CONTEXT-AWARE COGNITIVE RADIO[1]

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ABSTRACT

To make effective decisions, a cognitive radio needs to understand its operating context. Over the past several months, the Wireless Innovation Forum's Cognitive Radio Work Group has been exploring how to enable a cognitive radio to represent, understand, and share its context. Material to be covered in this paper includes the following:

- What exactly is meant by "context" in varying published existing context-aware applications
- The role of context in communications and information systems
- A survey of tools and software for developing context-aware applications
- A new model of the interactions of the real world, symbolic reasoning and representation, and acting on the reasoning
- Relating the components of a key context-aware tool to the new model
- Initial work coding a java-based context-aware application for a cognitive radio to reason and act on its context

This paper provides greater detail and context to a presentation given at WinnComm 2013 and reviews work performed on the subject since the earlier presentation.

1. INTRODUCTION

The CRWG's study into the development of context-aware cognitive radio (CR) came together from a few different threads of discussion. How to manage and reason over the vast amount of information that will be soon available to CR applications is a problem we call "Big RF", which we think is made more usable by better understanding of the context of collected data. How to ensure effective and efficient communications across a wireless link was the subject of an earlier study where we saw that an understanding of the originator's, recipient's and the message's context was critical. Finally, the emergence of CR applications that require information beyond what is available as metrics from an RF chipset implies that a CR be able to understand at least its operational and communications context. This section discusses those three motivating insights in more detail to facilitate a better understanding of the envisioned applications of this work.

1.1. Big Data and Big RF

In the IT world, IBM notes that [1]: "Every day, we create 2.5 quintillion bytes of data — so much that 90% of the data in the world today has been created in the last two years alone."

This data is produced by a variety of sources - users posting to Facebook, records of banking transactions, cell phone GPS data for E-911, video and imagery. This data in theory provides the raw information needed to gain critical insights about customers but is complicated to extract because of the dimensions of:

Volume the amount of data, e.g., Intel's factories generate 5 Terabytes / hour [2] and 12 Terabytes of Tweets are created daily [3]

Velocity the rate of data acquisition, e.g., high frequency trading

Variety the range of data types and sources, e.g., text, HTML, pictures, sound, etc.

Veracity the accuracy of the data, e.g., weather forecasts are only valid for a certain period of time but also include an element of confidence

Because traditional relational database algorithms have proven insufficient for the task, the IT world is turning to "Big Data" to address this problem. Big Data is a loosely defined term that refers to both: a) a collection of emerging techniques and processes for rapidly acquiring, classifying, and synthesizing meaning from Terabytes or Petabytes of data and b) the data itself. Numerous tools have been developed for Big Data analysis with many being open

[1] This Document is Not Export Controlled. This Information is approved for publishing per the ITAR as "Fundamental Research" and the EAR as "Educational Information".

source, such as Hadoop for batch analysis, Storm for real-time analysis, Alteryx for Analytic, and Drill for interactive analysis.

Similarly, the wireless community is beginning to develop and deploy massive databases for collecting real-time data about the RF environment. This includes ambitious projects such as the nationwide Spectrum Dashboard [4] which hopes to maintain a view of spectrum usage for the entire nation, the TV White Space and other Dynamic Spectrum Access (DSA)-enabling databases, and the real-time data collection, monitoring, and management of commercial, public safety, and military wireless networks. The advent of cognitive radio (CR) introduces both potential consumers of this data (to gain better insights into how to manage radio resources in real-time) and potential sources of more data (from the spectrum sensing capabilities proposed for most CRs).

Because of the volume, velocity, variety, and veracity of the data in these envisioned RF databases, we believe that, like with Big Data, traditional relational database techniques will be insufficient for the purpose of gaining meaningful insights about the RF environment in a way that can be used by CRs, regulators, and network managers. For example a real-time nationwide Spectrum Dashboard could be faced with the following problems.

Velocity A single spectrum logger, such as D-TA's RFVision 2 logs data at the rate of19.2 Gbps [5]. To maintain a nationwide network of such sensors mounted at each cell tower in the US (260,000 towers) [6] would generate approximately 5 Petabits of data per second.

Volume To analyze trends over a single year without loss of data, this would then require 15.7 Zetabits of storage

Variety More realistically, spectrum measurements would come from a variety of sources, such as cell phones, base stations, and access points, which would have differing data formats and often duplicate observations of the same phenomena though with seemingly disparate measurements.

Veracity An important aspect of many communication links and networks is verification of the identity of the radio to determine the validity of the data being transmitted.

