Software Radios
Survey, Critical Evaluation and Future Directions

J. Mitola III, Chief Scientist, Electronic Systems
E-Systems, Melpar Division
11225 Waples Mill Road, Fairfax, VA 22030

Abstract

A software radio is a set of Digital Signal Processing (DSP) primitives, a meta-level system for combining the primitives into communications systems functions (transmitter, channel model, receiver...) and a set of target processors on which the software radio is hosted for real-time communications. Typical applications include speech/music, modems, packet radio, telemetry and High Definition Television. Low cost high performance DSP chips promote delivery of enhanced communications services as software radios. Time to incorporate a new service into a product is reduced dramatically using this approach. Low costs and new services will continue to increase demand for software radio tool sets and CAD environments.

This paper relates performance of enabling hardware technologies to software radio requirements, portending a decade of shift from hardware radios toward software intensive approaches. Such approaches require efficient use of computational resources through topological consistency of radio functions and host architectures. This leads to a layered topology oriented design approach encapsulated in a canonical Open Architecture Software Radio model. This model underscores challenges in simulation and computer aided design tools for radio engineering. It also provides a unified mathematical framework for quantitative analysis of algorithm structures, host architectures and system performance for radio engineering CAD environments of the 90's.

I. Introduction

An ideal software radio transceiver is illustrated in Figure 1. D/A and A/D converters at the transmit/ receive antenna and at handset allow all radio transmit, receive, signal generation, modulation/ demodulation, timing, control, coding and decoding functions to be performed in software.

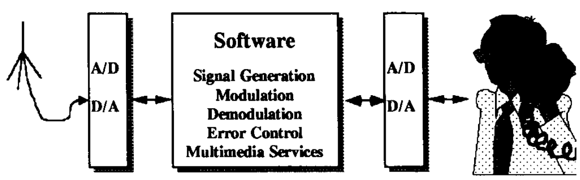

Figure 1, An Idealized Software Radio

This "software" radio of course includes many non DSP hardware components like RF conversion, RF distribution, anti-aliasing filters, power handling, etc. But the increased performance and continually dropping costs of the enabling technologies of A/D and D/A converters, high speed digital signal distribution, DSP chips and embedded computing are facilitating a shift toward software intensive approaches especially in large scale telesystems applications.

A. Software Radios Expand Multimedia Services

The ideal software radio interoperates with any communications service in its RF preselector band and A/D bandwidth. By running a different algorithm, the software radio instantly reconfigures itself to the appropriate signal format. This opens interesting possibilities for expanded radio services. A future software radio might autonomously select the best transmission mode (Personal Communication Network, Mobile Cellular Network, etc), send probing signals to establish a link, explore communications protocols with the remote end and adapt to the remote signal format. It could select the mode for lowest cost, service availability or best signal quality. The software radio reconfigures itself on the fly to support the required services.

This kind of flexibility opens opportunities for reduced costs and improved services for military as well as civilian applications. Prior generation military radios used single signal formats. Comms centers require different radios for different modes: SINGCARS for voice, TACFIRE for data, etc. Radios under development embed computing resources for a wider range of data formats. The Commanders' Tactical Terminal Hybrid (CTT-H), for example, will interoperate with several signal families in UHF, providing voice, data and imagery data relay [1]. CTT radios are multi-media capable today using a separate image compression unit. In the future image compression services may be embedded in a software radio service of CTT. Such software radio technology will also offer expanded services. Instead of calling target coordinates to a missile battery by voice, a future forward observer might uplink a video frame of the target from his night vision goggles to an airborne relay and thence to the terminal guidance of a missile. Later, he might send a battle damage assessment video frame to headquarters using the same airborne relay but a different protocol. Such advanced services require flexible signal generation, wideband Intermediate Frequency (IF) Analog to Digital (A/D) conversion, adaptive signal processing in the radio relay and data-driven routing.

B. Software Radio Telesystems Architecture

Such advanced services are on an evolutionary path which began in the early 1980's. The data links, mobile radios and LAN's of Figure 2 illustrate the system architecture of software radio oriented wide area telesystems.

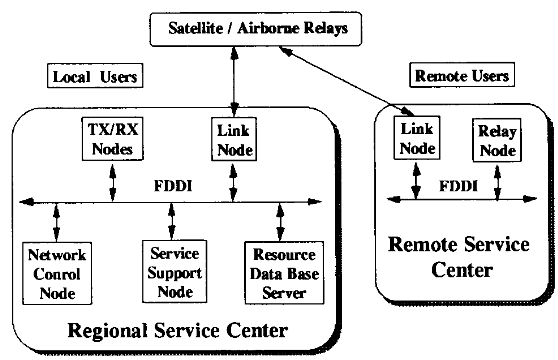

Figure 2 Telesystems Architecture

A regional service center provides central control while local service centers provide statistical multiplexing, bandwidth management and ancillary data. These telesystems have used message passing for distributed remote control since 1982. Layering and message passing have provided a robust, extensible applications architecture through several generations of hardware and operating systems. Figure 3 shows how telesystems connectivity services are layered according to the International Standards Organization/ Open Systems Interconnect (ISO/OSI) model (a) within a service center, (b) on line of sight radio data links and (c) on wide area remote satellite links. With this approach 44 thousand Lines of Code (KLOC) allocated to connectivity layers insulates over half a

