Software Radio

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***Abstract*— This paper aims to provide an overview on rapidly growing technology in the radio domain which overcomes the drawbacks suffered by the conventional analog radio. This is the age of Software radio – the technology which tries to transform the hardware radio transceivers into smart programmable devices which can fit into various devices available in today's rapidly evolving wireless communication industry. This new technology has some or the entire physical layer functions software defined. All of the waveform processing, including the physical layer, of a wireless device moves into the software. An ideal Software Radio provides improved device flexibility, software portability, and reduced development costs. This paper tries to get into the details of all this. It takes one through a brief history of conventional radios, analyzes the drawbacks and then focuses on the Software radio in overcoming these short comings.**

I. History

Radio, as anyone would perceive, is a device that can wirelessly transmit or receive signals in the radio frequency (RF) part of the electromagnetic spectrum. J.C Maxwell postulated the theory of electromagnetic wave propagation which was confirmed by H Hertz. These electromagnetic waves travel through space either directly, or have their path altered by reflection, refraction or diffraction. When EM Waves come in contact with a conductor; they get converted to an electrical energy, radio or micro wave depending on its wavelength. Radio waves can carry information by varying a combination of the amplitude, frequency and phase of the wave within a frequency band. Nikola Tesla and Guglielmo Marconi invented devices that used radio waves for communication.

Earlier, radio systems relied entirely on the energy collected by an antenna to produce signals for the operator. Radios became more useful after the invention of electronic devices such as the vacuum tube and later the transistor, which made it possible to amplify weak signals.

Today most of our gadgets contain a radio system in it. From a cell phone to television , a walkie-talkie in a toy, space vehicles, cell phones or Satellite phones, Audio/Video broadcasting, Navigation Systems, RADAR and many other applications. Traditional Radios were built only for a particular frequency range, modulation type, and output power. "Figure 1. shows a typical traditional radio receiver.

The RF signal is converted to Intermediate Frequency (IF) using a programmable local oscillator. The IF signal is a fixed frequency and the IF signal is then amplified and filtered before feeding it to demodulator. Each kind of radio will have its own type of demodulator to extract the audio data for playing it on speaker. These radios would require hardware changes to modify these fundamental characteristics like frequency range, modulation type etc. Moreover, with the advancement of technology, new communication standards keep coming and are used to varied degree in different countries e.g. CDMA, GSM EDGE, 3G, etc. The Conventional radios cannot cope with these advances, due to compatibility issues. Hence, there was a need for dynamically configurable radios which could be used for various applications by simply re-configuring the software running in them. They can also be made to comply with the various communication standards, just by changing the implemented protocol. This is the world of Software Radio.

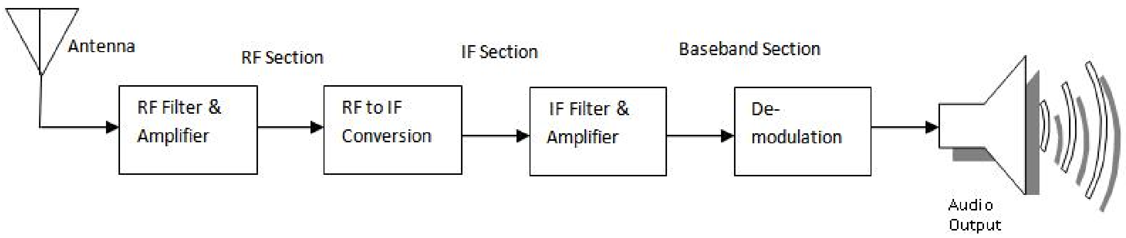

Figure 1. Block Diagram of a Traditional Radio Receiver

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II. What is a Software Radio?

Joe Mitola, who came up with the term Software Radio defines it as "A radio whose channel modulation waveforms are defined in software. That is, waveforms are generated as sampled digital signals, converted from digital to analog via a wideband DAC and then possibly up converted from IF to RF. The receiver, similarly, employs a wideband Analog to Digital Converter (ADC) that captures all of the channels of the software radio node. The receiver then extracts, down converts and demodulates the channel waveform using software on a general purpose processor." [2]

The software radio, by his definition, should have as little hardware as possible.