To refer to this problem space, the Cognitive Radio Work Group (CRWG) in the Wireless Innovation Forum (WinnF) has adopted the term "**Big RF"** to reflect the similarities between the IT and RF problem domains. Big RF conditions apply across all network domains from relatively small local networks to larger nationwide deployments. Big Data resources, techniques and concepts could be applied and extended to RF data analysis problems once we account for the unique properties of radios (e.g., data converter and sensor limitations, component nonlinearities) and the radio environment (e.g., propagation effects, lossy channels, interference, and bandwidth constraints).

In many Big Data problems, and likely with emerging Big RF problems, it is often necessary to remove the context from, or at a minimum anonymize, the data in order to provide for data security and privacy. It is envisioned that new tools will need to be developed in order to properly frame metadata the data to have useful information for both the Cognitive System and for the user of the information. In this paper, we address the special needs of Big RF and Cognitive Systems in the identification and application of context to data and provide additional thoughts on the tools and techniques that will be required to meet these challenges.

1.2. Context in Communications

In an earlier project [7], the CRWG explored how actionable communications occur and identified that shared context between the originator and recipient of a message was critical to both understanding the communication (effectiveness) and minimizing the bandwidth required for communications (efficiency). These concepts were encapsulated in the Information System Flow Model shown in Figure 1, which represents a single functional cycle of an information system.

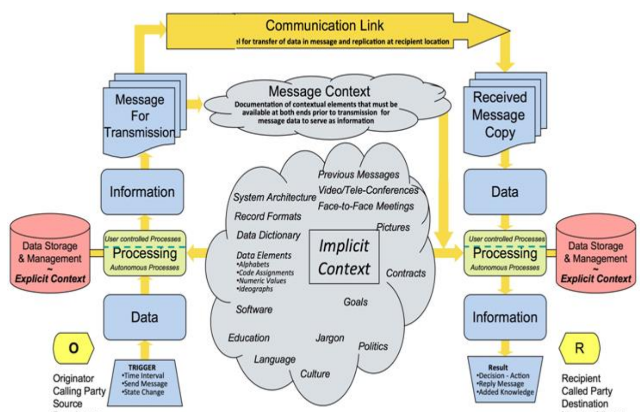

Figure 1. Information System Flow Model. From Figure 9 in [7].

The model has three basic parts: Origination (O), Communication, and Reception (R). An event at the Originator triggers the cycle and creates data, often called a transaction. After O-space processing, that data becomes useable information. A message for transmission is extracted from the information and delivered to the Recipient over a communication link. Upon receipt, R-space processing restores transmitted data to the state of useful information, available for use by the recipient. Completion of a cycle often serves as a triggering event for subsequent cycle chains in the system. To understand the transmission, O and R must have a shared message context. That context can include formatting (syntax), enabling the received bit stream to serve as data, as well as a means to properly understand the meaning of the data (semantics, e.g., if "apple" refers to the company, the fruit, or the record label). The figure also shows the existence of implicit context, a variety of rarely considered but necessary conditions such as a common language and shared goals that enable cooperative action between O and R. [7] and [8] showed that this model can be applied to a wide variety of communications systems, including Air Traffic Control, Amazon transactions, TV broadcasts, and public safety dispatch.

[7] and [8] also presented security as an inverse function wherein denying a (presumably unwanted) recipient the necessary context hinders reception of the message. For instance, denying access to the communications format of the data (e.g., encryption) or hiding the meaning of the data (e.g., communicating in code words) both are means of obscuring the context of data transmitted in a message.

1.3. Context, Cognitive Radio, and Intelligent Decisions

While subsequent sections will consider a more formal definition of *context*, for a cognitive radio (CR), consider context to be all relevant information about the CR's operation. Thus a CR's context includes the metrics that measure the CR's communications performance – the so-called "meters" of a CR [9] – such as BER, jitter, end-to-end delay, and signal-to-noise ratio. But relevant information may go beyond waveform stack metrics, such as CR location, information from or about other radios in the area, mission objectives, user identity, and the specific application(s) being supported.

Thus for the purpose of this paper, a *context-aware cognitive radio* is a CR that is also aware of information about its operation beyond the metrics provided by the waveform stack. By virtue of being a cognitive ***radio***, this additional information is then used to control (adjust the knobs of) radio behavior. Such a scenario is illustrated in Figure 2, though it should be noted that the same concept could be extended to a cognitive network or cognitive system depending on what hardware is controlled by the intelligent software.

While most CR publications only make use of waveform chipset statistics (e.g., [9]), several publications have taken the broader view advanced in this paper of incorporating additional operational information into the CR decision process.

