Abstract

This paper summarizes the author’s keynote address to the first European Workshop on Software Radios in Brussels on 29 May 1997. The software radio is an emerging technology for rapidly building flexible, modular, multiband multimode radio systems. It has great potential for creating radio infrastructure that can be programmed for new standards and that can be dynamically updated with new software personalities that define the air interface. These waveforms may be downloaded to software radio nodes "over the air", reducing OA&M costs and reducing the need to purchase new hardware for value-added services. Although the technology has been proven in the field, there are technical, economic and institutional challenges remaining before the benefits of this technology are fully available to our customers. This paper highlights key technical challenges and opportunities. The author would like to thank the European Commission for their kind invitation to present this talk, and especially Joao da Silva and Jorge Pereira.

1.0 Introduction

Guten Morgen. Bokher Tov. Saalem. Bon Jour. And Good Morning. If I were a multiband multimode (digital) radio operating in the audio band, then each of you would hear the rest of this talk in your native tongue. But I have to warn you, only those of you who speak German would be at all happy with what you hear because I do not speak Hebrew very well and I can hardly say “hello” in French and Arabic. But - and this is the exciting part - if I were a software radio, then each of you could take a few minutes before this talk began to upload a vocabulary data base and a few software radio “applets” for my language generator to execute and then each of you would hear this talk in your native language with good pronunciation and proper grammar. This illustrates one of the reasons for this workshop on software radios: software radio’s multiband multimode waveforms are software-defined and this promises to service providers (military, civil and commercial alike) next-generation flexibility in the design and evolution of wireless networks, infrastructure and services. But like my language skills, most of the potential has not yet been realized. So we are here to work through the related challenges and opportunities.

1.1 Disclaimer

As many of you know, I am employed by The MITRE Corporation, a not-for-profit company that operates Federally Funded Research and Development Centers (FFRDCs) for the US Department of Defense (DoD). At present, I am on loan to the DoD where I am technical director for modeling and simulation of telecommunications systems. But my remarks are drawn primarily from the radio engineering course that I have just finished teaching in Stockholm and London. Thus, these views are mine alone and are not necessarily the views or policy of The MITRE Corporation or the US Government.

1.2 Perspective

Software radio technology has its roots in the Electronic Warfare (EW) programs of the
1980’s which accessed the entire electromagnetic spectrum to monitor threats and to inject jamming signals. Thus, the military radio and EW experts at this workshop know that we can build wideband antennas; wideband radio frequency (RF) modules; high sampling rate Analog to Digital Converters (ADCs) and DACs; and the high performance digital signal processors needed for software radios - but at what cost? Commercial applications and large scale military and civilian radio markets are cost sensitive. So the focus of my remarks will be on technologies for improved cost/benefit and broader applications of software radio technology.

1.3 Motivation

The software radio may emerge as a key enabling technology of the “future-proof” infrastructure needed by wireless service providers as illustrated, for example, in BellSouth’s December 1995 Request for Information for the Software-Defined Radio [1]. The US Federal Aviation Administration (FAA) also requested industrial participation in inserting this technology into future avionics and ground based radio infrastructure [2]. Finally, a cross-section of over 100 government and commercial players created the MMITS Forum in March of 1996 to promulgate the benefits of open architecture plug-and-play software radio and digital communications to an expanding marketplace [3]. MMITS has included Alcatel (France), Ericsson (Sweden), Orange (UK), Samsung (Korea), Raphael (Israel). With so many players across the global landscape engaged in an emerging technology it is essential to first agree on a few definitions.

2. Software Radio Definitions

2.1 Functional Definition

The service providers - military, civilian and commercial - are most interested in the functional capabilities and cost of the software radio and less interested in the technical details. The functional definition of Table 1 captures the significant functional dimensions of the software radio. SPEAKeasy, the first widely published military software radio, demonstrated the functions shown in bold in the table [4, 5].

