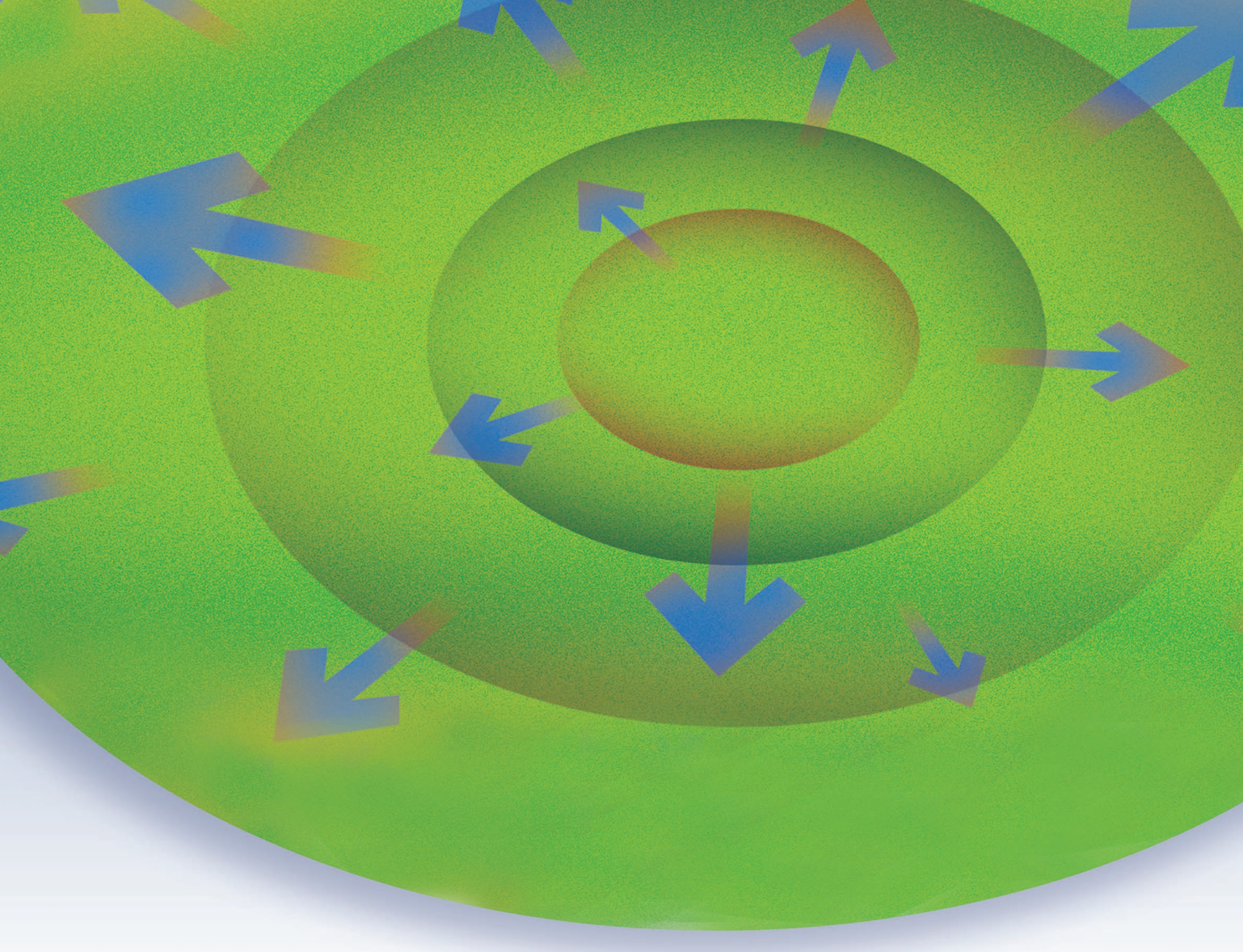

AN OPEN-SOURCE ARCHIVING SYSTEM

RF-Propagation Measurements and Radio-Channel Modeling and Simulation

Despite recent advances in high-frequency simulation tools based on ray tracing and similar techniques, collection and reduction of large amounts of experimental channel response data remains the mainstay of wireless channel modeling. In other scientific fields where collection of experimental data is also time consuming and expensive, researchers have begun to establish a tradition of sharing their data through the establishment of Web-based data repositories and management systems. This makes it possible for researchers to pool their data sets to yield more reliable or broadly