CR-One proposed in [10] incorporates information about the user's intentions to help guide the radio's adaptations. The WinnF Public Safety Special Interest Group's report on applying CR to a chemical plant disaster scenario [11] proposed automatic role-based reconfiguration wherein CRs would automatically recognize the role being fulfilled by the users and the current scenario being faced by the users to dynamically adjust device priorities, manage device profiles, and define talk-groups. [12] considers the role of CR in a disaster response wherein the extent of the damage is unknown, and replacement transmitters may unwittingly interfere with transmitters that survived the disaster while formal coordination of replacement through FCC processes is impractical. In this scenario, frequency allocations, power levels, operating waveforms, and device configurations are all dynamically managed based on information gathered about the type of scenario, specific information gleaned on the presence, location, and identity of systems from sensing and databases, and from interactions with human users (an example of the context concept known as *mediation*). Finally, the rules for US TV White Space operation [13], and geographically-constrained CRs in general, provide a salient example of context-aware CR wherein information beyond what is available to the chipset (specifically, location and emitter information managed in an online database) determines the frequencies and power levels available for communication.

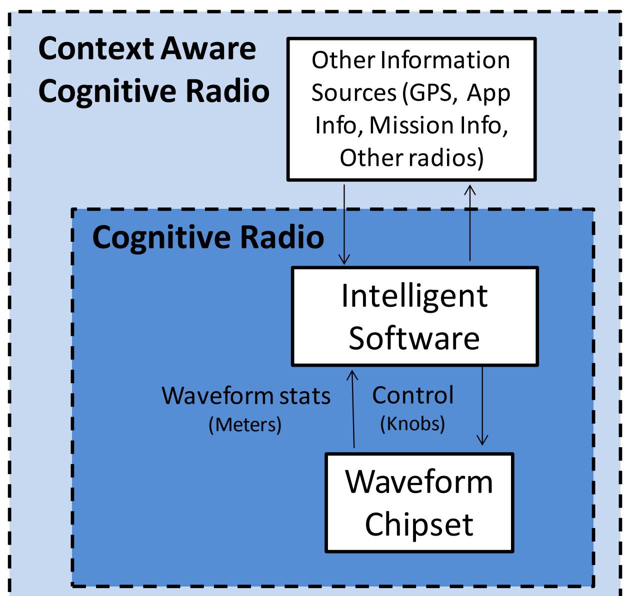

Figure 2: A Context-Aware Cognitive Radio incorporates sources of information beyond what is available to a baseband chipset.

Thus to allow CRs to better process the expected vast wealth and variety of data that will soon be available (Big RF), to make communications more effective and efficient (IPA Communications Cycle), and to enable a myriad of potential CR applications, CRs should be aware of and reason over their context. In the following sections, this paper considers what is meant by context in communications and wireless applications, proposes a generalization of how an intelligent system interacts and reasons about the real-world, presents an initial context-aware CR application, and makes recommendations for developing context-aware CR applications.

2. CONTEXT IN RELATED LITERATURE

To better understand the role of context, the CRWG surveyed over 100 papers on developing context-aware applications, models, tools, and languages. This section presents a selection of these papers to highlight varying perspectives and subtle differences on the meaning of context and related terms, specific context-aware applications, and tools and languages developed to support these context-aware applications.

2.1 Context and Related Terms

Dictionary.com defines context as "the parts of [communication] that precede and follow a word and passage and contribute to its full meaning" and as "the conditions and circumstances that are relevant to an event, fact, etc." [14] defines context as "any information that can be used to characterize the situation of an entity." Other authors have different definitions, but all share the common thread of additional information about some "thing" that aids in the understanding of that "thing". Depending on what it is being applied to, the content of context can vary greatly.

For instance, message context considered in Section 1.2, provides additional information about a transmitted message and may be critical to understanding the message. As discussed in [7], this context can be explicitly conveyed as part of the message, as in the first definition from Dictionary.com, or may be understood to be shared implicitly between sender and receiver based on past communications or a shared understanding of the world (consistent with all three definitions). Context in the Big RF implies the use of meta-data (and meta-meta-data…) to better understand and process the data. The applications considered in Section 1.3 imply a need for operational context (e.g., location, what the user is trying to do, who is nearby) and communications context (e.g., the past, current, and expected future state of the link or network). Each of these types of context is important for a context-aware CR application.

Beyond the term context, the following are additional terms used in context-aware applications.

Ambiguous – information that cannot be resolved by a mediation process, information having two or more possible meanings. [15]

Confidence – degree to which the subject and object are valid. [16]

Mediation - the dialogue between the user and computer that resolves questions about how the user's input should be interpreted [15]

Situation - external semantic interpretations of context objects having properties and standing in relations to one another [16]

2.2 Context Aware Applications

The following is a small selection of context-aware applications that have been developed.