<table>
<thead>
<tr>
<th>General Properties</th>
<th>Universal air interfaces (source coding, channel coding, error control and protocols), regardless of multi-technology (FDMA, TDMA, CDMA or hybrids), multi-band and multi-standard environments.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Services*</td>
<td>Seamless internetworking of AM, FM, cellular (analog, TDMA, CDMA), PCS, mobile data and paging; <strong>seamless bridging of multiple bands and modes</strong></td>
</tr>
<tr>
<td>Standards*</td>
<td>HF ALE, VHF/UHF voice/data, privacy; GSM, PCS and Frequency Hop (FH).</td>
</tr>
<tr>
<td>Technical Flexibility*</td>
<td>Flexible RF, Channel, Time Slot, Power, Bit rate, Equalization, Channel Coding and Error Correction.</td>
</tr>
<tr>
<td>Supports Advances</td>
<td>Adaptive networks, <strong>transparent bridging</strong>, innovative signaling and improved quality. Over the air downloading of radio personalities</td>
</tr>
<tr>
<td>Growth Path</td>
<td>Velcro radio (multiple hardware personalities) -&gt; <strong>DSP-enabled radio</strong> -&gt; Multi-personality radio -&gt; Variable personality software radio.</td>
</tr>
</tbody>
</table>

Lists are illustrative, not exhaustive [SPEAKEasy Demonstrates the Capabilities Shown In Bold]
The software radio growth path envisions a shift from multiple chip sets, one for each air interface (the “velcro” radio) to the Digital Signal Processing (DSP) - enabled radio in the near term. DSP includes not just DSP chips such as Texas Instruments’ TMS320, but also Field Programmable Gate Arrays (FPGAs) and general purpose processors such as the INMOS Transputer and Intel’s Pentium/ MMX. Later, software alone will define the air interfaces dynamically over the air.

2.2 Architecture Definition

The architecture of the software radio is described in detail elsewhere [6, 7]. Fundamental to the definition of the software radio is the use of wideband ADCs, DACs and high performance DSPs to move the software-defined waveform from baseband to Intermediate Frequencies (IF) or Radio Frequencies (RF). The other fundamental concept is to host all the software (DSP and otherwise) on general purpose programmable processors. All aspects of the air interface including the channel waveforms are thus defined in software and implemented in real time through isochronous software and/or firmware (versus dedicated digital hardware as in "digital" radios). These fundamentals cannot be achieved without wideband antennas, wideband RF amplifiers and RF distribution and (for now at least) wideband IF ADCs and DACs.

The software radio functional block diagram of Figure 1 shows how the wideband ADC provides simultaneous access to a large population of channels, e.g. for subscribers in Mobile Telephone Switching Office (MTSO), or Personal Communications System (PCS) base stations. Software-based isochronous signal streams support the air interface. The environment characterization near-real-time stream provides parallel access to all the channels, e.g.

1 The SPEAKeasy I military software radio, for example, used three antenna bands between 2 MHz and 2 GHz, approximately 2-30, 30-300 and 300-2000 MHz.

for adaptive channel assignment algorithms. Software radios also have a role in R&D where advanced services like joint source-channel coded variable data rate air interfaces are defined and targeted for software, firmware and hardware implementations via C and VHDL.

![Figure 1 Software Radio Architecture](image)

2.3 The Phase Space Definition

Digital radios and software radios may also be defined in the “phase space” of Figure 2. [Phase spaces are used by physicists to represent changes in the states of matter as a function of key external parameters like temperature and pressure; we borrow the terminology to reflect the states of radio devices with respect to the key parameters of maximum frequency accessed digitally and degree of programmability.] The “ideal” software radio accesses RF directly via super-wideband ADC/DACs and accomplishes all processing using general purpose computer chips (see the circle marked X in the upper right corner of the figure).
Figure 2 Software Radio Phase Space

Such software radios cannot be built economically yet, but they represent a migration goal for contemporary hybrid digital/software radios. The pure digital radio, on the other hand, accomplishes most functions in Applications-Specific Integrated Circuits (ASICs) (circle C in the figure). The software radio maximizes flexibility and therefore truly future-proofs the infrastructure against new standards. The digital radio, conversely, maximizes hardware efficiency and therefore minimizes the size, weight and battery drain critical for handset applications.