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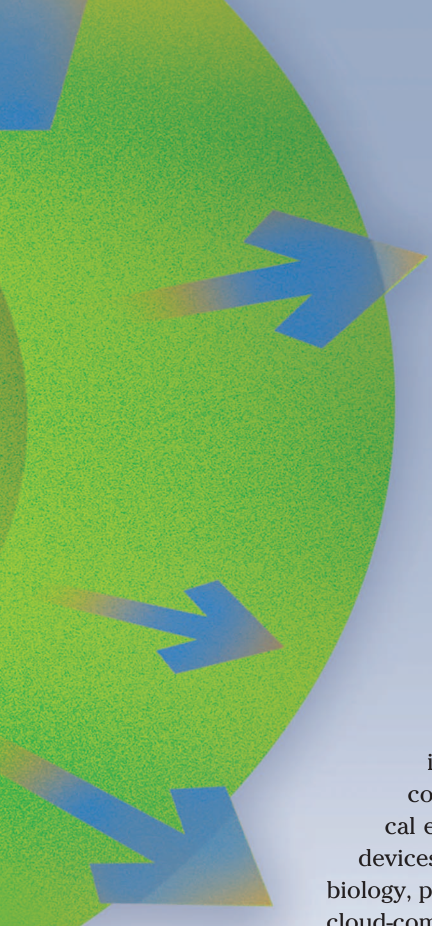

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applicable results or to extract additional value from data that may have been collected for other purposes. Moreover, recent developments in Web technologies will greatly add to the capabilities of such systems in the coming years. Account must also be taken of the significant differences between channel-response data and data collected in other scientific fields.

Wireless technologies are expanding at a tremendous rate. New wireless technologies for vehicle-to-vehicle, vehicle-to-infrastructure, millimeter-wave devices, and other innovative applications are pushing wireless beyond the traditional realms of cellular, radio, and satellite communications. A side effect of this brisk expansion is a rapid increase in the types and numbers of channel models and measurements collected by industry and the research community, as each new system or application has new uses in common bands or operates in new, unexplored frequency bands (e.g., 60 GHz) or a new physical environment (e.g., within a vehicle). This increase in data due to the proliferation of new devices or applications is not unique to the wireless community. Indeed, the fields of medicine, biology, power systems, and astronomy, among others, have begun to use novel semantic Web and cloud-computing approaches to make the experimental data more useful and available [1]–[4]. These approaches result in the creation of collaborative data repositories and tools that encourage new technologies and help researchers and practitioners to determine areas of a subject that have not been completely explored or elucidated. These approaches also result in standardized models that can be easily transported across platforms, greatly reducing the confusion and facilitating model comparisons by the research community. By adopting semantic Web- and cloud-computing technologies, the wireless research community will benefit as it develops emerging areas such as vehicle-to-vehicle communications and yet unimagined use cases. The wireless community should invest in creating an online semantic Web tool for modeling channels and archiving channel data.

Modeling and Measurement Campaigns—The Need for Improved Data Sharing

Tables 1–3 illustrate the recent breadth of propagation measurement, modeling, and simulation efforts for wireless technologies in addition to the wide range of software tools available to study wireless channels. Recent efforts to understand vehicle-to-vehicle channels, vehicle-to-infrastructure channels, millimeter-wave channels, and channels in novel environments such as cruise ships, airplanes, and public safety/emergency areas underscore the growth in wireless beyond traditional cellular radio services. A broad range of tools, including simulations of impulse responses for channels with impulse noise (SIRCIM), WinProp from AWE (AWE is a German company that specializes in the production of software for modeling wireless propagation to facilitate wireless network design and estimation of electromagnetic compatibility), EDX Wireless Signal Pro, LANPlanner from Motorola/Wireless Valley, Mentum Planet, and CINDOOR, (a computer tool for planning and design of wireless systems in enclosed space), allow the researchers to study a broad range of environments. However, most of these tools are proprietary, and researchers often cannot afford the expensive fees required to use them. This nonstandardized approach results in many models being presented once at a conference or in a journal and then being subsequently abandoned or forgotten or being put into a useful but proprietary tool. It also means that researchers who often have great intuition about innovation are constrained in their ability to use these data to test new ideas or applications. By creating an open semantic Web repository and data-management tool, the research community will increase the value of propagation measurement and modeling campaigns, thereby encouraging practitioners and research to make high-quality models that are as useful as possible. A Web-based tool would also allow the channel models to connect to other online databases, such as geographical information service (GIS) databases like Google Maps [5], to discover new correlations

TABLE 1 Channel measurement campaigns.