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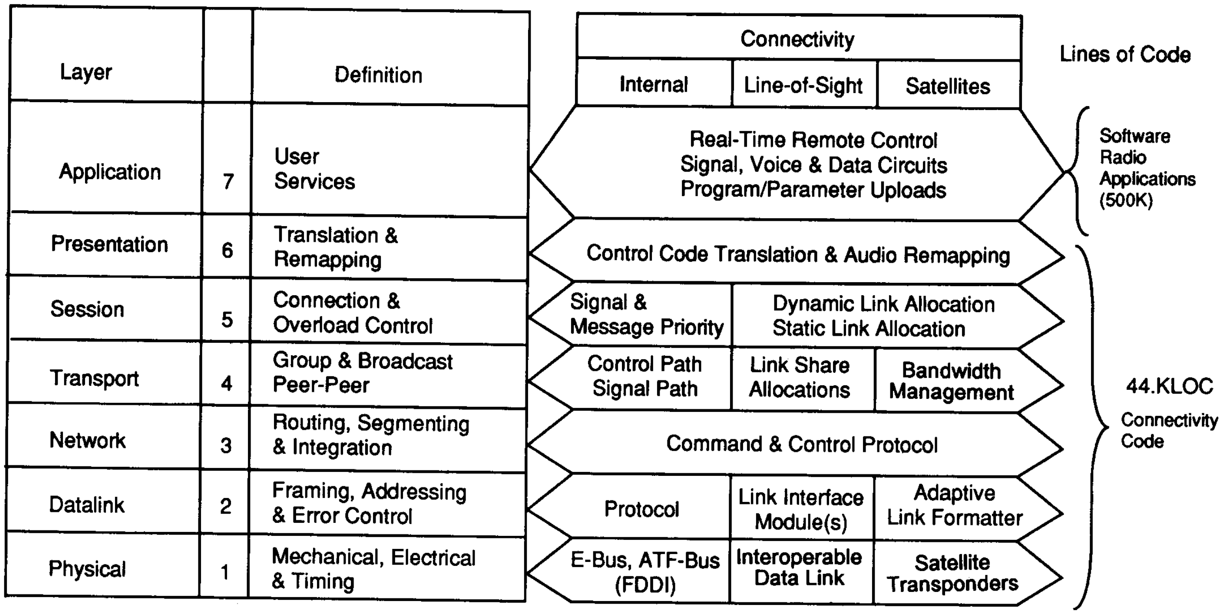

Figure 3. Layered Connectivity Architecture

million lines of software radio applications code from changes in the implementations. This open architecture now extends to server nodes based on the VME backplane (Figure 4).

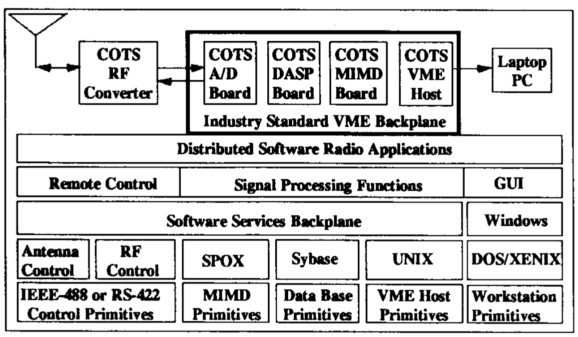

Figure 4 Open Architecture Node

The Digital Multimedia Workstation is a typical VME node [2]. It provides remote voice, video and data acquisition and control including full motion video and facsimile services. Earlier generations were limited to voice and data. But increased DSP processing capacities of Commercial Off The Shelf (COTS) boards have made it practical to integrate video, extending the ISO model to multimedia. Earlier systems also required dedicated PCM backbones for signal routing and separate audio intercoms. Current systems integrate these functions on a COTS FDDI network.

Each VME node has a signal flow architecture. But closer examination reveals the VME Open Architecture Myth. Although the multiple DSP boards conform to VME at the physical level, that is where open-ness ends. With no organizing paradigm at the applications layer, the integration of useful primitives like digital filters into radio systems is highly labor intensive. The system developer manually structures the data sets and signal and control flows. SPOX provides non-application specific support, but lacks a radio engineering paradigm for applications layer interoperability. The Software Services Backplane developed by E-Systems provides interoperability for signal processing data bases between VAX/VMS-ORACLE and Sun/UNIX-Sybase. But the Fast Fourier Transform (FFT) output from a DASP/ Fast Fourier Transform (FFT) board is not structured for the TMS320 MIMD board. If VME board and software vendors followed a common signal flow model, the open-ness of the VME architecture would begin to extend to software radio applications. The open architecture software radio offers insights into necessary applications layer interoperability.

The Celltap node [3] illustrates the reductions in product development time realized through software radios. This law enforcement node was conceived in 1990. An initial AMPS based product was delivered in a laptop computer with a COTS DSP board in 1991. Product extensions from AMPS to TACS to Nordic Mobile required only a few months of software development with a small Independent R&D staff. The product is a flexible receiver rather than a complete transceiver. This simplification contributed to product success as a "pure" software radio. Such software-only evolution of new communications services is possible if (1) New services are in the preselector RF band, (2) New instantaneous bandwidths are within the A/D - D/A bandwidths and (3) The new signal, data and service complexities are within the capacities of the embedded processing. Such software radio applications will grow as the enabling technologies increase in instantaneous bandwidth and capacity of embedded processing.

II Enabling Technologies

Technologies which support A/D, DSP/embedded computing and high speed digital interconnect define feasible applications and evolution paths for software radios.

A. A/D and D/A Conversion

Placement of the A/D converter in the software radio architecture drives sampling rate and dynamic range. Baseband A/D samples a single subscriber bandwidth exclusive of hopping or spreading. Agility band IF A/D samples the predetected, hopped or spread spectrum bandwidth. Wideband IF A/D samples the instantaneous bandwidth of a network of users. RF A/D samples filtered antenna signals without RF conversion. RF/IF-A/D needs greatest dynamic range because of the "near-far" situation in which strong nearby signals and weak distant signals must be processed by one A/D. Table 1 shows the relationship between potential software radio applications and representative A/D converter requirements. HF-IF requires large dynamic range due to propagation, fluctuating noise and small coherence bandwidth [4]. Dynamic range requirements diminish with increasing frequency [5] and increase for multiple users due to the near-far problem.