A Software Radio consists of a receiver and a transmitter. For the reception case as shown in "Figure 2. " [1], when the Antenna receives the signal, it passes the signal to the receiver section for filtering and separating the signal from noise and interference. The signal is then converted to a desired frequency and amplitude which is compatible with the analog to digital converter (ADC), and finally to digital data. The digitized data is then processed using digital signal processing techniques for further use.

For the transmission process as shown in "Figure 3. [1], the software programmable digital signal processing techniques are used for generating the modulated signal(s) in the digital domain. The digital samples are then converted to analog signal using Digital to Analog Converter (DAC) and then amplified to the appropriate voltage, current or power before transmission through the antenna.

III. Components of a Software Radio

Software Radio provides a flexible radio architecture that makes it re-programmable for different usages with no or minimal change in the hardware. This is supported by features like interference rejection techniques, encryption, voice recognition and compression, software-enabled power minimization and control, different addressing protocols and advanced error recovery schemes.

The technology provides the flexibility to combine different grades of hardware and software to strike the right balance between cost and network resilience. The reconfigurable blocks in Software Radio allows easy changes to the radio's fundamental characteristics such as modulation types, operating frequencies, bandwidth, multiple access schemes, source and channel encoding/decoding methods, frequency spreading/de-spreading techniques, and encryption/decryption algorithm.

The various components of a software radio are shown in "Figure 4. and described below:

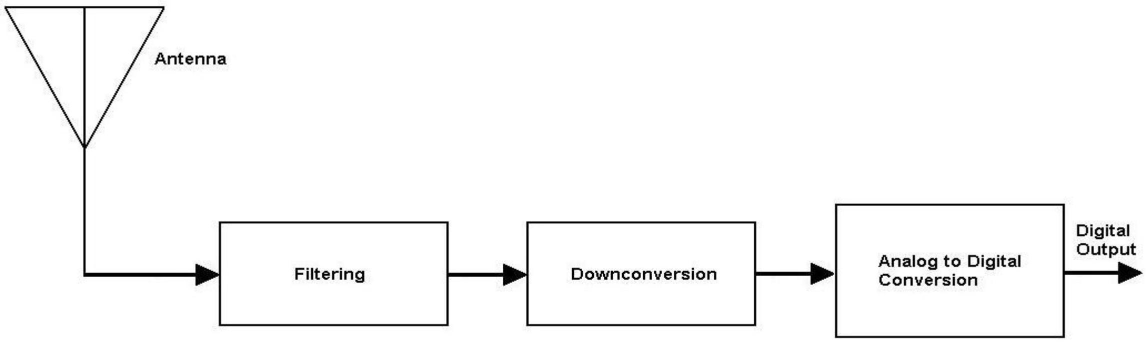

Figure 2. Radio Signal Reception Process

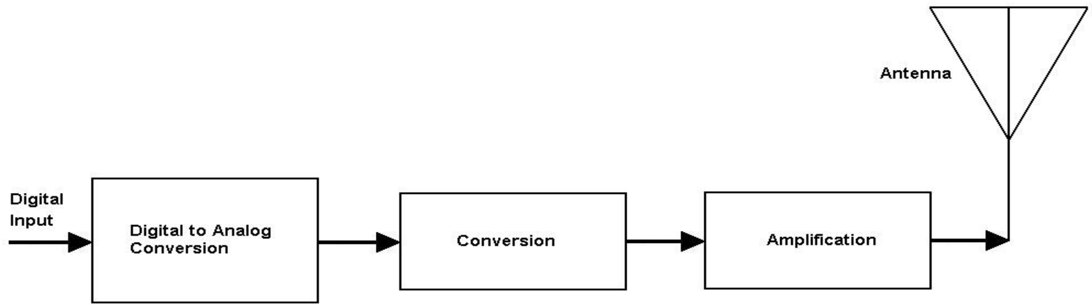

Figure 3. Radio Signal Transmission Process

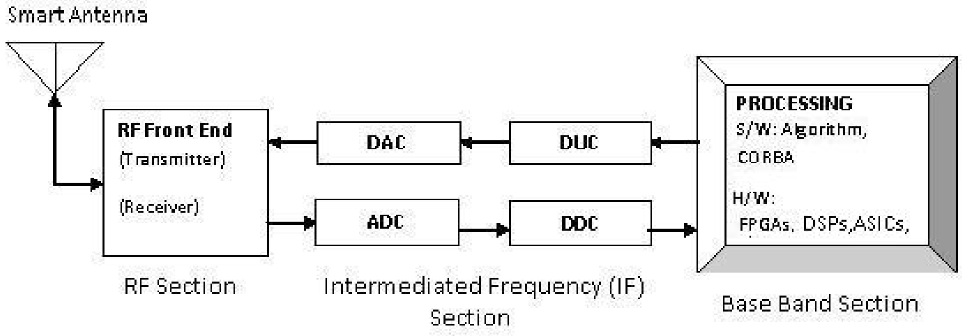

Figure 4. Block diagram of Software Radio

A. Smart Antenna

Antennas are conducting devices which transmit or receive electromagnetic radiations. An antenna array consists of distributed antenna elements whose outputs are combined and is a practical tool for enhancing wireless system performance. The choice of an antenna for a software radio is crucial as it is expected to support multiple bands [1].

It is an antenna array system with in-built signal processing “smart” algorithms to help adapt to different signal environments. It can also identify the direction of arrival of the signal; add phases to the signal to create a constructive radiation pattern to nullify interference. Smart antennas mitigate fading through diversity reception and beam-forming while minimizing interference through spatial filtering. Software radios provide the flexibility needed for effective smart antennas and smart antennas put help in effective implementation and utilization of software radio.

B. RF Front End

It appears before the Intermediate Frequency change state and after the signal is received from the antenna. It does the job of converting the incoming signal to IF frequency by using a tunable local oscillator.

RF front end design process for a software radio has the challenge of catering to a variety of waveforms with widely changing parameters such as amplitude, frequency, phase etc. Due to this wide spectrum, the presence of noise and interference is manifold. This makes the process of achieving a dynamic range even more difficult. The dynamic range is the measure of the highest and lowest level signals that can be simultaneously contained in a radio. In case of mobile communication, increase in dynamic range would mean more battery consumption, which becomes a major trade-off for mobile phones.

Low level signals suffer from the problem of noise. Noise enters at the bottom of dynamic range due to the thermal effects of the components, deviation in quantization or sampling aperture jitter in an ADC. High level signals are limited by interference. Interference is caused at the high end due to adjacent channel, co-channel or is self induced by transceiver. Traditional wireless communication receivers require single RF front end for each channel. Software radio, however, has only one wideband RF front end which can digitize desired signal into separated channels via software to provide a low cost solution.

C. Analog to Digital Conversion

Before all the processing can be done in the software, the analog signal received at IF stage needs to be converted to digital samples by use of Analog to Digital converter. Ideal Software Radio would require a wide bandwidth and good dynamic range from the ADC. As shown in “Figure 5. , the translation of the signal from analog to digital is performed via sampling and quantization. Sampling changes the signal that exists continuously in time to a signal that is non zero only at discrete intervals of time. Quantization changes the continuous valued signal to discrete valued signal.

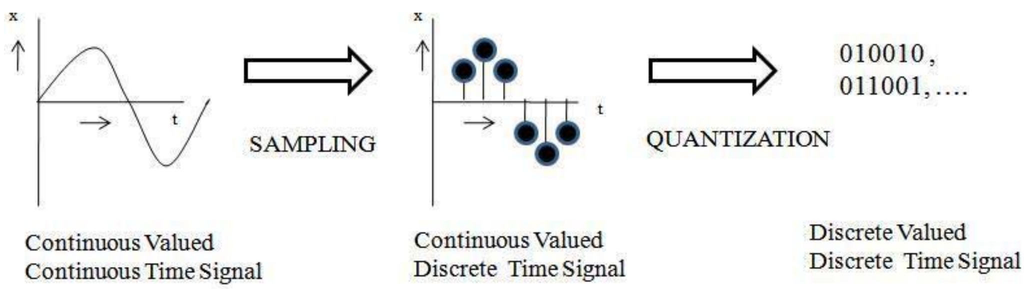

Figure 5. Analog to Digital Conversion

In an ideal software radio, Analog to Digital conversion should occur near the RF end. This would require the following criteria's to be met:

- A very high or variable sampling rate to support wide signals bandwidth.
- Greater number of quantization bits to support a high dynamic range.
- Operating bandwidth of several GHz to allow conversion of a signal over a wide range of frequencies.
- Lesser distortion and wide dynamic range to allow recovery of low level signals in the presence of strong interferers.
- Economical components to meet the above criteria's without consuming an excessive amount of power.