Reference, Year, Affiliation	Frequency/BW	Environment/Use Case	Method
[8], 2009, Lund University, Sweden	5.2 GHz, 240 MHz	Vehicle-to-vehicle, ad hoc vehicle	Switched array orthogonal frequency division multiplexing (OFDM)
[9], 2010, University of Genova	2.4 GHz, narrow band	Cruise ship, passenger aps	Vector network analyzer (VNA)
[10], 2010, Ericsson, Lund University, Sweden	2.6 GHz, 200 MHz	Outdoor ground level, sensor arrays	OFDM wide-band VNA
[11], 2010, University of Vigo, Spain	2.4 and 5.8 GHz, narrow band	Forest, peer-to-peer, emergency	Narrow-band VNA
[12], 2010, DECOM UFES, Brazil	3.5 GHz, 900 MHz	Urban,skyscraper to ground, WiMAX	VNA wide band
[13], 2010, Sandia National Labs, New Mexico	50, 150, 225, 450, and 900 MHz, narrow band	Large buildings, indoor to outdoor, emergency	VNA narrow band
[14], 2010, IMTEK, Freiburg, Germany	0.5–2.2 GHz, wide band	Collapsed buildings, emergency response	VNA broad band
[15], 2010, University of Nicosia	62.4 and 1 GHz	Lecture rooms and corridors	VNA swept frequency
[16], University of Ilmenau, Germany	2.53 GHz, two bands of 45 MHz	Urban, MIMO base station (BS)	RUSK TUI-FAU Medav, GmbH
[17], 2010, Heinrich-Hertz Institute	2.53 GHz, 21.25 MHz	Urban, MIMO BS capacity improvements	HyEff multitone sounder
[18], 2009, Heinrich-Hertz Institute	5.2 GHz, 120 MHz	Campus	MIMO multitone sounder
[19], 2002, Virginia Polytechnic Institute	60 GHz, wide band	University campus	Sliding correlator
[20], 2002, Vienna University of Technology	5.2 GHz, 120 MHz	Urban courtyard, MIMO capacity	RUSK ATM*
[21], 2004, Virginia Polytechnic Institute	60 GHz, wide band	University campus, hallways	Sliding correlator
[22], 2007, Tokyo Institute of Technology	4.5 GHz, 120 MHz	Rural, MIMO	RUSK Fujitsu MIMO sounder
[23], 2009, University of Ilmenau, Germany	60 and 3 GHz	Airline cabin, in-flight entertainment	Multiantenna, spread spectrum

* A RUSK-type channel sounder is a commercially available measurement device for estimating the impulse response of wide-band channels and MIMO wide-band channels. RUSK channel sounders may be purchased or rented from MEDAV GmbH, a German firm specializing in channel sounding. Please refer to http://www.medav.de.

TABLE 2 Recent channel modeling efforts.

Reference, Year, Affiliation	Frequency	Model Type
[8], 2009, Lund University, Sweden	5.2 GHz	Stochastic geometric
[10], 2010, Lund University, Sweden	2.6 GHz	MIMO, statistical
[27], 2010, IEH, University of Karlsruhe, Germany	915 MHz, 2.45 GHz	Body area network
[28], 2004, IHE, University of Karlsruhe, Germany	5.2 GHz	Ray tracing optical
[7], [29], and [30], On-going to March 2011, intergovernmental European effort	Multiple bands, 3GPP bands (e.g., 2.1 GHz)	Geometry-based stochastic MIMO
[31]–[33], 2001–2005, intergovernmental European effort	Multiple bands UHF-millimeter wave	Geometry-based stochastic MIMO
[34]–[36], through 2011, WINNER + Industrial and Academic Consortium	IMT-Advanced, 4G bands	Geometry-based stochastic MIMO
[37]–[39], 2004–2007, WINNER Industrial and Academic Consortium	2 and 5 GHz	Geometry-based stochastic MIMO

between channel parameters and users. Certain evolutionary steps toward creating an online open-source repository have been taken in Europe [6], [7]. However, these Web sites do not offer the simulation and collaboration tools that are needed to make them of sufficient interest to a wide range of users. Also, by using an eXtensible Markup Language (XML)-encoded data approach, a new online open-source tool could greatly improve data integrity by

TABLE 3 Many channel simulation tools, both open source and proprietary, are available.