Neither approach is a panacea: the key question is the degree of programmability required for the intended market. Contemporary radio designs therefore vary across the dotted line in the phase space that represents the technology frontier, comprising a mix of ASIC, FPGA, DSP and general purpose processors using ADCs and DACs at baseband or IF. Aggressive designs move above and to the right of this line, while conservative designs remain lower and to the left. Advancing microelectronics technology moves all implementations upward and to the right over time.

Handsets favor ASICs and/or FPGAs with chip level integration. Emerging cellular base stations, on the other hand, favor larger granularity hardware modules. Some use block up and down conversion with 12.5 to 25 MHz bandwidth ADCs/DACs (30 to 70 M samples per second) to accommodate 100-plus subscribers. This software radio approach reduces the hardware complexity of a cell site from several racks of discrete single-channel radios to one or two shelves of open architecture PCI, VME or other low cost DSP hardware. Military radio and avionics requirements fall between handsets and base stations. Typically two dozen channel waveforms ("modes") are needed from HF to SHF for interoperability, but no more than a half dozen modes are in use at any one time per platform (e.g. tank, aircraft, etc.).

2.4 The Vector Space Definition

Two years ago, nobody had a “software radio” and now almost every radio vendor on the planet claims to have one. This confuses customers, program managers and investors. We may clarify things somewhat by defining the degree to which a product meets four key technical and economic criteria that bridge the gap from applications to key technologies. The criteria are:

1. The number of air interface channels simultaneously supported (N),
2. Programmable Digital Access (PDA),
3. Hardware Modularity (HM), and
4. Software Flexibility and Affordability (SFA)

Table 2 defines these criteria. It is useful to group (N), the number of air interface channels, into four types: single channel; dual channel; multiple channel (i.e. less than 6); and full access (i.e. the full number of subscribers in an allocated RF band) to define four levels of N. Multiple channel nodes are typical of military, civil and law enforcement building blocks while the full multiple channel nodes are typical of cell site infrastructure.
Table 2 Definitions of Four Key Software Radio Dimensions (N, PDA, HM, SFA)

<table>
<thead>
<tr>
<th>N: Number of Channels</th>
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<tbody>
<tr>
<td>n: 1, 2 or a few (&lt;6) simultaneous air interface channels;</td>
</tr>
<tr>
<td>NN: The full number of subscribers in the RF band.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PDA: Programmable Digital Access:</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (0), Baseband (1), IF (2), RF (3);</td>
</tr>
<tr>
<td><em>Baseband</em> bandwidth is defined by single subscriber service (e.g. voice, data modem, video)</td>
</tr>
<tr>
<td><em>IF</em> is defined as that bandwidth which simultaneously supports all NN subscribers in the allocated RF service band (e.g. 12.5 MHz analog FDMA)</td>
</tr>
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<table>
<thead>
<tr>
<th>HM: Hardware Modularity:</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (0), Receiver/Exciter/INFOSEC/Network Modules (1), COTS DSP Modules (2), Second Level Modules (ADCs, FPGAs, Receiver Chips, etc.) (3);</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SFA: Software Flexibility and Affordability:</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Air-interface-defining software (0), Single-supplier software (1), Multiple supplier but single host platform (2), Multiple supplier multi-platform software (3).</td>
</tr>
</tbody>
</table>

The level of Programmable Digital Access (PDA) is the level of the conversion to digital at which the radio is functionally programmable in the software radio phase space. The types are: none (totally analog or fixed function digital radio); baseband programmability; IF programmability; and RF programmability. A Joint Tactical Information Distribution System (JTIDS) that hops over 250 MHz but that cannot be programmed for any other waveform may have a wideband digital IF, but it would not have a *programmable digital access at IF*, which is the criteria specified in this definition.

The Hardware Modularity (HM) indicator recognizes the differences in upgrade path between relatively coarse grain (possibly programmable) modules such as receivers and exciters; other types of coarse grain modules (e.g. COTS ADC and DSP boards); and finer grain modules such as FPGA, ADC and DSP chips. The hardware modularity value is not prejudicial: in many applications it is preferable for line replaceable modules to be electronically self-contained, a key feature of type 1 HM. The key is to explicitly decide what type of modularity is called for by the life cycle of the application and to match that type in the implementation. HM types 1-3 are therefore equivalent in the sense one cannot say a-priori that one approach is preferred over another; it is the match to the modularity needs of the application (e.g. maintenance strategy) that determines value in this dimension.