Due to the limitations of the fabrication technology, few of the above mentioned criteria's need to be traded off for an acceptable design solution for the software radio.

D. Digital to Analog Conversion

In Software Radio, entire waveform and modulation is generated in digital domain and is then fed to Digital to Analog Converter before final transmission. As shown in "Figure 6. , the translation of the signal from digital to analog is performed via voltage mapping and reconstruction, where the digital signal is changed to a continuous valued signal. The number of bits and the frequency range of the DAC are the important factors as they would determine the reconstruction of the continuous signal.

In a traditional analog radio, the frequency synthesis is performed via bulky devices like quartz crystal, inductor, capacitor, mechanical resonators etc. But different frequencies and waveforms can be generated in the digital domain by Direct Digital Synthesis (DDS) techniques and it is fast replacing the analog devices as they provide better accuracy, frequency can be changed with software and is simple to implement.

E. Digital Down Conversion

A digital down converter (DDC) provides the link between the analog RF front end and the digital baseband of a receiver. The received signal is usually sampled at much higher sampling rates than required to relax the specifications of the anti-aliasing filter required. But to reduce the computational power required from Digital Signal Processors (DSPs), the sampling rate is immediately reduced by down converter. DSP requirements are directly proportional to sampling rate and reducing sampling rates reduces CPU cycles required to perform the same digital signal processing algorithms and thus saving significantly on cost and DSP power consumption.

F. Digital Up Conversion

A digital up converter (DUC) provides the link between the digital base band and analog RF front end and is required on the transmitter end. The signal to be transmitted is generated by digital signal processing at lower sampling rates to reduce computations of DSP. But before it can be fed to DAC for converting to analog signal, it is up converted to higher sampling rate by Digital Up Converter to relax interpolation filter specifications.

G. Digital Signal Processing

DSP is the brain behind all digital radio technology. A DSP core consists of an arithmetic logic unit (ALU), accumulator(s), multiply and accumulate MAC unit(s), data and the address buses. A DSP is designed to support high performance, repetitive, numerically intensive tasks and very high I/O performance. Large accumulators in DSPs help reduce the precision problems. The digital signal processor performs all the functions of filtering, demodulating, generating the signal for transmission using various modulation techniques in software radio. DSPs also perform functions of data compression, encryption and special functions like speech recognition, image enhancement, neural networks for artificial intelligence etc. The three main categories of digital hardware are ASICs (Application Specific Integrated Circuit), FPGAs (Field Programmable Gate Array) and DSPs. A DSP represents the most generalized type of hardware that can be programmed repeatedly using high level programming language to perform various functions. An ASIC is the most specialized piece of hardware and can be used only in the specific application for which it has been designed. ASICs are generally used when DSP has insufficient processing power and function to be performed is fixed. The set-up of ASICs is implemented on fixed silicon, which optimizes the speed and power consumption of the circuit.