- A wearable device that automatically provides the user with information about the paper and presenter at a conference, e.g., if a recording is being made, based on the room the user is in, the time, and the conference schedule. [17]
- Nokia Situations, an app that adjusts the operation of your phone (ringer settings, launching other applications, changing voicemail, auto-replying to emails) based on location, and calendar information. [18]
- Word prediction and auto-completion for severely disabled users based on location, previous words, and other indicators [15]
- Context-aware light source from Disney that changes light based on the scene [19]

A much longer list will be provided in a context-survey paper being prepared by the CRWG.

While many different context-aware applications have been created that modify the behavior of an application, there are very few publications that consider using context information to modify the behavior of radio hardware. The one application of context-aware CR that is commonly discussed is policy controlled DSA radios, which is effectively a context-aware CR app that controls transmit characteristics based on geo-fencing (database approach) and direct measurements of the RF environment (sensing approach).

2.3 Context Models and Tools

The following is a short selection of available models and tools for developing context-aware applications.

- Qualcomm's Gimbal [20] uses location, time of day, web history, apps and app usage to infer information about the user and provides a series of libraries (e.g., geo-fencing) to build and deploy context-aware applications for iOS and Android platforms.
- Really Simple Context Middleware [21] is open source software for developing context-aware applications for Android platforms. It provides libraries for sensing battery levels and location and for reasoning about user activity (e.g., inferring if the user is walking).

- Context Modeling Language (CML) [22] is a graphical-based modeling language for analyzing and specifying requirements for a context-aware application. It provides varying context classes for context sources, can represent imperfect information, and can model dependencies, histories, and constraints for context fact types.
- Ontological models of context-aware applications that are principally driven by reasoning over spatial and geographic considerations. [23]
- Context Broker Architecture, an OWL-DL based middleware for modeling context-aware applications and facilitating communications between components. [24]
- A hybrid model that mixes both fact-based context capabilities with ontologies and reasoning to model, design, and implement context-aware applications. [25]

As tools already exist to develop context-aware applications for smartphones, the principal challenge for developing context-aware CR will be to translate this into context-aware applications that also control radio hardware.

2.4 Context ToolKit

Developed initially by researchers at Georgia Tech [26], the Context Toolkit is an open-source collection of software modules and processes for modeling and developing context-aware mobile applications in Java and XML. The code for the Context ToolKit can be downloaded from http://contexttoolkit.googlecode.com/ and documentation is available at www.contexttoolkit.org. The principle components of the Context Toolkit are the following:

Widgets are all purpose class that can store information, or context and the base class for other components

Sensors are widgets that turns real world data into contextual information where one or more attributes are normally accessible to other widgets

Enactors perform reasoning on inputs (attributes from other widgets) to create outputs

Generators update the sources of information used by the sensors and models real world processes when no real world component exists and is typically implemented as an enactor without an input

Services are the actuators of the model and are responsible for performing actions in the real world based on computations in the context reasoning model.

To support the reuse of contextual information and reasoning across applications, to better enable distributed applications, and to support dynamically constructed systems, the Context Toolkit provides a *Discovery System*. The Discovery System maintains a repository of running components, the addresses and ports used to communicate with components, descriptions of components, and mechanisms for subscribing to the computations of components. The Context Toolkit has also been extended to provide a means for mediation whereby the user or other context-aware applications can be queried for clarification when the context may be unclear. [14]

A particularly attractive feature of the Context Toolkit is built-in support for controlling hardware via its Services / Actuators components. Thus, constructing context-aware CR applications may only require extending the Context Toolkit to support Services that specifically control radio hardware. This is examined further in Section **Error! Reference source not found.**.

3. DEVELOPING A GENERALIZED MODEL OF CONTEXT-AWARE INFORMATION SYSTEMS

Building on the context survey and prior work in the IPA efforts, the CRWG has been exploring how to appropriately model context-aware information systems. This has led to development of a new model for context awareness, the Wireless Information System Descriptive Model (WISDM), which, though intended for wireless applications, is general enough to encompass all of the context-aware information system models surveyed by the CRWG to date. This section briefly overviews WISDM and how other context-aware reasoning models fit into the WISDM framework.

3.1 WISDM

People have communicated with each other for thousands of years, initially verbally, then with written symbols. But a dramatic disruptive change has occurred in the past one hundred years. Information, represented by binary digits, can be manipulated and stored using electronic computers, and communicated electronically at the speed of light, often without wires. Wireless information systems make information instantly available anywhere in the world, are accumulating vast amounts of stored data, and provide new insights into all aspects of society.

