible:

- Automating communications leader communications resource management in a way that recognizes and facilitates reaction to the dynamic nature of major incident/disaster responses. This generalizes to disrupted context scenarios where the communications network was planned to accommodate assumptions (pre-defined contexts), but a radically different and rapidly evolving environment (contexts) is encountered.
- Enabling smartphones to automatically adapt their wireless behavior based on what other users are nearby, what services the smartphone is trying to support, time-of-day, location, calendar information, and models of user intentions.
- Improving spectrum sharing, management, and co-existence of cognitive radios by incorporating a better understanding of the changing capabilities, constraints, and goals of radio systems.
- Increasing the market-size, applicability, and robustness of wireless devices by incorporating a context-aware software module (possibly with additional software defined

radio capabilities) that adapts the behavior of the communications assets to the varying needs of different customers and changing situations

- Simplifying the deployment and configuration of self-organizing networks (small-cells) in existing cellular bands and considered spectrum sharing bands (e.g., 3.5 GHz) by having radios automatically detect and monitor their operating context and adapting accordingly.

7.3 Description

Context refers to

a) information associated with a message that is not directly communicated with the message that influences the message's meaning
b) a set of relationships that one object has with other objects.

While most cognitive radio literature considers the context inferable from a wireless chipset, a context-aware cognitive radio should have a wider scope of information to draw upon in its decision processes, including what the radio should be trying to do, what it is doing, what messages it is conveying, or the meaning of data in accessible databases.

Examples of valuable contextual information to cognitive radio processes include the following:

- Locations, trajectories, and patterns of movement of radios and their users,
- Relationships between the users of radios,
- Characteristics of the radio users, such as their changing goals and objectives, calendars of activities, and general preferences,
- Services provided by and receiver characteristics of other radios and networks in the area,
- Current and intended activities and applications of the users of the radios,
- Meaning, and urgency of messages being carried over communications networks,
- External environment conditions, such as RF load density, general propagation and interference characteristics, weather conditions, time-of-day, and sensor data,
- Platform specifics such as power consumption, calculation and measurement precision, permissible operating environments and policies, and
- Metrics commonly used by cognitive radio designs such as RSS, BER, end-to-end delay, and packet loss rate.

Understanding the following three types of context will be particularly valuable to further development of cognitive radio applications.

Operational context

Operational context refers to the object relationships pertaining to the operation of the radio. This includes information such as what a user is trying to do, where the radio is located, the current needs of the situation, and the changing relationships with other users and radios. Understanding operational context is critical to automating communications resource management.

Communications context

Communications context refers to information associated with a message that is not directly communicated with the message that nonetheless influence the message's meaning. Much operational context can be inferred from the meaning of messages conveyed by the communications system. Further, an understanding of communications context can lead to better cognitive radio decisions, new forms of encryption (by withholding context from unintended recipients), and more efficient communications (by understanding the context of intended recipients so that less contextual information needs to be transmitted).

Data context

Data context refers to the provenance, reliability, and relationships of data made accessible to cognitive radios, such as is envisioned for white space databases. This includes meta-data about the provenance and reliability of data, relationships with other data, and the objectives of the system. Understanding data context can help address Big-Data-like problems in the RF space, such as synthesizing and extrapolating meaningful patterns of behavior from accumulated sensor measurements.

As a new field, realizing context-aware cognitive radio will require the development or adaptation of several supporting technologies and innovations, including the following:

- Extensible languages and tools for modeling and reasoning on contextual information drawn from a diverse and changing set of sources,
- Mechanisms for automating the creation and updating of context models from observations and data shared from other sources and internal reasoning processes,
- Algorithms for improved contextual pattern recognition to reduce ambiguity and rapidly determine the applicability of existing solutions,
- Processes for innovating new solutions and interfacing with users when existing solutions are determined to be inappropriate to the determined context,
- Programming languages that allow end-users to easily specify how their communications assets should behave under varying scenarios,
- Improved interfaces and processes for translating data (e.g., from sensors or online databases) into formats suitable for contextual reasoning,
- Methods and paradigms for interfacing with users to provide contextual information to the user and corrective feedback to the systems when ambiguous or erroneous contexts are identified,
- Big Data tools applicable to RF problems (i.e., Big RF) for collecting, correlating, weighting, and reasoning over disparate pieces of information in a timely, precise, verifiable, and accurate fashion at varying degrees of granularity, and
- A flexible regulatory framework that will support the kinds of temporary, cooperative, and opportunistic applications that will emerge from context aware cognitive radio.

8 Innovation #8: Interference Mitigation Techniques

8.1 Executive Summary

Improved mechanisms are required to reduce 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.

8.2 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, misplaced of towers, exceeding necessary power levels, etc.) or emission spillover from Out of Band Emissions (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 and unlicensed 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 substantially degrade quality of service or deny service entirely. This can range from impaired or obliterated voice quality in a voice system and data degraded or denied throughput in a data system.