The Software Modularity (SFA) dimension characterizes the service provider’s ability to buy plug and play software modules based on the vitality of the marketplace. Software that runs on just one platform and is available from only the original manufacturer tends to box the service provider into single-source (sometimes very expensive) maintenance. If the functionality of the unit will not change over its life cycle, then this may be a perfectly acceptable path. This would be a rare occurrence in today’s fast changing marketplace. When radio software is available from multiple suppliers, such as with the Texas Instruments DSP Cooperative, costs tend to be lower and there are generally software alternatives to the original supplier should they become necessary. Software that runs on many platforms (e.g. JAVA) and is available from multiple vendors generally gives the service provider a better software product with more flexibility and at a lower cost over the life cycle than the alternatives. These cost/benefit rules of thumb provide useful quantization of the software dimension, but
are only a general guide, not an indictment of single-vendor software.

It is convenient to think of each of these four criteria as a dimension in a feature space, yielding a characteristic vector for a given radio (software or not) as:

\[(N, DA, HM, SFA)\]

Each element varies between 0 and 3 per the assigned type, so the vectors range from \((0000)\), the unprogrammable analog radio to \((3333)\), the totally programmable software radio. Since there are four levels of capability for each of these four features, there are a total of 256 points in this feature space. It is instructive to see how these points cluster in practice.

### 2.5 Software Radio Capability Levels

The clusters of software radio feature vectors consist of the four aggregate “software radio capability levels” shown in Table 3. Radios at level zero have fixed functionality and cannot be programmed in the field. Level one radios have programmable digital basebands while level two radios have programmable digital IF access. Level three, programmable digital RF, is the ideal software radio which with today’s technology is unaffordable. But it defines the upper limit of the technology. Point X in the software radio phase space of Figure 2 corresponds to point \((3,3,3,3)\) in the feature space.

The aggregate software radio level of a product is not prejudicial. That is, level zero is not necessarily bad or low-technology. Level zero includes digital baseband dedicated function chip sets that can have very high levels of device technology (e.g. GSM handsets). For example, simple dual mode handsets need no air interface programmability, so dedicated non-programmable digital chips may be most cost effective (e.g. for GSM/CDMA handsets). They may match subscriber needs better than more programmable levels of technology.

But the aggregate software radio level does indicate the degree of programmability in the field. And this in turn is the primary determinant of “interoperability” for the military and of “future-proof” qualities for the commercial sector.

<table>
<thead>
<tr>
<th>Software Radio Level</th>
<th>Characteristics [Examples with level rating (N, PDA, HM, SFA)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Fixed Functionality</td>
<td>Analog Radios [Walkie Talkie (1,0,0,0), FM FDM (NN,0,0,0)] Digital Readout [Pager (1,1,0,0) Direct Conversion Handset (1,1,0,0)]</td>
</tr>
</tbody>
</table>
| One Programmable Digital (Baseband) Radios | “Narrowband” reprogrammable, modular (*,1,>0,>0)  
[Contemporary programmable digital radios  
Closed architecture (1-n,1,0,1), modular (1-n,1,1,1)  
“Open Architecture “ (1-n,1,2,1-2), Goal (1-n,1,1-3,3)] |
| Two Programmable Digital-IF Radios | “Narrowband” programmable, some wideband hardware (*,2,>0,>0)  
[SPEAKeasy Class (1-n,2,2/3,1 or 2?)  
A Few New Cell Site Products (NN,2,1/2,1)] |
| Three The Software Radio   | Programmable Digital RF [“Ideal” Software Radio (NN,3,1-3,3)]  
- Not affordable yet, but useful as a migration challenge |
Most contemporary programmable digital radios meet level one criteria, with narrowband programmability through baseband digital signal processing and internetworking software. Using the software radio feature vectors, it is easy to see the differences among level one implementations with closed architectures and no real hardware modularity or growth path (1-n,1,0,1), modular hardware (1-n,1,1,1), some degree of modular hardware and software for nominally “open architecture” (1-n,1,2,1-2); and the highly modular, widely supported open architecture goal (1-n,1,1-3,3).