Table 1 A/D Conversion Requirements

Software Radio	Sampling Rate	Dynamic Range (dB)
HF Baseband	.5-8 kHz	24-64
Modems	8-32 kHz	48-64
Music	20-100 kHz	60-96
VHF-UHF BB	50-150 kHz	20-60
UHF-SHF FDM	.1-25 MHz	48-96
HF-IF	.2-10 MHz	72-120
Cellular Radio	.2-75 MHz	48-90
UHF Air Nav	2-25 MHz	48-90
SHF QAM	12-100 MHz	30-72
LVHF-IF (FH)	12-200 MHz	66-108
VHF/UHF-IF	25-500 MHz	60-96
HF RF	75 MHz	130
SHF CDMA	125-500 MHz	60-90
VHF RF	650 MHz	96
SHF Agility	.5-3 GHz	48-72
SHF-IF	1-8 GHz	48-90
UHF RF	5.4-10 GHz	48-90

Figure 5 shows dynamic range as a function of sampling rate for representative A/D converters. Phillips described a 650 MHz 7.8 bit A/D with input signal bandwidths up to 150 MHz [6]. A 1 GHz optical A/D with 1.8 bits of noise free dynamic range has been demonstrated [7]. The 8 GHz 8 bit converter goal was announced by DARPA [8]. Resolution in dB is not equal to linear dynamic range. Generally, A/D resolution is 3 to 6 dB greater than spurious free noise free linear dynamic range. For example, the Burr Brown 10 MHz 12 bit model ZPB1603 has a spurious free dynamic range of 72 dB, but a Signal to Noise Ratio of 67 dB [9].

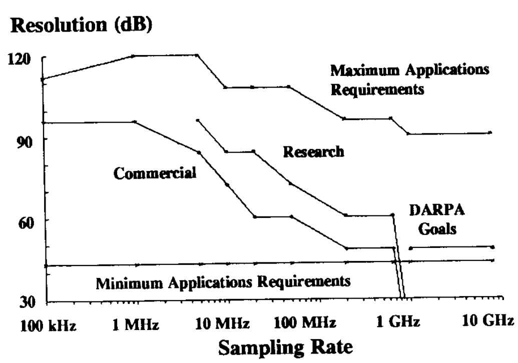

Figure 5. A/D Converter Products/Plans

Comparing A/D requirements to capabilities shows the feasibility of software radio applications in speech, IF and agility band VHF and UHF; and wideband applications of limited instantaneous dynamic range (e.g. microwave QAM with constellations < 64 and symbol rates < 30 MHz).

Critical Assessment: The noise free spurious free linear dynamic range of A/D converters is limited by aperture uncertainty and device noise of the sample and hold circuit. The aperture uncertainty tolerated by a B bit converter is approximated for a signal V(t)= A cos(wt), dV/dt= Aw sin(wt) and [dV/dt]*Dt = A/2**(B+1). Thus, aperture uncertainty Dt is approximately 1/(w*2**(B+1)).

Table 2 Aperture Uncertainty Requirements

f (MHz)	B (bits)	Dt
250	8	.64 ps
500	10	.16 ps
1000	12	20 fs

Aperture uncertainties increase linearly with frequency and exponentially with the number of bits (Table 2). Thus, an 8 GHz 8 bit converter requires aperture uncertainty < 100 fs. Hundred femtosecond stabilities have been reported in conjunction with optoelectronic RF sampling circuits with bandwidths of 275 GHz [10]. Thus an 8 GHz x 8 bit A/D is within reach in terms of aperture uncertainty. Conversion of the sample and hold signal depends on switching speeds. An electron-gas GaAs Schottky diode with 3 THz cutoff frequency has been reported [11].· Such switching device technology is sufficient to evolve toward 300 GHz A/D rates but aperture uncertainty requirements will limit dynamic range. There are many untapped software radio applications within this growing envelope of evolving A/D technology.

Software radio algorithms extend the linear dynamic range of A/D devices. Oversampling with interpolation extends effective SNR and linear dynamic range. Thao and Vetterli [12] reported an optimal 4th order projection filter which improves SNR by 80 dB vs 12 db from oversampling. This extends the theory of reconstruction of signals from level crossings [13]. Such techniques are useful if the bandwidth allocation to a set of users is large but each user baseband is small. For example 200 cellular radio channels of 25 kHz occupy a 5 MHz IF requiring a 12.5 MHz sample rate which limits dynamic range to 60 dB. Using [12], each user's SNR may be improved by 38 dB to 98 dB. Such advanced algorithms improve overall software radio performance beyond the capabilities of the A/D devices at the expense of additional DSP capability.

B. Digital Signal Processing Hosts

DSP hosts embed software radio functions with the rough order of magnitude computational demands of Table 3.

Table 3 Illustrative Processing Demands

Radio Function	Bandwidth	Nominal MIPS/MFLOPS
T1 Modem	1.544 Mb/s	2/0
GSM Radio	60 MHz agility	5/5
Modem	9.6 kb/s	6/8
Adaptive Relay	25 MHz	5/750
HDTV	50 MHz	2000/500
SDH Equalizer	620 Mb/s	20,000

Processing demands shown in the table vary by up to three orders of magnitude. For example, the T1 multiplexer has been benchmarked for variations of language, programming style and host hardware (Table 4). Ada packages promote software reuse but are inefficient with subroutine calls in the inner multiplexing loop. In-line Ada improves throughput, but in-line C and hand coded assembler provide the best throughput margins. Nominal processing requirements of Table 3 may be compared to processing capacities of chip-sets, multi processors and dedicated hardware of Table 5. SPECMark, Linpack, DRHYSTONE and other instruction mix benchmarks are more representative than peak performance but are not always available.