Recognizing these changes and building upon the insights and generalizations gleaned from the Information System Flow Model of Figure 1, the CRWG is developing a general model of how contextually aware information systems operate, which is called the Wireless Information System Descriptive Model (WISDM). WISDM, shown in Figure 3 is a high-level abstraction of information systems that has the objectives of describing the common characteristics that disparate systems have to facilitate interaction between them, designing better information systems, and suggesting new ways they can aid civilization. The concept of "systems" includes both physical systems and their information footprint in the digital world.

The WISDM space, as shown in Figure 3 is divided into four quadrants. The horizontal divider separates the real world (physical space embodied with atoms) from digital information space, i.e., the conceptual world, with binary digits (bits) as the fundamental unit. The vertical divider has systems in operation on the left and development and enhancement of those systems on the right.

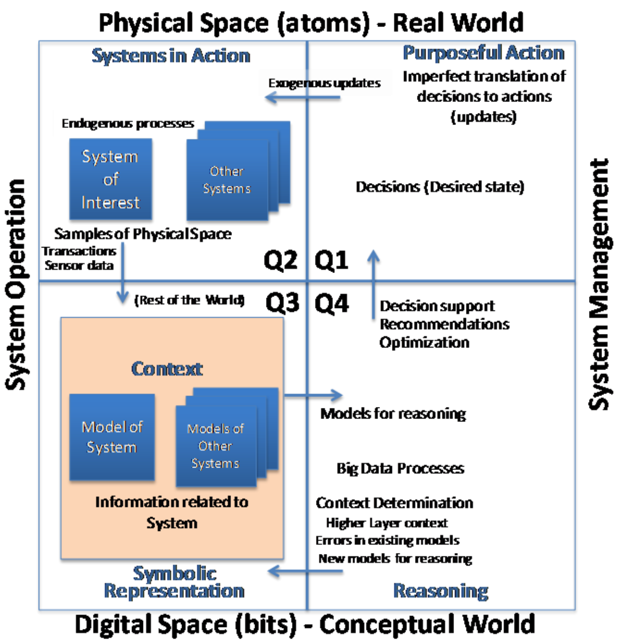

Figure 3: Wireless Information System Descriptive Model (WISDM)

Each of the quadrants has its own perspective. The upper left quadrant, Q2, is Systems in Action, the common real world in which we live. The lower left, Q3, is the system's information model of the real world, with all of the inherent limitations of models[2]. The lower right quadrant, Q4, represents the processes applied by the system to the models and accumulated data of Q3 to gain insights about the real world (context determination) and to alter operation of the system (decisions). The upper right, Q1, imperfectly translates these decisions into actions taken by the system in the real world, and represents the creation of new things, processes, and systems, and modification of how systems work.

The basic flow within WISDM is generally counter-clockwise. Q3 information gathered about the Q2 real world (context acquisition, e.g., sensor data) is used in Q4 to update the models and their context (relationships between models and additional information about the system). These models are then reasoned over, decisions are arrived at, and then imperfectly translated into real world actions, which may or may not lead to the desired result.

However, the flow is not always counter-clockwise, as Q4 reasoning about the models can lead to further insights about the models themselves and delivery of revisions directly to Q3. We call this resulting context about the context "higher-layer context" and it is used to discover additional relationships and improve decision support. This is conceptually similar to the learning modes supported by back-propagation analytics developed for neural-net architectures in the 1990s.

These concepts will be more fully fleshed out in a subsequent paper and report to be released by the CRWG.

3.2 Relationships Between Context Models

While working on WISDM and surveying existing models of context-aware systems, the CRWG had the insight that the models were generally isomorphic to one another. In other words, one context model could be used to represent or implement another. To illustrate this, consider Figure 4 and Figure 5, which show how WISDM represents the Context Toolkit components and the CR OODA (Observe-Orient-Decide-Act) loop model.