Tool	Use Cases and Features	Availability
SIRCIM [40]	10 MHz–60 GHz, indoor, outdoor, wide band, and narrow band	Open source
EDX Wireless Signal Pro [41]	Channel parameters, GIS linking, standards simulation	Proprietary
Mentum Planet [42]	Channel parameters, model tuning, GIS linking	Proprietary
Winprop [41], [43]	Channel parameters, GIS linking, standards simulation	Proprietary
CINDOOR [41], [44]	Ray-tracing indoor environment simulation for network planning, wide band, and narrow band	Proprietary
LANPlanner [45]	802.11 a/b/g/n network simulation, import building models, channel capacity	Proprietary

requiring the submitters to fully document and explain all aspects of a data set.

Works in [6] and [7], while being good first steps, lack such safeguards, thus limiting their potential. Figure 1 (from [24]) illustrates the paradigm shift such a tool would represent. The current approach of letting measurement results lie fallow in often-forgotten literature will be tremendously improved by an online tool that will make the channel models persistently available to researchers and companies for maximum utility.

An example of where a semantic Web tool would be useful in channel modeling was provided in 2010 by Rappaport et al. [25], who created a simulation tool for understanding the impact of out-of-band emissions (OOBE) from cellular services on noise-limited digital mobile services such as satellite radio. The tool's source code is readily available through the Federal Communications Commission, but its reach is limited because it relies on MATLAB (a proprietary software suite) and requires a manual download with no technical support. The simulation tool provides users with the ability to model realistic mobile-to-mobile channel interference effects and takes real-life traffic data into account with Google Maps [5]. By porting this code over to an open-source platform such as Scilab scientific computing environment [26], it could be easily accessed using cloud infrastructure-as-a-service resources such as Amazon's elastic cloud (EC2). Figure 2 illustrates the GIS-enabled tool developed by Rappaport et al. [25]. If this tool became part of a larger collaborative model and simulation-repository tool, then other researchers could link to this simulation to study new effects such as the correlation between vehicle density and channel capacity.

Efforts in Other Fields of Research

Movement toward using cloud computing and semantic Web for scientific purposes has already begun in many other fields. For example, in the field of anatomy, an entire virtual human body has been placed online through the project Prometheus [1]. Space telemetry has utilized novel modeling paradigms of the semantic Web to store and share astronomical data [2]. Chip-design companies have invested in collaboration tools such as wiki's that share many aspects of the semantic Web [3]. The power industry