Critical Assessment: With careful interpretation, peak capacity is adequate for rough order of magnitude analyses. Processing efficiency is the ratio of peak capacity to achieved performance. Efficiencies of 80% are rare. Efficiencies less than 100% occur because of (1) inadequate interconnect bandwidth, (2) inability of an algorithm to access available capacity and (3) statistical

Table 5 Nominal Processing Capacities

Technology	Device	Parallelism General/DSP	MIPS/MFLOPS (Peak)
[14]IBM PC/AT	i80486	1/0	5/2
[15]DSP Chip	TMS320	0/1	25/50
[16]DSP Board	i960/i860	1/1	40/80
[17]DSP Chip	PA-RISC 7000	1/1	120/120*
[18]SIMD	AMT/DAP	1024/	20000x1/39
[19]MIMD	PC/MC860	1/4	5/320
[20]SuperCPU	Convex-210	1	200/200
[21]DSP Chip	Fujitsu VPU	0/1	70/289*
[22]SIMD	MASPAR	1/4096	6400/325
[23]SuperMIMD	CSP	1/4	36/600
[24]MIMD	GT860	1/8	10/640
[25]Hardware	G-FEC	N/A	1250
[26]MIMD	DSP-3	1/64	10/1280
[27]Super MIMD	Convex-3800	8	2000/2000
[28]DSP MIMD	VASP	1/16	5000/5000*
[29]Super MIMD	Cray YMP90	16	/16000*
[30]MIMD	Kendall	/1088	21760/43520*
[31]SPARC MIMD	TMI CM-5	16384	/128000*
[32]i860 MIMD	iParagon	4096	/327000*

* Announced but not yet delivered

patterns of demand. Interconnect includes all memory and system busses and interprocessor communications paths. Interconnect utilization is the ratio of interconnect demand to bandwidth. If this is < 0.1, the system is processor limited, but if it is > 0.6 on any path, the system is interconnect-limited. Software radios are reliable with interconnect utilizations < 0.5.

Table 4 Software T1 Multiplexors

Software Style	Host	MIPS per T1
Ada/Package	VAX	2000
Ada/Inline	VAX	200
Ada/Inline	Gould	40
C/Inline	Gould	8
Assembler	Gould	2

Efficiency also depends on the statistical pattern of service demand. Figure 6 shows how achieved software radio performance depends on aggregate demand on a typical MIMD host. A function which requires 280 msec to run to complete in a non-loaded environment requires over 700 msec during peak loads. The general shape of this curve is well approximated by a multiple server queue latency model [33]. As demand exceeds 60% of resources, service time grows exponentially. A robust software radio host therefore provides capacity in excess of the average loads by an amount predicted by queueing theory, typically 3 times the average demand.

To compare the nominal demands of software radio applications to the nominal peak capacities of hosts, one must account for interconnect utilization, algorithm partitioning to the host architecture, software implementation efficiency on each processor and statistical patterns of service demand. Generally an order of magnitude excess capacity is required to reliably support software radio functions. Thus, comparing Tables 3 and 5, software radio products for DS0 voice channel modems, T1 multiplexing and cellular radio appear within the capabilities of current hosts. High Definition TV research is conducted on Convex supercomputers and SIMD image processors with real time signal acquisition and non real time signal processing [34]. But wider bandwidth real time systems seem to be on the horizon due to the MIPS/MFLOPS of planned massively parallel systems. The pace of transition to massive parallelism and related software intensive approaches will be accelerated if the new supercomputing architectures provide the interconnect bandwidth required for software radio topological flexibility.

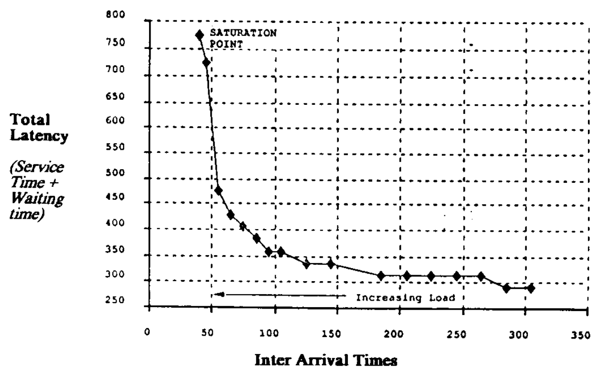

Figure 6 Performance Depends on Demand Patterns

C. Interconnect and Packaging Technology

The 1980's focused on increasing the capacities of DSP chips. Along with continued thrusts to improve chip capacities, there has been recent emphasis on integrating unpackaged die into Multi Chip Modules (MCM's). MCM's increase functionality per unit volume by replacing board level interconnect with substrate interconnect. The traditional board, backplane and system level interconnects persist, resulting in the interconnect hierarchy of Table 6.

Table 6 Simplified Interconnect Hierarchy

Level	Width	Layers	Clock Limits
Die	micron	3	GHz
MCM	50-10 um	4-10	500 MHz
Board	50 mil	5-15	100 MHz
Backplane	100 mil	N/A	20 MHz
FDDI	N/A	N/A	100 Mbit
HiPPi	N/A	N/A	800 Mbit
Fiber	N/A	N/A	2 Gigabit

Differences in speeds across the interconnect levels may be overcome through parallelism. The functional transparency desired for software radios requires ultra wideband N x N non-blocking switching among all levels of system interconnect. Massively parallel processors strive for flexible interconnect with desirable theoretical properties [35], functional transparency [36] and/or general malleability [37]. But physical limits to the interconnect technology are at hand. MCM line widths with 50 ohm resistance require thirty layers to interconnect a typical 4" MCM. Eden [38] has shown that when copper interconnects reach 1 um x .5 um the line resistance on a 4" MCM is 7000 ohms. Thus reduction of line widths to reduce the number of interconnect layers for large MCM's is impractical.

High Temperature Super Conductors reduce the 1 um line resistance to near zero, reducing the number of layers to 2. In addition, CMOS integrated circuits have a 2X speed improvement at HTSC temperatures. This technology is at the research stages, reaching demonstrations in 1994 [39]. Chip-to-chip integrated optical interconnect circuits have been studied with GHz bandwidths [40]. Free space or fiber optic paths could provide interconnect at the MCM and board level.