In general, contemporary programmable digital radios achieve aggregate level one of software radio technology with varying degrees of modularity. Most seek to achieve level two in the near to mid-term. The US SPEAKEasy program, for example, reaches toward level two, programmable digital IF, with medium bandwidth ADCs and DACs as do a few emerging cell site, wireless PABX and wireless local loop products. But the need for simultaneous channels and flexibility in the field provided by software radio technology must be balanced against other competing demands of the market segment as illustrated in Figure 3.

### 3 Key Challenges

In order to move as an industry from level one to level two of software radio flexibility and affordability, we need higher quality RF access and better partitioning of the systems and software for modular plug-and-play services and support as highlighted in Figure 4. None of these challenges has an easy, inexpensive and near-term solution, but all can certainly be addressed by the significant expertise represented at this workshop.

- **High Quality RF Access**
  - Increased Useful Wideband Dynamic Range with Improved Noise Immunity
  - Lower Cost of Broad RF Access
  - Reduced Cosite Interference
- **Partitioning for Plug-and-Play and Reuse**
  - MMITS “API” Approach
  - Real Time CORBA
  - Z.100 Communications Language

### Figure 4 Key Software Radio Challenges

#### 3.1 High Quality, Low Cost RF Access

Software radios depend on high quality low cost access to broad ranges of the RF spectrum. Although the ADC plays a key role, the useful dynamic range is defined by two-tone spurious-free dynamic range (SFDR) which is established by the multiplicative effects of RF conversion, ADC and subsequent digital filtering. As noise and interference from the environment aliases into the ADC passband, it reduces the sensitivity of the overall system. The key challenge in the short term is to reduce such noise and interference through technical advances in antennas, RF analog filters, ADCs and digital filters.

But the costs of RF access are driven by mechanical RF structures (antennas, waveguide, coax and other "plumbing") which are large and expensive because of the relatively large num-

### Figure 3 Market Segment Drivers

<table>
<thead>
<tr>
<th>Market Segment</th>
<th>Simultaneous Channels/Modes</th>
<th>Architecture Drivers</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handset</td>
<td>1-2+GPS</td>
<td>Mfg Volume “Velcro”</td>
<td>Chip Level Interfaces</td>
</tr>
<tr>
<td>Manpack/Avionics</td>
<td>4-20</td>
<td>Size, Weight, Power</td>
<td>PCI, PCMCIA</td>
</tr>
<tr>
<td>Law Enforcement</td>
<td>20-100+</td>
<td>Cost</td>
<td>?</td>
</tr>
<tr>
<td>PBX, WLL</td>
<td>20-100+</td>
<td>Call Quality</td>
<td>?</td>
</tr>
<tr>
<td>Base Station/ &amp; Mobile Bases</td>
<td>&gt;100</td>
<td>Future-Proof DSP Leverage</td>
<td>VME-like, Wideband Bus</td>
</tr>
</tbody>
</table>
ber of discrete parts and the high labor content of assembly and installation. The recurring costs of software radio nodes may include upwards of 60% for wideband antennas, RF distribution, RF conversion and IF processing but as little as 10% for Commercial Off The Shelf (COTS) DSP hardware. Clearly, as digital hardware moves towards the antenna, it brings the advantages of rapidly advancing microelectronics technology including reduced production costs. RF assemblies have been resistant to standards thrusts: there are standard RF packages, waveguide and connectors but many RF assemblies are virtually hand crafted on the production line. The matching of voltage standing wave ratios, trimming of capacitance, and other touch labor increases costs. The use of digital technology, on the other hand, reduces or eliminates most such manufacturing steps. Digital technology is also much more amenable to standards and economies of scale in manufacturing. The key challenge for the long term is to move more rapidly from analog to digital RF.