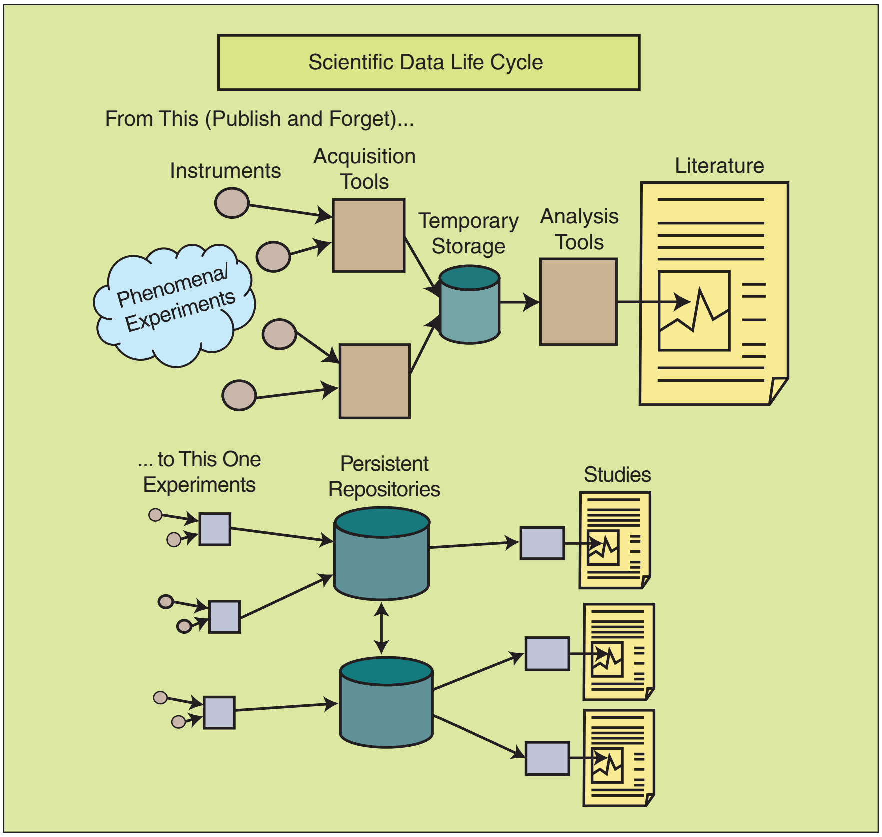

FIGURE 1 Improvement on the use of scientific data, such as channel measurements, by making them persistently available to users is shown (from [24]). (Image courtesy of Mario Valle.)

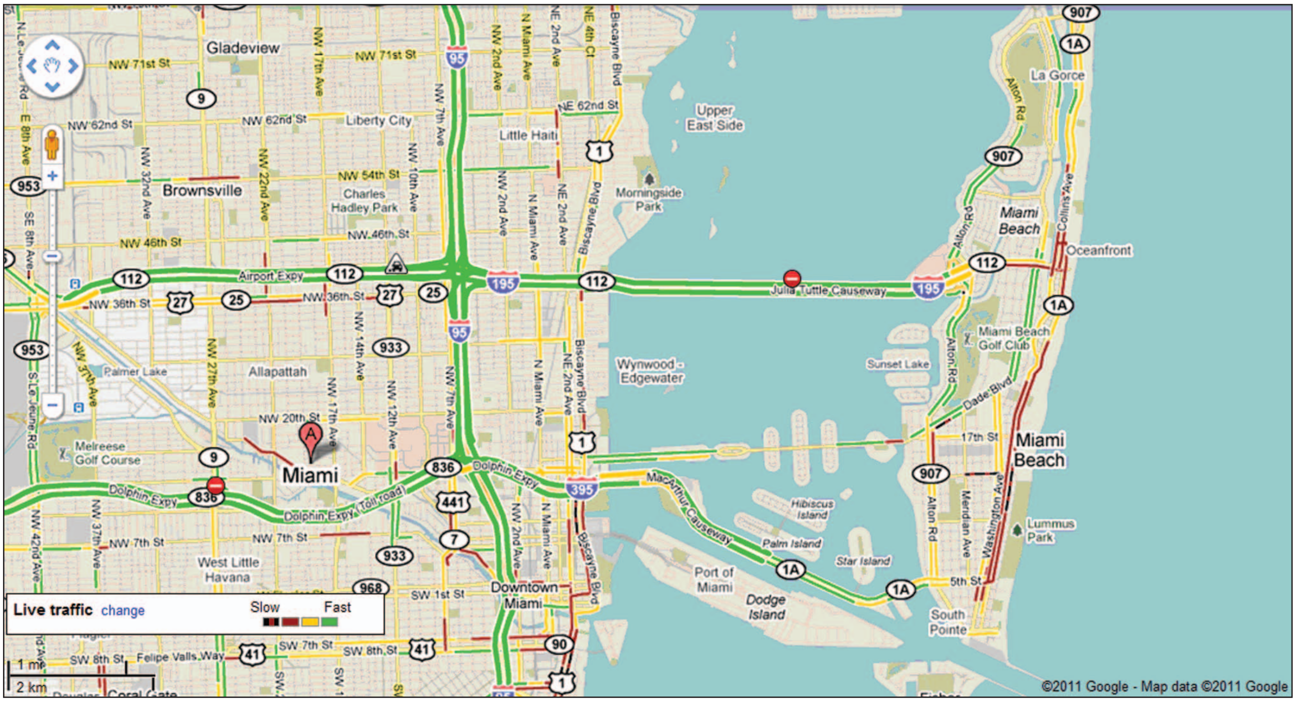

FIGURE 2 In [25], Google Maps [5] was part of a simulation that studied the effects of OOBEs on satellite radio. Because the simulation links to an online database and could be supported with open-source software platforms such as SciLab [26], it would be ideal for inclusion in an online collaborative semantic Web model and simulation repository.

and other utilities are deploying novel unified modeling language resource description framework (RDF) methods for sharing infrastructure information in deregulated markets [4]. These projects in other fields should convince the wireless community of the value in using novel Web-based technologies for channel modeling.