Critical Assessment: Although the focus on improved interconnect devices is important, little is known about interconnect topologies for software radios. A pyramidal architecture based on vision theory and algorithm structure has emerged for computer vision. But the topological structure of radios is not guided by a strong theory. Instead, it depends on bandwidths, signal complexity and service demands in an application dependent way. As the A/D converter moves inexorably from baseband towards RF, increasingly wideband front end interconnect is needed. If the interconnect bandwidth is three orders of magnitude faster than the signal flow, then the interconnect network is functionally transparent to the application [36]. Such transparency in future hardware architectures would help hosts provide the flexibility required for software radio service growth.

D. Technology and Applications Trends

Figure 7 illustrates communications technology trends relevant to software radios: analog instantaneous bandwidth in research environments, bandwidth of RF sampling circuits (e.g. in sampling oscilloscopes), equivalent bit rate of digital communications products, 8 bit commercial A/D rates, DSP chip capacities and massively parallel processing capacities. Fiber optics research achieves an order of magnitude more bandwidth than contemporary sampled RF circuits, while digital communications products lag by two orders of magnitude. Synchronous Digital Hierarchy (SDH) radio modems will reach 2.4 Gbit/sec this year. Signal complexities have increased to pack the higher bit rate signals more efficiently into limited bandwidth allocations. PSK has given way to 16 and 64 QAM for production radios, with successful research in 256 and 1024 QAM. Such signal complexities create demand for increased DSP capacities in ASICs, gate arrays and general purpose DSP chips. Gigabit FEC Codec chips and programmable 289 MFLOP DSP chips for HDTV receivers have been announced [41]. Such low cost high performance modules are ideal hosts for software radio functions. Increased demand thus fuels the device markets, creating continued investments in these enabling technologies. Software radios clearly ride this technology wave.

As the figure shows, during 1992 the enabling technologies will cross the frontier from baseband/ audio DSP applications to the IF/video range of software radio applications. Along this trend line even wideband SDH and HDTV products and systems will become software intensive soon. The communications industry is in transition from digital (hardware) radios to software intensive radio systems. The open architecture software radio provides a framework for capitalizing on the advantages of this trend.

III Computational Models and Architectures

The importance of topology in radio engineering is evident by examining signal flows, structure of algorithms and related systems architectures.

A. Computational Models Shape System Architectures

Software radios are beginning to embed extensive computational models to achieve high performance with a high degree of autonomy. Today's voice mail systems use dial tones for interactive control, but tomorrows will respond to spoken

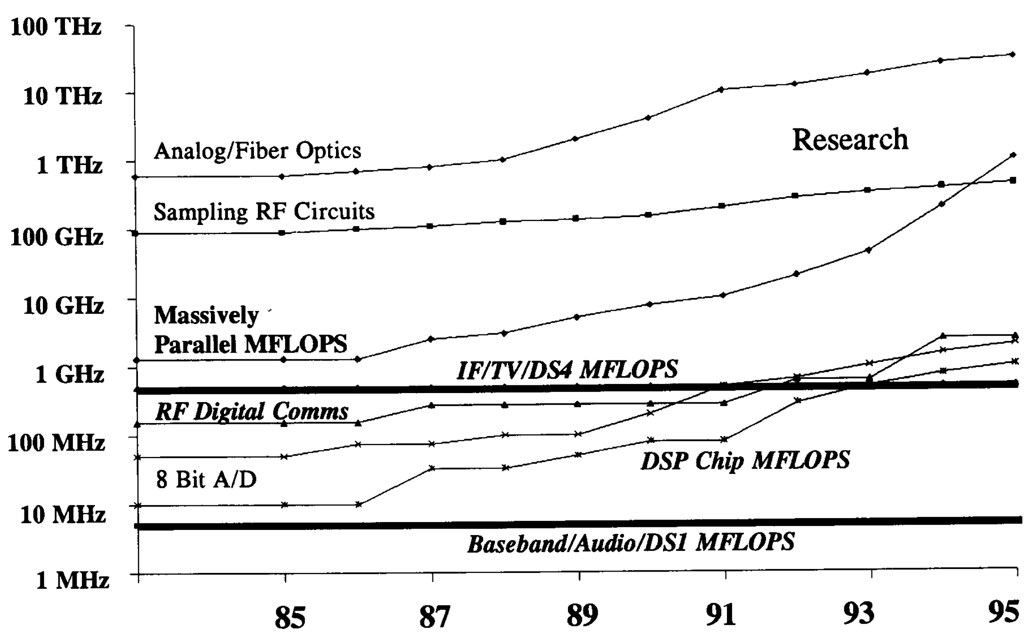

Figure 7 Enabling Technology Trends

commands. If DARPA's WHISPER program is successful, the necessary speech understanding technology will be available soon [42]. Hearsay and Harpy were exemplary speech understanding systems of the 1970's. Both embedded a priori characteristics of speech and language in computational models. Hearsay encapsulated information in Knowledge Sources (KS's). KS expert system rules, attached procedures and data transformed signal information on a global hierarchical Blackboard. Hearsay's high computational demands led to a coarse grain multiprocessors, C.mmp, with a Blackboard hosted on a global memory and KS's hosted on parallel processors, providing an isomorphism between algorithm and processor structures [43]. In software radios, SIMD architectures provide bulk signal processing (equalization, demultiplexing, FEC coding/decoding...). MIMD architectures provide multiple asynchronous channel processing. Neither SIMD nor MIMD architectures alone are adequate for large scale applications because the mix of signal flows mandates a mix of architectures as illustrated in Figure 8.