8.3 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 are certainly 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 design tradeoffs or other factors may not have their deployment. It is recognized that cognitive radio techniques, whereby the frequency plans could be modified to operate in non-interfering bands, might be a solution, but the implementation cost of such techniques would be prohibitive for many applications. In the present cases, other techniques are sought. Examples are given below.

- 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.
- Uplink and downlink power control throughout the communications system, using only enough power to maintain communications at prescribed levels of acceptability. 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.

- Adaptive beamforming to maximize antenna gain in the direction of the communications path and minimize gain in the interference direction.
- Adaptive polarization, including linear and circular, to optimize desired communications while reducing or nulling interfering signals. This could include minimizing co-channel interference first, followed by transmission of desired signals using conjugate polarizations.
- 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 including 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.
- Adaptive frequency control to increase frequency separation of the interference sources from the desired radio path. This implies the use of dynamic spectrum assignment wherein interference avoidance is a key decision factor in choice of channel.
- 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.
- Improved roaming algorithms (Change sites or systems to one that has a better Signal to Noise plus Interference ratio).
- Change channel coding algorithms to relax the required signal to interference plus noise ratio at the expense of more data overhead.
- Adapting to the temporal or spectral cadence of interfering signals.

9 Innovation #9: Standardized Computer Interpretable Policy Language for Cognitive Radio

9.1 Executive Summary

The ability of RF equipment to operate legally and agilely across multiple bands and in multiple places using machine readable policies as the means for a radio to check whether it is legal and eligible constitutes "policy awareness." The policies can include regulatory and system specific guidance. They can specify when spectrum is available and the conditions for its use. It is important to recognize that many RF equipment are currently being architected to support multiple applications i.e. communications, navigation, radar, electronic warfare, and sensing. Thus, in a wide sense, policy enabled radios are a type of RF equipment in which the radio ***is aware*** of its environment, which may include location, time, or other operational parameters related to its application and internal state. The radio can make ***decisions*** about its operating behavior (e.g. choice of multiple bands) based on this information and predefined objectives.

Future innovations are required to allow regulatory policies and rules for dynamic policy based radio control to be automatically interpreted and executed and to create the methods to articulate the policy for radio execution. Current rulemaking in database managed spectrum sharing provides the first step of the evolutionary path toward this vision by providing the infrastructure that in the future may manage and distribute policy to radios. The ability for communications between cognitive radios that may come from different vendors requires compatibility in the decision making process and thus a standardized, deterministic machine computable policy language.

9.2 Applications

A policy language with computer process-able semantics could be used to support a number of problems identified by the Wireless Innovation Forum that require innovation. Some of the problems that could be dealt with using such a language are listed below.

- Interoperability: Communication systems (and other applications that use spectrum) can use machine understanding to interoperate and control their functionality because they share a common knowledge base and can understand each other as they speak a common language. This applies to the military (coalition and inter-system interoperability), public safety (among various agencies, services and emergency responders), commercial (Cellular and WLAN), and various combinations of the aforementioned.
- Run time configurability: Communication nodes can understand requests for reconfiguration and implement the requested functionality (e.g., a waveform) according to the specification provided by another node.
- Validation: Formalization allows for detection of inconsistencies and formal validation of functionality.
- Self-awareness: Communication nodes can describe their own structure and capabilities, and tell others about it.
- Flexible querying: Communication nodes can query other nodes about their functionality and capabilities.
- Communication economy: No need to transmit information that can be inferred locally at the receiver node.
- Radio certification: Formal specifications of the structure and the functionality of particular communication systems can be utilized in the process of certification. Only the components that are modified will need to be certified.
- Support Dynamic Spectrum Access: Policies for dynamic spectrum access can be expressed in the policy language and then automatically interpreted by an Inference Engine running on either a base station or on a handset (or other RF equipment). The policy decisions then can be enforced by the device.

9.3 Description

The future policy language will be designed to enable radio nodes to exchange information – both object (data) information and process (control) information. It will support RF equipment designed for multiple applications i.e. communications, navigation, radar, electronic warfare, and sensing and will enable both corporative and synergistic operation among these applications. The interaction of radio entities with the policy language will be formally specified including affirmative and/or exceptional actions to be taken by the involved entities. The policy language will be able to interact with a knowledge representation.

The future policy language should have the expressive capability of describing at least the following aspects of communications:

- capabilities of the nodes (e.g., frequency bands, modulations, MAC protocols, access authorizations, etiquettes, transmitter and receiver characteristics, bandwidths, and interconnections),
- networks available to a user (parameters, restrictions, costs),
- security / privacy (capability, constraints, policies),
- information types (an emergency call vs. just a "how are you" message),
- local spectrum situation (spectrum activity, propagation properties),
- network to subscriber and subscriber to network control (policies),
- manufacturer matters (hardware and software policy),
- types of users (authority, priority, etc.),
- types of data (Asynchronous, Isochronous, narrow band, broad band, etc.),
- local regulatory framework (e.g., policies at a given geo location, time of day, emergency situation, etc.),
- time of Day (at both ends of session and important points in between),
- geographic Location (in three space, surrounding geography/architecture), and
- fuzzy, probabilistically defined events and actions.