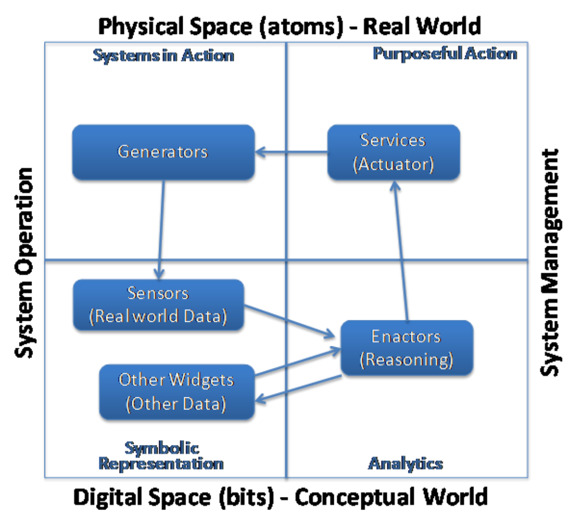

Figure 4: Context Toolkit components in WISDM

In Figure 4, the Context Toolkit assumes the existence of a "real world" (i.e., systems in action in Q1) whose processes of interest can be modeled with generators. The current states of systems in action are sampled by sensors which are stored in widgets (Q2) that provide attributes that can be used for contextual analysis (Q3). The Enactors (Q3) implement the reasoning processes which can then lead to the use of Services (Q4) that yield changes to the real world (e.g., increasing light levels). Alternately Enactors can derive new contextual information that updates widgets that store this new context information in Widgets that correspond to Q2.

In Figure 5, the Outside World of OODA corresponds directly to Q1 and the sampling of the Outside World leads to a low level awareness in Q2. The Orienting and Learning

[2] "All models are wrong, but some are useful," George E. P. Box, *Empirical Model-Building and Response Surfaces* (1987), co-authored with Norman R. Draper, p. 424.

processes of OODA span Q2 and Q3 of WISDM to reason to new contextual awareness and new models based on learned insights and detected errors. The results of Deciding and Planning of OODA in Q3 of WISDM lead to the Acting process in Q4, which is then realized in Q1 (Outside World).

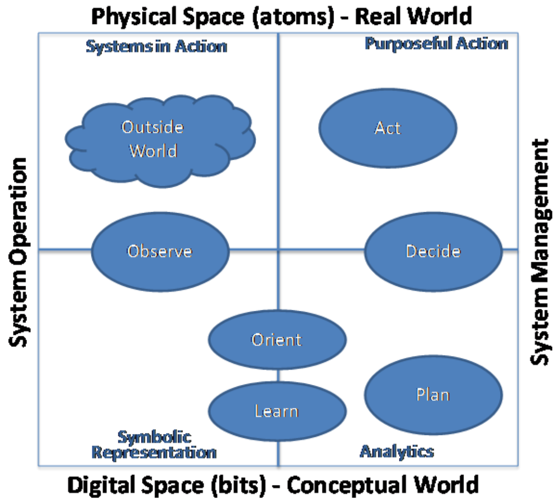

Figure 5: Mapping the CR OODA model [10] into WISDM

In both cases, the principle flow between components in the Context Toolkit components and the CR OODA loop match the counter-clockwise flow of WISDM. Further, it is relatively easy to see how human reasoning similarly maps into WISDM with mental (or physical) models of the system of interest substituting for WISDM's symbolic (digital) models. Because of the wide applicability of WISDM to context-aware systems and context-aware models and tools, WISDM appears to be a valuable tool for context-aware CR.

4. DEVELOPING A CONTEXT-AWARE CR APPLICATION

To better understand the utility of existing context tools and models for developing context-aware CR applications, to help refine the CRWG's study into context aware systems, and to identify potential gaps in existing capabilities for context-aware CR, the CRWG is developing a context-aware CR application using Context Toolkit components, illustrated in Figure 6. This example uses information commonly incorporated into other context-aware applications to control radio hardware – selectively enabling transmission and controlling the network to communicate over. This is a key differentiator between traditional context-aware applications and context-aware CR.

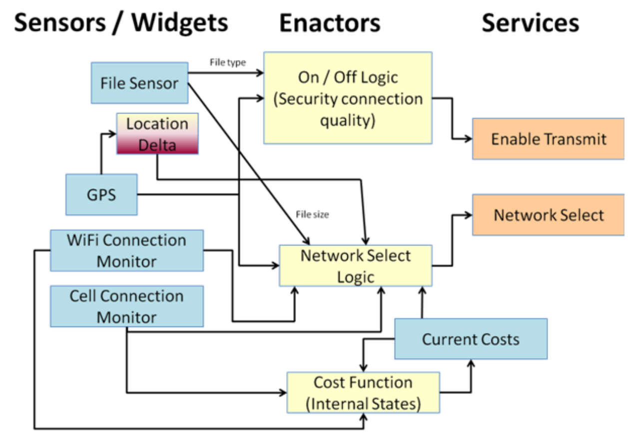

Figure 6: Block Diagram of Context-aware Cognitive Radio Application using Context Toolkit components. Blue blocks indicate simple sensors, yellow blocks enactors, orange blocks services (actuators), and the mixed color block an example of a widget providing a derived context attribute (which necessitates derivation from an enactor).