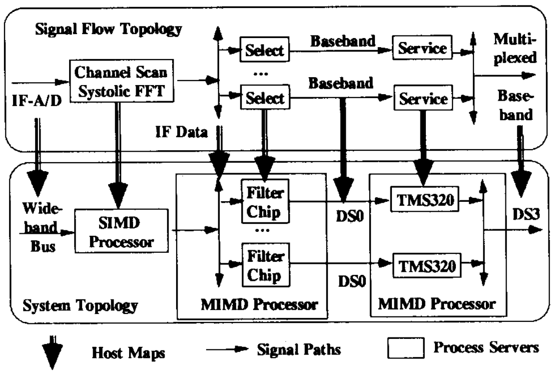

Figure 8 Effective Capacity Is High If Host System Topology Matches Radio Function Topology

The figure shows a data-driven radio relay signal flow mapped to a notional multiprocessor. The software radio algorithm topology is evident in signal flows among signal spaces (IF-A/D, Baseband, etc). Each radio function is a transform or map from one signal space to another. Signal streams partition radio functions naturally into functionally cohesive transforms coupled by signal streams. The multi user IF signal is hosted on a 200 MHz bus. The scan function is hosted in a systolic FFT processor. A DSP MCM hosts each subscriber's service algorithms. Each signal space and transformation in the signal flow is mapped 1:1 to a physical host which is compatible with the bandwidth or computational demands. Thus each signal space maps to a host interconnect and each function maps to a host processor providing high effective capacities. Study of topological structure therefore leads to a well balanced radio system design. Topologically efficient hosts for representative software radio functions are shown in Table 7. Large scale radio systems rely on such topological efficiency at all levels from chip to system.

Table 7 Topologically Efficient Hosts

Radio Function	Architecture Level	Host Topology
HDTV FEC Codec	Chip	Function Specific
FFT	MCM	Systolic [44]
Digital Filter	MCM	Serial MIMD
Switching	Board	SIMD
Equalizer	Board	Serial MIMD
FAX Modems	Board	Parallel MIMD
Bulk Modem	Chassis	Mixed MIMD
TX Control	Board	IEEE-488 Network
Voice Mail	System	FDDI Network

IV. The Software Radio Model

The need to efficiently map radio functions to hardware architectures led the author to apply the topological theory of algorithms [45] to radio engineering [46]. The resulting study of the set-theoretic topological properties of analog hardware radios, DSP algorithms and computational architectures provides organizing principles for telesystems design and insights relevant to future radio CAD environments. Signal processing theory, DSP algorithms, problem oriented languages and the hosting of algorithms onto DSP chips all share a common mathematical structure of mappings and operators on topological spaces. This section provides a brief overview of this approach to radio system engineering.

A. The Topological Model

A topological model of a software radio is a formal system {X, Y, P, H, M, F} (Figure 9). X is a space of radio system abstractions: infinite dimensional signal spaces, control spaces and transformations. X is organized by a radio engineering taxonomy consisting of information sources, transmission facilities, radio channels, reception facilities and information sinks. Y is a space of finite approximations to the signal and control spaces of X. P is a set of primitive maps from Y onto Y. P are the transforms and control algorithms of digital signal processing. H is a set of hosts for Y and P. H consists of physical channels, users, DSP chips, memories, etc from which one configures a radio system. M is a meta-level system for extending P and for mapping primitives in P onto hosts. F is a set of constraints among X, Y, P, M and H.

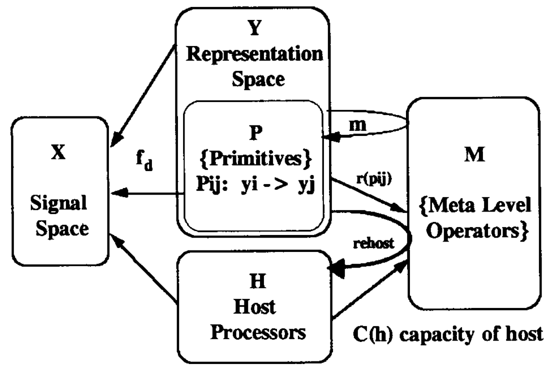

Figure 9 The Topological Model Unifies Concept, Design and Fabrication

A topological space is a set and a family of subsets with certain properties [47]. The theory of iterative algorithms induces topological spaces on subsets of X (e.g. random processes and decision parameters [48]). In {X,Y,F} for each y in Y there is an x in X such that y approximates x with acuity d and there is a map f_d in F which makes this relationship explicit. For example, an A/D stream y_k in Y could represent a band limited random process x_t in X. If y_k is a "good" approximation of x_t, there is an accuracy bound d such that $f_d(y_k)$, the set image of y_k in X, is "always within d of x". If x_t has bandwidth W and y_k is sampled at the Nyquist rate, then there exists d such that:

$\|[k+1]-[k]\| < d$ - the sample interval and (1)
$(2*W) < 1/d$ - the Nyquist rate. (2)

The map f_d: y->x maps subsets of y_k to corresponding subsets of xt according to Nyquist sampling and makes the Nyquist accuracy explicit. The distance d induces a topology of "open balls" for x_t. The map f_d is continuous, One To One and ONTO and the inverse image of open sets are open sets; so f_d is a homeomorphism, a topology preserving map [49].

B. Topological Constraints Encode Semantics

The creation of formal maps f_d and the proofs that "y approximates x with accuracy d" is the science of digital signal processing. Nyquist sampling is just one example of a theory which implicitly establishes such maps. The maps f_d are not DSP functions. They are the formal definitions by which the approximations of DSP are linked to the abstractions of communications theory. In the topological model, the constraint map f_d:Y->X expresses these relationships explicitly. Suppose, for example, p_{ij} is a digital filter. Domain $D(p_{ij}) = y_i$ is the filter input space. It includes an A/D converter stream with resolution and sampling rate and inherited information such as the original RF carrier. Control inputs like 3 db bandwidth W of the filter are also in y_i:

y_i = {Continuous Sampling;
RF = 240 MHz;
Rate =100 Ksa/sec;
Resolution = 8 bits;
W = 350 Hz;
Stream @ FIFO.1;}

The abstraction in X which yi represents is:

x_i = {Bandlimited Signal;
UHF Signal;
Nyquist Bandwidth = 50 kHz;
Nominal Dynamic Range = 48 db;
Information Bandwidth = 350 Hz;
Stream = 'From Antenna Element #1';}

The map f_i: y_i -> x_i establishes the semantic constraints of y_i , e.g. mapping the approximation "Continuous Sampling" to the abstraction "Bandlimited Signal", and so forth for all the corresponding entries in y_i and x_i above. All input and output spaces in a well formulated software radio system have such definitive maps whether expressed in documents, data bases or computational models. Expert system rules and attached procedures are computational models of such constraints as research in qualitative physics, for example, has shown [50]. A spreadsheet model of radar design used a rule base to encode such constraints [51]. In traditional development environments, the maps are expressed in documentation but seldom in computational models. In future CAD environments based on the software radio paradigm, such maps would be made explicit through topological constraint maps.