The semantic Web, which is revolutionizing the field of knowledge representation, expands the ability of Web users to collaborate online by clarifying complex structures ranging from complex human sentences to channel models [46]. This technology uses formal ontology languages and unified modeling languages (UMLs) (formal logical languages with strict rules for grammatical correctness) to create easily expandable descriptions that are as useful to a machine as they are to a human reader. This facilitates software that can more usefully manage information than in the first iteration of the Internet so that the software can be easily written that encourages human collaboration.

The Semantic Web, Resource-Description Frameworks, and Cloud Computing

A key technology of the semantic Web is RDFs [47], which are the formal methods of describing structures typically encoded in XML. Formulating an RDF begins with a map of the structure to be described, as shown in Figure 3, to describe a wireless channel (based on the explanation in [48]). The map describes Triples, statements that relate a subject to an object using a predicate. For example, a triple that describes a channel is "outdoor channel 23 has a root-mean-square (RMS) delay spread of 50 ns." The subject of the statement is "channel 23." The object is "RMS delay spread," and the predicate is "has a" indicating possession. "RMS delay spread" in the sentence is also a subject with objects "time unit" and "value." These triples are written into XML for interpretation and automatic management by a computer. For example, we might write this triple in XML with the following (which uses several fictional Web sites).

In this example, the first Web site is a link to a fictional namespace, which is a large repository of precise definitions. For example, this namespace contains definitions for RMS delay spread (represented by rmsdelay), units of time (represented by timeunit), and numeric values (represented by value). The second Web site is a uniform resource identifier (URI) that uniquely specifies the location of an object or resource (Channel 23) in a database with a uniform resource locator (URL) (http://ieeevts_future_website/models/ in this example) and uniform resource name (URN) (Channel 23) in this example.

A key strength of an RDF implemented in XML is that it requires data to be explicitly and correctly formatted to be considered as compliant data. By using this approach, the online archiving tool would address the key concern of data validity and integrity that has prevented greater success of other efforts such as [6] and [7]. The RDF will require data submissions to contain full measurement parameters, including measurement-equipment specifications and simulation environments.