In this application the functions of primary concern are the policy considerations for utilizing the link, the physical availability of the network, the technical quality of the link, and lastly the economics of using the link. The application determines if the radio should be allowed to transmit or not and over which network (cellular or WiFi), the control of which is implemented in two different Services modules (Enable Transmit and Network Select). Enactors, which manage the reasoning logic in the Context Toolkit, are driven by the input from the following Sensors:

- the presence and achievable speed of a WiFi connection
- the presence and achievable speed of a cellular connection
- location via GPS
- movement rate (derived from GPS)
- file type and size to be transmitted.

We are currently implementing these objects in Java, whose widespread adoption can facilitate the incorporation of components originally intended for other uses. For example code from British Telecom Labs widget for interfacing with a GPS device was repurposed for use in this application with little if any modification. The flexibility of the Context Toolkit also allows for implementation via XML descriptors via the WidgetXML function that allows for the creation of a Widget from an XML schema file. This potentially could be the basis for a Context Factory – a mechanism being explored in the CRWG for automatically managing the loading and unloading of context applications and the sharing of components and information across context-aware CR applications.

From a CR perspective, the weakness of the Context Toolkit is that it takes over where the communication link ends, i.e., it was not designed with radio applications in mind. For instance, the Context Toolkit puts the data provided by a communication link in a useable format, but it may not provide the necessary meta-data to establish a communication link. Establishing these links may be necessary for an application to operate, e.g., if it depends on a wirelessly connected sensor. However, it should be possible to create lower level Sensors, Widgets, Enactors and Services to fill this gap and to work largely within the existing framework.

5. CONCLUSIONS AND FUTURE WORK

As CR applications become more sophisticated and incorporate information from an expanding and more varied set of sources, being able to quickly process and extract meaning from the sea of data will be increasingly important. Because this is analogous to the Big Data problems faced in the IT world, we call this set of problems "Big RF". By reasoning to higher layers of context from the raw sensor data, we believe that CRs can better handle Big RF problems.

Understanding what context is and how it is shared between the originator and recipient of a message allows for more efficient communications by permitting significantly fewer bits to be transmitted to convey the same resulting information. Similarly, by concealing message context from undesired recipients, message security can be enhanced. These were concepts first examined in the previous CRWG IPA projects, and are serving as a springboard into the CRWG's further studies into enabling context-aware CR and information systems.

CR will benefit from understanding its context – message context of transmitted data, operational context of the system, and communications context of its managed link or network. While the role of context for CR has been briefly examined by previous authors, e.g., [10], [11], [12], we believe this is the first paper to systematically consider how context can be incorporated into CR processes.

As part of this process, the CRWG first conducted a broad survey of existing literature on developing context-aware applications, and subsequently focused on mobile applications. However, among the different authors, there were varying perspectives and subtle differences on the meaning of context and on which attributes were most critical to determining a device's context. We saw where tools and languages had been developed to support these context-aware applications, and we identified the Context Toolkit as a promising starting point for developing context-aware CR applications.

As part of this effort, the CRWG developed the Wireless Information System Descriptive Model (WISDM). WISDM models context-aware information systems and divides basic operations into four quadrants – (Q1) Systems in Action, (Q2) Symbolic Representation, (Q3) Analytics, and (Q4) Purposeful Action where Q1 and Q4 capture operations in the Physical Space (Real World) while Q2 and Q3 represent operations in Digital Space (Conceptual World) and where Q1 and Q2 describe system operation and Q3 and Q4 describe system management. Within and between the quadrants are various processes for updating models, e.g., from sensors, from reasoning, or from modeled endogenous processes. By comparing WISDM to the surveyed models of context-aware systems, we showed that WISDM applies to a wide variety of context-aware information processing systems, including humans!

To better understand the utility of existing context tools and models for developing context-aware CR applications, to help refine the CRWG's study into context-aware systems, and to identify potential gaps in existing capabilities for context-aware CR, the CRWG is developing a context-aware CR application using Context Toolkit components. The application determines if the radio should be allowed to transmit or not and over which network based on context sensed data from location, network availability, and intended file transmission type.

In the future, the CRWG will continue to explore and refine the concepts outlined in this paper. Planned activities include developing a Big RF tool to automatically manage changing context applications via a mechanism we tentatively call the Context Factory. In general, much of the work will focus on identifying what would constitute a comprehensive toolset for managing CR context with an emphasis on identifying which tools are still in need of further development and what kinds of applications could be deployed today.