C. Topological Information Hiding

P is the set $\{p_{ij}\}$ of predefined primitive signal processing functions. In typical DSP design tools, 50 to 200 primitives are supplied. Any DSP function may be analyzed as a potential topological map. One first explicates the topology of the function's domain and range. From these topological spaces, one tests p_{ij} for homeomorphism by determining whether p_{ij} is continuous, 1:1, ONTO and has a set inverse. The analysis leads to refinement of $\{y_i, x_i, y_j, x_j\}$ and p_{ij} towards simple topological structures easily mapped to data structures, algorithms and host hardware.

The designer constructs radio functions from the primitive set through function composition. Composition provides a signal oriented model of information hiding. Suppose P = $\{p_{ij}, p_{jk}\}$. From p_{ij}: y_i->y_j and p_{jk}: y_j->y_k, the meta-level composition operator m in M yields:

$m(p_{ij}, p_{jk}) = p_{ik}$, where

p_{ik}: y_i-> y_k,

Domain, $D(p_{ik}) = D(p_{ij}) = y_i$

Range, $R(p_{ik}) = R(p_{jk}) = y_k$

but $R(p_{ij}) = D(p_{jk}) = y_j$ is *hidden*, embedded in p_{ik}.

The new primitive p_{ik} hides the embedded space y_j. The composition operator propagates constraints from y_i and p_{ik} onto the output space y_k. The information hiding of composition of primitives induces structure in software radios. As a primitive, the composite map p_{ik} is a virtual machine embedding lower level machines p_{ij} and p_{jk}. This virtual machine hierarchy extends from an initial set of primitives at the lowest level to complete software radios. These machines define a virtual machine hierarchy the key levels of which generalize the layers of the ISO/OSI model (Figure 10). The physical layer contains the host hardware. A host imbued with a software radio function is a hosted primitive. This corresponds to the ISO link layer because a the virtual machine map from y_i to y_j is analogous to a point to point link. The highest level is the Radio System, the Application Layer. Within each layer, composition of primitives and information spaces in Y define signal oriented information hiding. The layered virtual machine architecture isolates the software investments in the communications functions of layers 3 - 7 from the rapidly evolving implementation technology of the lower layers.

Layer	OSI	Radio	*Software Radio Virtual Machines*
7	Application	Radio System	User, Transmit, Channel, Receive, User
6	Presentation	Control	Communications Events and Controls
5	Session	Resource	Radio Functions Mapped to Hosts
4	Transport	Signal Flow	Signal Streams & Connectivity
3	Network	Function	Signal Scripts / Composition of Primitives
2	Link	Primitive	Lower Level DSP Primitives
1	Physical	ISA	Instruction Set Architectures & Hardware

Figure 10 Topological Virtual Machine Hierarchy

D. Host Models Facilitate System Design

The set H provides the physical hosts for the communications functions of P and for the interconnect spaces of Y. In the topological software radio, device properties are encapsulated in topological maps as in Table 8. Such maps are complete specifications of input, output, function, resources (supplied/demanded) and design constraints of the device. The widespread use of such formal computational models of radio system devices would make it easier to assess relationships between resource requirements of radio services and resource capabilities of potential system components. Electronic publication of such models would make it easier to find the right component for a given job.

E. Computability And The Meta-Level Model M

The set M contains meta-level operators m:P -> P by which to combine primitives to create new radio functions which themselves are primitives. The operators of M are sufficient for primitive recursion. Partial recursion is the most powerful computational model, equivalent to Turing Computability [52]. Partial recursion employs unbounded minimalization and is not guaranteed to terminate for all inputs. Total recursion is defined everywhere but may use unbounded resources. Primitive recursion uses the bounded resources of bounded minimalization. It allows iteration only over a bounded search space and returns the result "it can't be determined within these resources" if such is the case. Primitive recursion is defined for all inputs, even if the result is "out of resources". This computational model is compatible with a central design issue in software radios: fixed real-time computational resources.

M includes structured control primitives IF-THEN, DO-WHILE, etc. with system upper bounds on resources. M

Table 8. A/D Converter Topological Resource Map

```
Resource h: yi -> yj:
        {hij=pij: A/D Converter;
        Sample Rate = 750 kHz;
        Resolution = 8 bits;
        Dynamic Range = ?;
        Size = 3 x 5 x 2 in;
        Weight = 11 oz;
        Power max = 100 mW;
        Temp-Low = 0 C;
        Temp-Hi = 27 C;
        Shock = 'Office;
        Vibration = 'Office;
        Board-cost = $500 US;
        fi: yi -> xi:
                yi = {RF = ? MHz;
                        IF = ? MHz;
                        W < 350 kHz;
                        Analog Stream @ ?;};
                xi: {? RF Signal;
                        Predetected Signal;
                        Bandlimited signal;
                        Nyquist Bandwidth = 350 kHz
                        Analog BNC Connector Signal;};
        fj: yj -> xj:
                yj = {RF = ? MHz;
                        Continuous Sampling;
                        Rate =700 Ksa/sec;
                        Resolution = 8 bits;
                        W = 350 Hz;
                        Stream@ FIFO.?;};
                xj = {? RF Band;
                        Sampled Signal;
                         AT Bus Signal;
                        Band Limited Signal;}; }
        resource(h,*) = {Serves Analog-W = 350 kHz;
                        Demands Digital-W = 750 kB/s}
```

provides explicit composition through procedural languages. It also provides signal scripts in which a representation in X is interpreted by a script interpreter to create a sequence of primitives which will yield the desired signal. Script macros support interactive synthesis by analysis in which a signal processing procedure is the trace of user operations on a signal.