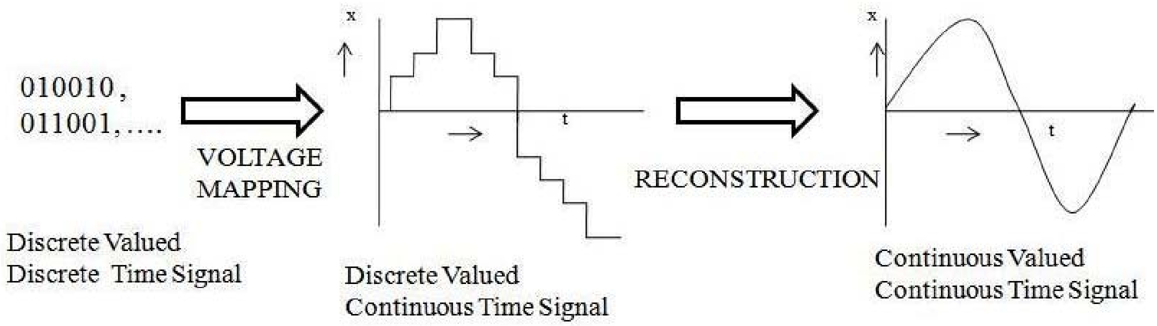

Figure 6. Digital to Analog Conversion

FPGAs help conserve silicon area since one chip can be configured to perform more than one function hence the configuration can be done at run time. Gate arrays offer higher degree of parallelism in comparison to DSP. A hardware description language (HDL) is used for designing highly complex circuitry. FPGAs are more flexible than ASICs but lesser than DSPs. FPGAs are being used because of their ability to perform high-speed parallel multiplication and accumulation functions and are especially well suited to handle algorithms like Finite Impulse Response (FIR) filters (for decimation or interpolation) and transforms like Fast Fourier Transformations (FFT) and Discrete Cosine Transforms (DCT). Also they have the advantage of providing flexibility to integrate logic design with signal processing. These three hardware components constitute a design space which trades flexibility, processing speed and power compensation.

In an ideal scenario, Digital signal processing (DSP) software should help to perform most of the radio functions at astonishing performance levels, enhance the performance using digital filtering and drastically reducing noise and interferences, all of it with less bulky equipments.

IV. Modulation and Demodulation

To understand the advantage and ease with which modulated signals can be generated and demodulation can be done in digital domain using digital signal processing, an example of **Amplitude Modulation** and **Demodulation** is discussed below.

A. Modulating the signal

The carrier signal as shown in "Figure 7. , can be generated using either DDS technique or using sine series library function. The modulating signal will be the output of microphone amplifier sampled at a particular rate by ADC. Here for illustration purposes, carrier frequency of 1000Hz and modulation signal of 20 Hz has been generated using the following equations with sampling rate of 10 KHz:

```
for ( i = 0; i < 1000, i++)
{
        Carrier = Sin(2 * PI * i * Fc / SR);
        ModS = 1 + Sin(2 * PI * i * Fm / SR);
}.
```
(1)

In (1) above,
SR is sampling Rate = 10KHz,
Fc = 1000Hz (Carrier),
Fm = 20Hz (Modulation signal).

Amplitude Modulation involves changing the amplitude of carrier as per the amplitude of the modulating signal. Since we have the samples of carrier and modulating signal in digital domain, the amplitude modulation in digital domain is simply multiplication of these samples. "**Error! Reference source not found.**", shows the generation of modulated signal.

ModSignal = Carrier * ModS. (2)

B. Demodulating the received signal

At the receiving end when this signal is received, it is full wave rectified which in digital domain is nothing but taking the absolute value of all the samples. "**Error! Reference source not found.** shows the output of full wave rectifier.

RectSignal = abs(ModSignal). (3)