6. REFERENCES

[1] http://www-01.ibm.com/software/data/bigdata/

[2] J. Bertolucci, "Intel Cuts Manufacturing Costs With Big Data",*Information* Week, March 18, 2013. Available online: http://www.informationweek.com/software/business-intelligence/intel-cuts-manufacturing-costs-with-big/240150978

[3] E. Naone, "What Twitter Learns from All Those Tweets," *MIT Technology Review*, September 28, 2010. Available online: http://www.technologyreview.com/view/420968/what-twitter-learns-from-all-those-tweets/

[4] FCC Spectrum Dashboard, http://reboot.fcc.gov/spectrumdashboard/

[5] D-TA, “Ultra-Wideband Scanning Transceiver with Signal Activity Detection, Real-Time Recording, IF Playback & Data Analysis Capabilities,” White Paper, July 2012. Available online: http://www.d-ta.com/verification.php?site=Applications/ultra-wideband-scanning-transceiver-July.pdf

[6] http://wiki.answers.com/Q/How_many_cell_towers_are_in_the_US

[7] Wireless Innovation Forum, “IPA – Information Process Architecture Volume I,” WINNF-09-P-0020-V1.0.0, Nov 01, 2010.

[8] Wireless Innovation Forum, “Information Process Architecture Volume 2: Survey of IPA Like Systems,” WINNF-09-P-0021, Jun 27 2012.

[9] C. Bostian, J. Reed, “Understanding the Issues in Software Defined Cognitive Radio,” Tutorial presented at *IEEE DySPAN*, Baltimore, MD, Nov. 2005.

[10] J. Mitola, “Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio,” PhD Dissertation, Royal Institute of Technology (KTH), May, 2000.

[11] Wireless Innovation Forum, “Use Cases for Cognitive Applications in Public Safety Communications Systems Volume 2: Chemical Plant Explosion Scenario,” WINNF-09-P-0015-V1.0.0, Feb 11, 2010.

[12] D. Devasirvatham, J. Neel, C. Tompsett and K. Link, “3 Layers of Disaster Recovery,” *MissionCritical Communications*, March 2013, pp. 62-65.

[13] FCC, “Second Memorandum Opinion and Order In the Matter of Unlicensed Operation in the TV Broadcast Bands and Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band,” FCC 10-174, Sep 23, 2010.

[14] A. Dey, J. Mankoff, “Designing Mediation for Context-Aware Applications,” *ACM Transactions* 2005.

[15] A. Dey, J. Mankoff, G. Abowd, and S. Carter, “Distributed Mediation of Ambiguous Context in Aware Environments,” *Proc. 15th Ann. Symp. User Interface Software and Technology (UIST '02),* pp. 121-130, Oct. 2002.

[16] J. Ye, S. McKeever, L. Coyle, S. Neely and S. Dobson “Resolving Uncertainty in Context Integration and Abstraction,” *ICPS'08*, July 2008 pp. 131-140.

[17] A. Dey, M. Futakawa, D. Salber and G. Abowd, “The Conference Assistant: Combining Context-Awareness with Wearable Computing,” *Proceedings of the 3rd International Symposium on Wearable Computers (ISWC '99)*, San Francisco, CA, Oct 1999. pp. 21-28.

[18] http://www.readwriteweb.com/archives/nokias_new_situations_app_makes_phones_self-aware.php

[19] O. Wang et al., “A Context-Aware Light Source,” ICCP 2010. Available online: http://zurich.disneyresearch.com/~owang/pub/context.html

[20] https://developer.qualcomm.com/mobile-development/mobile-technologies/context-aware-gimbal

[21] http://code.google.com/p/rscm/

[22] K. Henricksen, J. Indulska, A. Rakotonirainy, “Modeling context information in pervasive computing systems,” 1st International Conference on Pervasive Computing (Pervasive), vol. 2414 of Lecture Notes in Computer Science, Springer, 2002.

[23] A. Frank, “Tiers of ontology and consistency constraints in geographical information systems,” *International Journal of Geographical Information Science,* 15 (7), 2001, pp. 667–678.

[24] H. Chen, T. Finin, A. Joshi, “Semantic Web in the Context Broker Architecture,”*Proceedings of the Second IEEE International Conference on Pervasive Computing and Communications*, 2004.

[25] K. Henricksen, S. Livingstone, J. Indulska, “Towards a Hybrid Approach to Context Modelling, Reasoning and Interoperation,” *Proceedings of the First International Workshop on Advanced Context Modeling*, *Reasoning and Management*, 2004.

[26] A. Dey, “Providing Architectural Support for Building Context-Aware Applications,” PhD thesis, Georgia Tech, Dec. 2000.