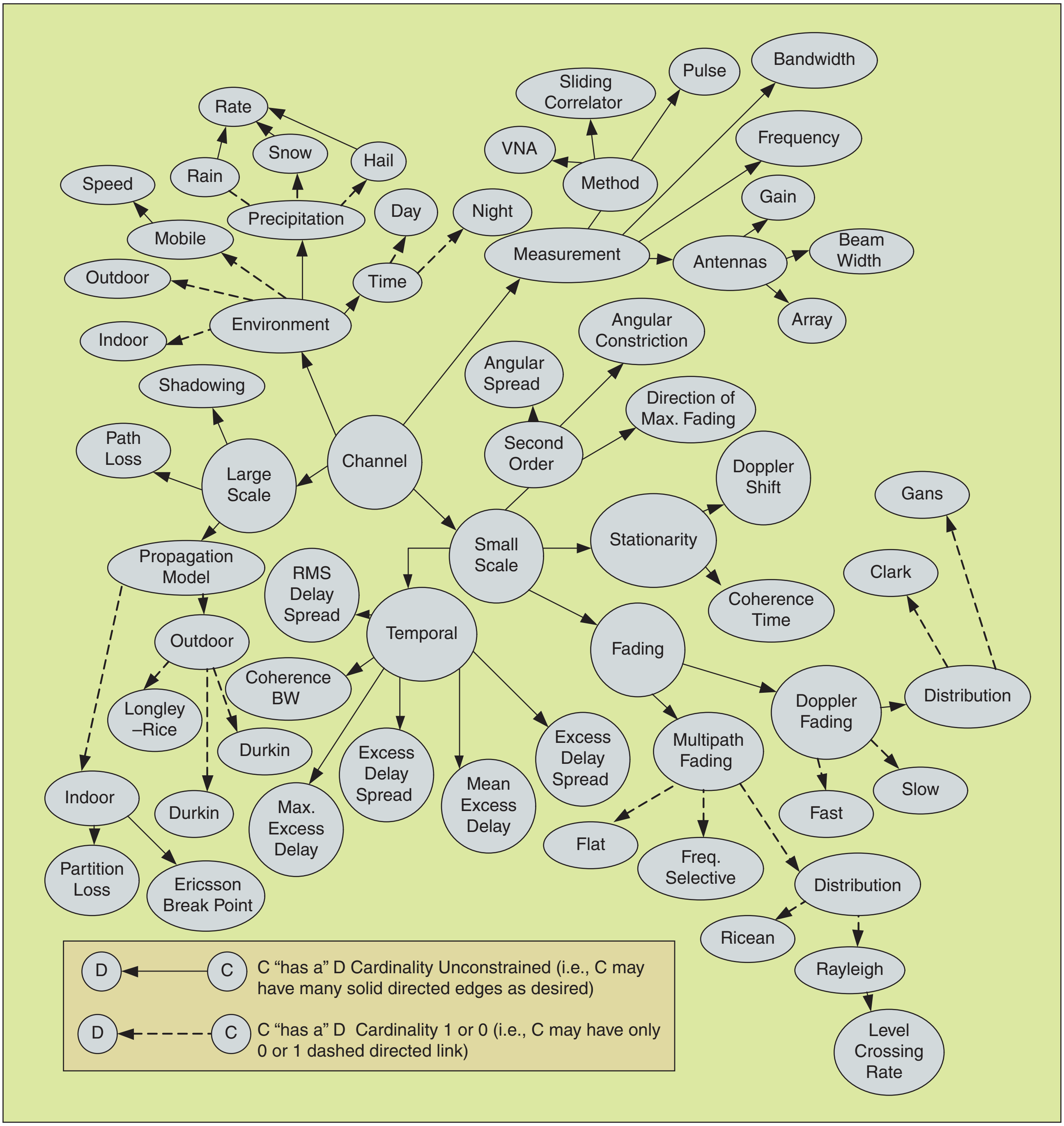

FIGURE 3 The map serves as the basis for creating an RDF to model a channel (based on [48]).

Describing channel measurements or models in a way that can be easily and automatically managed by computers is the first step to creating an online semantic Web application for wireless researchers. The second step is using these verbose representations in software and making them available to the research community. This may be accomplished using services such as Amazon Web service's elastic compute cloud (EC2) and simple storage service (S3), which allow the individual users or enterprises to rent virtual machines on the cloud and to store data for use by the virtual machines or downloading [47], [49]. Upon logging into the online tool through, for example, a link on the IEEE Vehicular Technology Society (VTS) Web site, the user could be seamlessly directed to the repository loaded on Amazon's EC2 and S3 platforms. If the user only needs access to model or measurement data, then he or she would only need to access the storage available on Amazon S3 using user interfaces specifically created for that purpose. Source code or binary representations of novel simulation tools could be saved in S3, and when a user