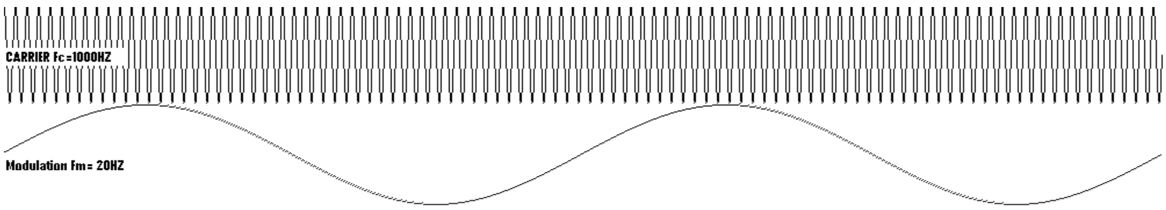

Figure 7. Generation of carrier and modulation signals

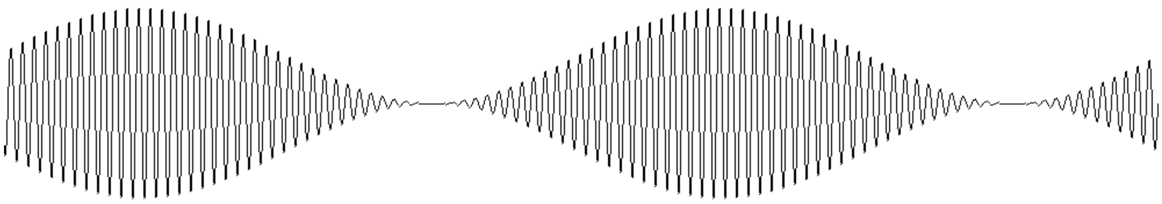

Figure 8. Amplitude modulated carrier

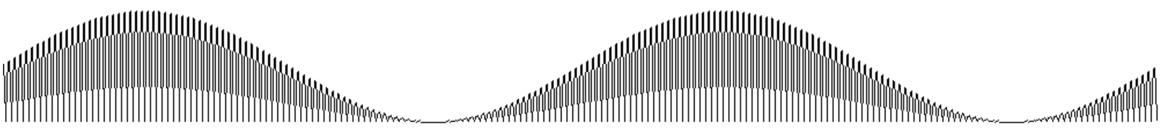

Figure 9. Full wave rectified AM waveform

Now the modulated signal is contained in the form of envelope of full wave rectified signal and can be recovered by applying a low pass filter to remove the carrier frequency. "**Error! Reference source not found.**shows the output of a first order Infinite Impulse Response (IIR) filter. The equation of filter used is:

$$Yn = 0.997*Yn\text{-}1 + 0.003*Xn. \quad (4)$$

In (4) above,
Xn is new input sample (RectSignal),
Yn-1 is previous output sample,
Yn is new output sample (demodulated signal).

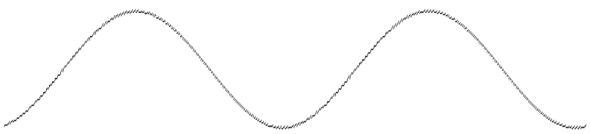

Figure 10. Demodulated signal after low pass filter

V. SOFTWARE RADIO AS A SOLUTION TO CONVENTIONAL ANALOG RADIOS

A Software Radio in contrast to a traditional Radio runs on a generic hardware platform to perform all the modulation/demodulation, frequency selection, filtering etc in digital domain as also explained above in the example. It can perform role of a cordless phone, cell phone, internet access tool, a GPS receiver etc. all in one. This is possible by changing the software used for processing. Hence, there is no limitation of any particular frequency range, modulation type, and output power in a Software Radio. All these flexibilities of software radio offer advantages which can be broadly classified as:

A. Frequency-Agile

The software programmable processing allows it to operate in the entire radio waves frequency bands.

B. Easy to plug n play

It is a radio into which multiple contractors could plug parts and software.

C. Global Mobility

It caters to the model as it is flexible to support most of the communications standards like CDMA, GSM, IS-136 etc.

D. Inter-operability

It can be made to inter-operate with different wireless protocols, incorporate new services, and upgrade to new standards etc by simply downloading a new program (or a newer version of the software) or by change of selection from the user interface.

E. Compact and Power Efficient

Due to reduced number of components used in Software Radio, its size is reduced resulting in ease of manufacturing. Also less hardware results in less power consumption.

F. Quality of Service

As Software Radio is Software dependent; hence a greater quality of service is delivered consistently.

VI. APPLICATIONS OF SOFTWARE RADIO

The ultimate goal of Software Radio is to provide a single radio trans-receiver which can play the roles of cordless telephone, cell phone, wireless fax, wireless e-mail system, pager, wireless videoconferencing unit, wireless Web browser, Global Positioning System (GPS) unit, and other functions still in the realm of science fiction, operable from any location on the surface of the earth, and perhaps in space as well. Few of the applications of software Radio has been covered henceforth and shows the variety of functionality to which it can cater to.

A. Pacemakers and Implantable Cardiac Defibrillators

Wirelessly reprogrammable and implantable medical devices (IMDs) such as pacemakers, implantable cardioverter defibrillators (ICDs), neurostimulators, and implantable drug pumps use embedded computers and radios to monitor chronic disorders and treat patients with automatic therapies. For instance, an ICD that senses a rapid heartbeat can administer an electrical shock also known as the software radio attacks to restore a normal heart rhythm, then later reports this event to a health care practitioner who uses a commercial device programmer with wireless capabilities to extract data from the ICD or modify its settings without surgery. Clinical trials have shown that these devices significantly improve survival rates in certain populations. [4]

B. Smart sensors

Software Radios can be implemented as smart sensors to determine the amount of various particles present in atmosphere, hence useful for pollution check, weather forecast etc. When used as Bio-sensor with configurable software, it can be used in study of complex anatomy.