Finally, cosite interference is mostly our own fault. In the early days of radio, the size and expense of the radio equipment made frequency domain duplexing economically infeasible for most applications. As a result, military users have a legacy of Time Domain Duplexed (TDD) air interfaces in the VHF/ UHF “push to talk” bands. Civil applications such as air traffic control also employ TDD. And some newer standards such as DECT also employ TDD for low cost cordless telephony. As a result, any software radio that attempts to service all the users in a TDD band with a single (low cost) RF/IF/ADC channel has the problem of “screaming in its own ears” as multiple TDD signals are transmitted and received at the same time. There are few technical approaches to mitigate such interference, and mitigation beyond 20 to 30 dB requires a research breakthrough. On the other hand, the economics of the single ADC channel in the low cost cell site or radio access node are beginning to compete with the economics of the handset and could lead to a different balance. The key challenge is to dramatically reduce cosite interference in the near term through a spectrum use paradigm shift.

3.2 Plug-and-Play and Reuse

Plug-and-play radio would bring the benefits of the open architecture desktop to wireless applications. Reuse can be accomplished on at least two levels: software reuse and waveform reuse. Both plug-and-play and reuse depend on a workable partitioning of the software into modular functions with clearly defined and broadly accepted interfaces. The MMITS forum is pursuing a partitioning based on an Applications Programming Interface (API). The Object Management Group (OMG) recently requested proposals for real-time multimedia support for its Common Object Request Broker Architecture (CORBA)[8]. The now popular JAVA web language is actually a variant of the CORBA Interface Definition Language (IDL). Multimedia support should add isochronous channels to a growing repertoire of capabilities that bear on plug-and-play and reuse in software radios.

But CORBA IDL - real-time or not - has essentially no domain specific representation ability. This is both a strength and a weakness. The strength is that IDL applies almost anywhere. The weakness is that one must define one’s own domain representations. As a result, the representation of radio engineering interfaces among software objects such as state machines must be found elsewhere. The Z.100 Recommendations of the ITU-T [9] describe the Specification and Description Language (SDL) that provides a rich set of expressions of telecommunications behavior including call processing; maintenance and fault treatment; system control; data communications; and telecommunications services. The key challenge is the leveraging of broadly applicable standards and technologies for partitioning software such as CORBA with formal domain-specific represen-
tations such as Z.100 in an API such as that contemplated by the MMITS forum to meet the needs of the relatively constrained domain of the software radio.
4.0 Technology-Enabled Opportunities

These are significant challenges, but many have related enabling technologies to which we can look for continued progress through investments focused as suggested in Table 4.

Table 4 Enabling Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Representative COTS Performance</th>
<th>Investment Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiband Multibeam Antennas</td>
<td>Decade (e.g. 0.4 to 3 GHz)</td>
<td>Gain, physical size, alignment, cost</td>
</tr>
<tr>
<td>Wideband RF</td>
<td>Octave to decade</td>
<td>Mechanical tuning, power handling</td>
</tr>
<tr>
<td>Wideband ADC</td>
<td>70 MHz x 12 bits</td>
<td>Dynamic Range x Bandwidth</td>
</tr>
<tr>
<td>HTSC Filters and Amplifiers</td>
<td>30-40 dB More Out of Band Rejection</td>
<td>Product Integration</td>
</tr>
<tr>
<td>High Performance Interconnect</td>
<td>140 to 1000 Mbytes per second</td>
<td>Realized throughput</td>
</tr>
<tr>
<td>Digital Signal Processors</td>
<td>25 MFLOPS to 2000 MIPS</td>
<td>Throughput, power consumption</td>
</tr>
<tr>
<td>Real Time Object Software</td>
<td>COTS Radio / Telephony Functions</td>
<td>Quantified Real-Time Performance</td>
</tr>
<tr>
<td></td>
<td>Real Time CORBA for Multimedia</td>
<td>Object Oriented packages</td>
</tr>
<tr>
<td></td>
<td>ITU-T Z.100 SDL Products</td>
<td>Integration of APIs</td>
</tr>
</tbody>
</table>

4.1 Sensitivity and Dynamic Range

The Commercial Off The Shelf (COTS) multiband multibeam antennas, wideband RF and wideband ADC products of Table 4 may be enhanced for software radio applications through the technology investment focus areas shown. In addition, SPEAKeasy I used automatic gain control and “roofing filters” to suppress high power in-band artifacts to accommodate near-far power differences and to suppress cosite interference.