10 Innovation #10: Flexible Regulatory Framework for Temporary, Cooperative and Opportunistic Access

10.1 Executive Summary

A new flexible regulatory framework is needed to enable the operation of advanced wireless devices and systems that meet certain reconfigurability requirements across multiple bands and wireless services on a temporary, cooperative or opportunistic basis.

10.2 Applications

This innovation will lower regulatory barriers to entry and promote technological innovation through easier and faster access to spectrum, enabling incumbents and entrepreneurs to pursue new business opportunities throughout the wireless value chain.

10.3 Description

Traditional international and domestic regulatory frameworks governing access to RF spectrum are based on "static" frequency allocations and assignments. While emerging multi-band, cognitive radio and dynamic spectrum access technologies are being introduced under modern flexible, market-based regulatory policies in some countries, a new supplemental framework that can overlay existing schemes will further enable innovative technologies, and such technologies can enable innovative frameworks. This new flexible regulatory framework would apply across multiple bands and wireless services. The rules would authorize advanced wireless devices and systems that meet certain reconfigurability requirements to operate across a wide swath of frequency bands on a temporary, cooperative or opportunistic basis depending on the nature and characteristics of the existing authorized systems, to the extent there are any. The following example is derived from SSC's Comments and Reply Comments filed by Shared Spectrum Company (SSC) in ET Docket No. 10-237 (Feb. and Mar. 2011):

- Under the proposed policy-based framework, regulators would require eligible RF devices to be reconfigurable to prevent spectrum squatters and ensure that the devices can be updated (or even disabled in certain bands) after being sold to end users. Equipment authorization/certification rules would establish minimum hardware and software capabilities for such devices, but they would include only baseline operating parameters (mirroring any existing technical rules) and would authorize deviation from the baseline be delivered and installed through policy controls managed by third-party band/database managers. The rules could also include a built-in enforcement apparatus to implement interference deconfliction remedies (e.g., activity logs, over-the-air policy updates or time-limited access policies that would have to be renewed).
- The policies themselves would implement the service rules and any licensing conditions or incumbent/stakeholder requirements. They could also be changed to reflect newly available operating frequencies or modified power levels. Regulators would defer to industry standards organizations such as IEEE working group P1900.5 and the Wireless Innovation Forum's Modeling Language for Mobility ("MLM") working group for the development of policy languages, ontologies and architectures. Based on such standards, entities can develop policy authoring and administration tools to create and manage the policies, which can be reviewed, tested and potentially modified by the regulator and other interested stakeholders. The regulator may also want to consider requiring a policy certificate security management feature that prevents unauthorized access by validating spectrum access polices in certain spectrum bands.

The following example is derived from the European Commission's Radio Spectrum Policy Group (RSPF) Report on "Cognitive Technologies" (Feb. 2010) and the RSPG "Opinion on Cognitive Technologies" (Feb. 2011):

- A simplified regulatory framework would focus on cognitive radio (CR) technologies that would be implemented/controlled through geo-location databases. This approach assumes that current regulatory mechanisms and models can be used as the primary basis for the introduction of CR technologies. However, new regulatory framework(s) would address the conditions/requirements that the databases and devices have to meet along with database accreditation issues. Specifications established by standards organizations would be needed for the exchange of information between the CR devices and the database(s), to ensure that CR devices will be connected with the relevant database(s), geo-location systems, and other assurances.

Another example of regulatory framework initiative is the European Union's project on a Techno-Economic Regulatory Framework for Radio Spectrum Access for Cognitive Radio/Software Defined Radio (TERRA) (http://www.cost-terra.org):

- This effort is focused on coordinating techno-economic studies for the development of a harmonized European regulatory framework to facilitate the advancement and broad commercial deployment of Cognitive Radio/Software Defined Radio (CR/SDR) systems. Specifically, COST-TERRA Working Group 3, "Economic aspects of CR/SDR regulation," will work on evaluating the economic aspects of the developed CR/SDR regulations, considering both the attractiveness of rules suggested by studies in Working Groups 1 and 2 and the development of any new regulatory paradigms based on economic (market-based) policies. Such studies would identify critical factors that have significant impact on economic benefits and viability of the proposed regulatory regimes for CR/SDR. Working Group 4 on "Impact assessment of CR/SDR regulation" will work on carrying out impact assessment for identified combinations of techno-economic sets of CR/SDR deployment rules with the aim of identifying the most attractive combinations to form the basis for the ultimate CR/SDR regulatory framework with any variations therein.