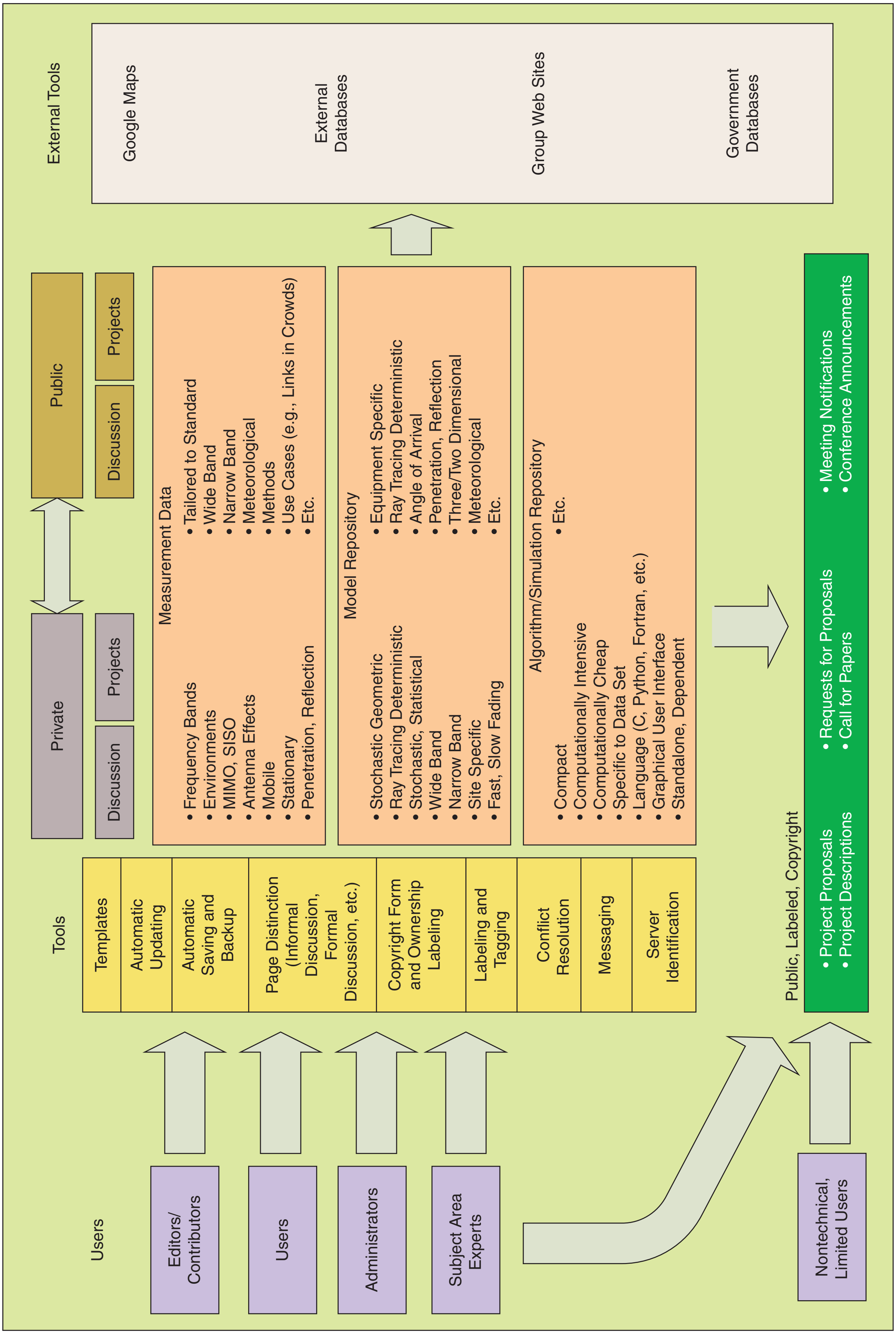

FIGURE 4 The structure of the proposed online archiving tool.

requests to use them, the system would automatically load and run the application in a virtual machine and then display the results.

The online collaboration tool that could be loaded on a cloud-computing service would be architected after successful online collaboration tools such as Wikipedia [3]. An example structure of the tool is shown in Figure 4. The users would have different roles according to their needs and responsibilities. Simple users would only have read access to the tool, while editors and contributors would have the privilege to add new data sets and simulation code. Subject area experts would have the privileges in mediating or deciding in disputes about model data or simulations, and administrators would oversee the functioning of the Web tool. The repository and simulation Web tool would be partitioned into measurement and model repositories, which would be stored on a service such as Amazon's S3, and simulation tools, which could be stored on S3 until needed, at which point they would run on a service such as Amazon's E2. Contributing users would have the right to make certain data sets, models, or simulation tools private until fully tested. All other content would be viewable in public pages by all users. Because it would be online, the tool could easily link to other databases such as Google Maps and measurement repositories maintained by the International Telecommunications Union (ITU). Users of the tool would benefit from forums targeted at discussions of measurement experiences, channel data analysis, and other topics. Such forums would aid new researchers in constructing measurement systems and would allow the users to identify faulty data incorrectly loaded onto the tool site.

Conclusions

Establishment of a Web-based repository for wireless multipath channel measurement data would make it possible for the researchers to pool their data sets to yield more reliable or broadly applicable results or to extract additional value from data that may have been collected for other purposes. It would also allow the validity of models derived from certain data sets to be more easily tested against other data sets than at present. Moreover, ongoing developments in Web technologies will greatly add to the capabilities of such repositories in the coming years. While the wireless community would greatly benefit from the establishment of such a repository for channel measurement data, account must be taken of the significant differences between wireless channel-response data and data collected in other scientific fields. A particular challenge is to ensure that essential details concerning the measurement equipment used to collect the data, the manner in which the equipment was calibrated and verified, the data collection procedure, and details of the environment in which the data were collected are adequately documented and linked to the channel-response data. Nevertheless, it seems likely that the return from such a wireless channel-response data repository would justify the effort required to set up and maintain it.

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