The formal system {X, Y, P, H, M, F} can be used in a system design paradigm to help a design team define a modular, extensible, computationally efficient radio system architecture. It can also be used this way to analyze an existing design. It may also provide some mathematical structure to guide the evolution of future radio CAD environments.

V. Future Radio Simulation and CAD Environments

Consider the process of designing and developing large scale software radio systems. The transitions from (1) service concept to (2) system definition to (3) simulation and validation to (4) delivery invariably require a mix of radio engineering disciplines. In one vision of the future, an ideal radio CAD environment would facilitate such transitions as suggested in Figure 11. In the software radio paradigm the environment would integrate systems analysis, software definition and system design disciplines. One technical basis for the integration of such disparate disciplines would be the consistent representation of algorithms, software components, existing chips, MCM's, boards, chassis and subsystems as maps among topological spaces. Thus a comprehensive computational model would be associated with each entity in the CAD environment. The CAD system would automatically hand off end item specifications to software, chip, MCM, and board level CAD tools from different vendors for detailed definition of components. As-built computational models (e.g. test results) of hardware and software would be integrated back into the larger CAD environment as items are designed and manufactured. Thus, difficulties in one area could be compensated by other areas early in the project (e.g. an A/D dynamic range limitation could be overcome by a more advanced filter algorithm using spare MFLOPS). These as-built computational models would persist, available for design analyses in future systems. Such environments could accelerate pace at which new services transition from the conceptual design and analysis stage into products.

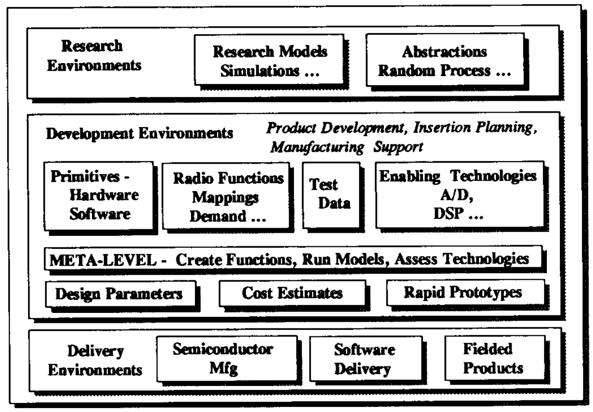

Figure 11 Future Radio CAD Environments

The applications scope of such an environment is shown in the radio system taxonomy of Figure 12. There is a tradeoff among (a) open architectures with large commercial bases, (b) high design coherence and (c) architecture efficiency with respect to the specific radio service requirements. Early software radios were designed and developed by an integrated team, were delivered on closed architecture hardware from a few vendors, had limited bandwidth and were relatively expensive. Yet the high design coherence of these systems contributed to the rapid and continued evolution of flexible services. These systems are in the field and their design coherence has supported more than a decade of product evolution including fairly radical hardware changes.

But recent projects which involved the use of commercial tools to the greatest extent possible underscored the lack of design coherence across tools from multiple vendors. While this is only natural, it is nevertheless an impediment to getting the most from the commercial base. Figure 12 also lists widely available tools related to radio system simulation and design. The marketplace is replete with general purpose hardware, software and simulation tools for signal processing. These tools are inadequate for large scale applications, lacking bandwidth and support for mixed MIMD/SIMD hosts. There are few widely available simulation tools which include communications specific functions. Computer aided design of the 80's provided hardware CAD tools for device designers and software CASE tools for software engineers. Extending these tools to the systems level and integrating them into networks of interoperable tool sets is the challenge of the 90's. Greater CAD focus on specific applications like radio engineering seems necessary to gaining the next plateau of enhanced productivity.

Considering radio systems and the rapidly evolving technologies from the perspective of the software radio is revealing. Reduced costs and increasing capacities of the enabling technologies are moving us rapidly towards software radios. Their reduced product cycles and software-only services create many opportunities and challenges. The topological model and resulting layered virtual machine model consitute an open architecture software radio model. When such models guide implementations, the investments in applications are insulated from the rapidly evolving host technology. The study of radio function and systems topology reveals unifying principles for better integrating the related hardware, software and systems engineering disciplines.

Radio System Taxonomy	Simulation & CAD Tools
System Level	
Structures	
Systems	-
Discrete Event Models	Many eg BONES[53]
Properties	
Information Capacities,...	-
Subsystems Level	
Users	
Sources...	-
Source Access (A/D...)	Many < 100 KHz
Transmission Facilities	
Source Coding - Audio	LPC Waves+[54]
- Video	Convex [55]
Bitstreams	
Error Control - BCH, RS	SPW [56]
Multiplexing	-
Channel Modulation	
Families - FM, QAM, PSK	SPW [56]
Structures	
Large Bandwidth	-
Large TW Product	MODAC [57]
Short Duration	-
Multiple Access	-
Timing Control	-
RF	-
Antennas	Ohio State [58]
Channels	
Models	Few e.g. SPW [56]
Noise Models	Few e.g. SPW [56]
Reception Facilities	
Channel Scanning	< 100 KHz
Demodulation	
Carrier Recovery	-
Timing Recovery	-
Analysis Facilities	
General	Many
Specialized	Few e.g.Elvira [59]
High Level Programming Facilities	
Signal Flow Languages	HyperSignal [60]
Script Interpreters	-
Targeting/ Rehosting Facilities (CAD)	
Hardware Description Languages	VHDL [56]
Microcode/PAL Downloading	SPROC, Xylinx[61]

Figure 12 Simulation and CAD Tools

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