C. One Cell phone for many standards

It is highly inconvenient for a regular inter country traveler to change his mobile connection for communication due to network issues. For example, 3GPP UMTS is popular in European nations, while C/TDMA standards are widely used across North and South America. So, every time one travels through a country he has to have the country specific cellular phone. But with the coming of Software radio, it can be a thing of past as the Software Radio can adapt to change in the local air interface by a simple software change. All the base stations and terminals using Software Radio architecture can support multiple air interfaces during periods of transition and be easily upgraded.

D. Cost Effective Up gradation of a Cellular Base Station

The growth in radio technology is in-step with the demand of today's customer, but is the business ready? The customer may have asked for audio files in his cellular services yesterday, but today they look for video streams in their phone and tomorrow they might ask for live data feed. The cellular industry cannot afford to lose business by not making such changes. Software Radio helps to save them millions by easy upgrades in software. There is no need for investment in the hardware, saving them both money and time. It is also a boon for customers as they don't need to purchase newer handsets for newer technology. Just as any individual or business can update a software program used on a PC, by using Software Radio technology, any cellular providers can upgrade software easily and quickly to make changes on their systems. As a result, the cost for cellular phone service can continue to be decreased for consumers; while the providers can see higher margins for the service they provide.

E. Usability in Emergency

As the software radio is compact and easily deployable, it can be useful for temporary coverage during emergencies and special events. A software radio can be programmed and mounted onto a vehicle and driven to the site of a natural disaster to bring in communications where they may have been damaged and to support multiple standards.

F. High Definition TV Applications

Software Radios are finding significant applications in the conversion of both analog and digital transmissions to HDTV, an upcoming broadcast technology.

VII. Challenges & Limitations

Software radio technology alters traditional radios in three ways namely moving A/D closer to antenna, substitute hardware with software processing and facilitating transition from dedicated to general-purpose hardware. This decreases the number of hardware components resulting in high degree of extensibility for a wide range of features. This will also eliminate the redundant hardware as found in dual band phones etc.

There are several technological challenges faced in Software Radio today, like the usage of faster A/D converters, requirement for less power consumption, implementing smart antennas and making the overall radio more cost effective. ADCs which can digitize the high range signal are very expensive. They also increase the level of SFDR (spurious free dynamic range). Hence, the signal received are down converted from RF signal and digitized at IF range via ADCs before sending the data to DSPs. To overcome this limitation, more research and development would be required to build less expensive ADCs covering more dynamic range and supporting greater sampling rates. For FPGAs, interval to reprogram FPGA's limits its usability.

The authenticity and security of downloaded software is another area of concern. There is a need for a globally recognized regulatory body which can control these processes. Certification from bodies like Federal Communications Commission (FCC) is another hurdle. FCC certification process presumes that any software that is bundled with the hardware be certified as a unit. But software radio being programmable at any time poses challenges in certification. A new certification procedure has been created. Software changes which can affect radio frequency, power and modulation are subject to more streamlined process. However, FCC does not certify any changes by third party software vendors. All modifications are the responsibility of the original manufacturer whose original hardware/software radio bundle was certified. This requires that all the independent vendors need to work via equipment manufacturers. Hence, certifying software radios pose a significant challenge because of cumbersome certification processes, especially for domains like aerospace and defense which require testing for all possible scenarios where software may misbehave.

VIII. Future of Software Radio

Ultimate aim of software radio would be to move ADC and DAC just next to Antenna and doing everything in software. Currently, the cost of high frequency ADCs and specialized hardware for digital signal processing are few of the factors limiting the application of software radios to high end use only. As the technology advances, the costs will come down and processing power of general purpose computing platforms will increase. Once the processing power crosses the threshold required for performing necessary radio functions, broader applications and scales of economy will come into place and we will see software radios being used in our day to day use gadgets. How soon it can happen is still an open question but software radio is likely to be an important technology in the years to come.

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