More significantly, High Temperature Super-Conductive (HTSC) filters now entering the market suppress adjacent channel noise and interference by 30 to 40 dB [10]. Otherwise, this interference would alias into a wideband programmable IF. Conductus, Inc. (Sunnyvale, CA) and Illinois Superconductor Corporation (Mt. Prospect, IL) are among several companies to offer HTSC filters and/or low noise amplifiers. In urban environments, the gain in SNR across the IF and the related opportunity to reduce infrastructure costs can be 30% or more.

4.2 Digital RF

In the Proceedings of the GaAs IC Symposium[11], Walden reported ADCs with 6 bits of resolution at 6 GHz, allowing one to sample a 2.5 GHz RF waveform above the Nyquist sampling criterion. The two tone spurious free dynamic range (SFDR) of this ADC may approach 30 dB, but GSM radio applications require 90 dB for near-far separation. This seems inadequate until oversampling is considered. The oversampling gain in dynamic range (DNR) is approximately the ratio of the sampling rate to the Nyquist rate as shown in Table 5.

A notional 25 MHz cell site frequency plan is recovered with 51 dB of dynamic range, and after additional frequency conversion and digital filtering, each subscriber’s 30 kHz signal is recovered with 80 dB of dynamic range. Vetterli has described projection filters that optimize dynamic range recovery [12], but the preservation of SFDR from GHz sampling rates to narrowband modulated channels has not yet been achieved in practice. Current research emphasizes higher speed and dynamic range ADCs and DACs [13] with the development of demultiplexers to reduce signal handling clock rates.
Table 5  Dynamic Range Improves With Oversampling

<table>
<thead>
<tr>
<th>(Over)Sampling Rate MHz</th>
<th>ADC’s SFDR</th>
<th>Cell Site Bandwidth MHz</th>
<th>Gain In DNR</th>
<th>Cell DNR</th>
<th>Subscriber Bandwidth kHz</th>
<th>Subscriber DNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>30</td>
<td>25</td>
<td>21</td>
<td>51</td>
<td>30</td>
<td>80</td>
</tr>
</tbody>
</table>

GHz ADCs and DACs should continue to emerge during the next five to ten years, ultimately leading to Digital RF with the benefits of digital fiber optic signal distribution, digital manufacturing, ease of installation and reduced maintenance. In the interim, the significant progress will be in relatively low power RF Integrated Circuits (RFICs) for handset and mobile applications. Subsequently, digital RF will bring the broader benefits of microelectronics technology another step towards the antennas of cell sites and large radio access points.

5.0 Plug-and-Play and Reuse

5.1 The MMITS API Concept

The MMITS Forum has begun to define open architecture standards for plug and play communications embracing digital and software radios. As a first step in this process, they deliberated several generic architectures (or reference models) for wireless “Information Transfer,” a refinement of which is shown in Figure 5.

The heavy lines in the figure represent Applications Program Interfaces (APIs) mediated by a common bus (e.g. the red or black bus). The dotted lines link successive levels of expansion of the hierarchical decomposition of the Information Transfer (IT) Thread. At the top level, the IT Thread consists of a front-end; an information security (INFOSEC) element; and a back-end for message processing (“inter-networking”), and input/output to user(s) and possibly to wireline interfaces. The functional interfaces at this level provide a reference model for building radio applications via a standard API.

At the next level of detail, (the abstract “module” level) there are additional API’s that map to software hosted on processors that communicate via a bus (or buses). These inter-
faces provide a starting point for API’s that are mapable to open architecture buses like VME and PCI and to low cost hardware/ software modules. A simple single mode handset like a police radio chip set may be configured from the IT thread by “nulling” some segments and modules such as signaling, bridging and routing. The refined module level of the IT Thread model (defined by the author) differentiates the IF Processing (IFP) and Baseband Processing (BBP) segments of the software radio and explicates the COTS digital receiver chip interfaces.

This is much more than a cosmetic change. IF processing now explicitly begins with a digital interface from a digital RF segment which may consist of an analog RF segment and associated ADCs and DACs. The modem functions are now explicitly baseband and the interfaces across these boundaries conform to commercially available parts. One may optionally aggregate the IFP and BBP in a single digital modem module. This refined reference model is also compatible with the insertion of two emerging technologies: Digital RF and Real Time Software Objects.

5.2 Real Time Software Objects

Non-recurring engineering often includes greater than 50% software development costs. The software is generally on the critical path with system integration and test as custom software, COTS hardware and operating systems and signal processing libraries are fused into a viable system. Object oriented languages and design have entered the mainstream of real-time applications [14,15], but the impact of Common Object Request Broker Architectures (CORBA and related standards[16]) has not yet reached the front end of the architecture. That is, a systems developer cannot yet substitute one RF modem software component for another without a relatively large amount of customized coding and system tuning. This is in part due to the lack of standard applications level software to software APIs and in part due to a lack of quantification of requirements for memory, buffer space and processing resources. It is difficult to tell if one can meet throughput, response time and other critical requirements when attempting to reuse code from one’s own libraries or from a third party. Quantified software objects specify applications layer interfaces and related memory and processing resource requirements for real-time performance. As such, they reduce the time required and risk of software reuse.

Isochronous and high speed message streams occur in IF, digital receiver and modem processing. These streams have in the past been implemented primarily in custom digital hardware. As we move to software radios, these streams are now carefully hand-crafted and tuned assembly language or microcode. Thus, these streams resist “plug and play” for the systems integrator. To bring open software architectures to the modem, we will have to apply CORBA technology to the isochronous stream.

CORBA was originally created so that dissimilar software packages could share applications data seamlessly. The object request broker (ORB) provides a kind of software bus. Through the use of an Interface Definition Language (of which the JAVA language is a subset), each software package is provided with a message passing interface to the ORB. Any package so interfaced can be plugged into any other such package. A quantified object uses CORBA interfaces for plug and play, but this does not guarantee performance. In fact, the CORBA overhead detracts from throughput and response time. So a quantified object is also characterized with respect to processing demand that must be supported for a given level of real-time performance plus data and program memory requirements.

5 Call for A Paradigm Shift

Cosite interference arises in large measure because of Time Domain Duplexing. The incremental cost of a Frequency Domain Duplexing
(FDD) appliqué’ for TDD radios has not yet been well characterized. Since dual mode handsets cost about 25% more than single mode handsets, it is unlikely that the FDD variant of a traditionally TDD radio would be much more expensive to produce.

But the difference in cost of the military radio access node will be the difference in cost between, say, 100 narrowband analog RF/IF and baseband channels on the one hand versus one wideband analog RF/IF channel with 100 digital receivers on the other. The military cannot pack even a half dozen TDD radios on a single vehicle due to cosite interference generated largely by TDD. It is possible to impose FDD in an RF band with a current TDD protocol by an FDD appliqué’. The FDD capable radios simply use the spectrum differently by exchanging channel use data on an agreed to signaling channel. As a result, dynamic frequency management and the FDD appliqué’ could bring the ability to pack many more subscribers into a single radio access point. And the software radio implementation would dramatically reduce the cost and improve the flexibility of that access point. Similar arguments may apply to an FDD appliqué in PCS applications of DECT. There are many issues to be addressed before such a concept could move forward; these remarks are offered to promote the necessary dialog.

6.0 Conclusions

As digital radios make the transition to software radios, industry strives for economic efficiency through the adoption of open architecture standards and through technology insertion. Workshops such as the first European Workshop on Software Radios certainly enhance that process through stimulating critical technical and business dialogs. By adopting standard terminology to describe different kinds of software radios, we can enhance our ability to communicate technically and with customers and investors. The software radio feature space is offered as an incremental contribution to the necessary definitions. And our frank discussion of the technical, business and regulatory challenges and opportunities provides the necessary foundation for the rapid emergence of software radio products and systems of the future.

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