"COGNITIVE RADIO IN BATTLEFIELD COMMUNICATIONS"

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Statement

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BRIEF REVIEW OF ARO CENTER FOR BATTLEFIELD COMMUNICATIONS

ARO Program Objective

The Army Research funded this project to create a center for Battlefield capability enhancements to support Line of Sight/Beyond Line of Sight (LOS/BLOS) lethality research:

Design of a Battlefield Situational Awareness Network Architecture that enables robust and Quality of Service (QoS) assured multi-service applications with an ad hoc wireless network to support the LOS/BLOS Lethality capability.

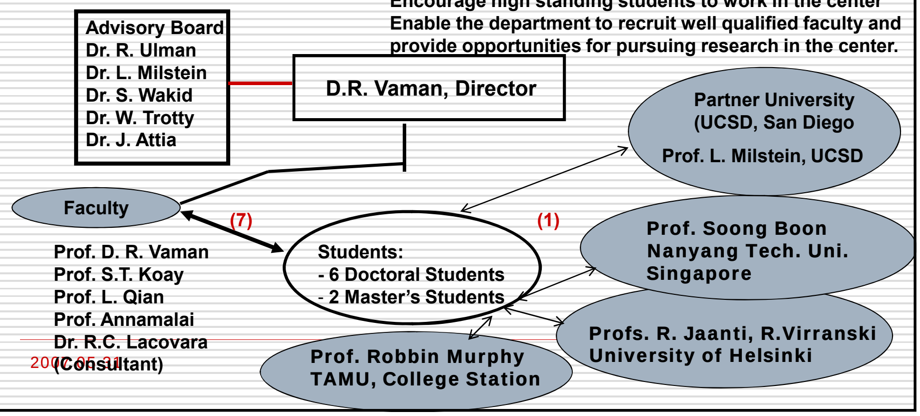
Design of multi-service applications support based on Internet Protocol (IP) based ad hoc wireless network transport while providing uninterrupted QoS assurance.

Design of distributed network management that uses very low bandwidth for management information transport, while allowing most of the network capacity to be used for end user multi-service applications.

About the ARO CeBCom

MISSION:
To Achieve National Excellence in Telecomm. Research, Techn. Transfer and Focused Education by collaborating with US DOD, Texas State and Industry.

GOAL:
Support US ARL in funded R&D.
Further R&D focus and Achieve Self-Sustenance in 5 years (ARO 2004 – 2011 funded; NSF 2009 – 2012 funded)
Evolve Graduate Programs to achieve national preeminence
Encourage high standing students to work in the center
Enable the department to recruit well qualified faculty and provide opportunities for pursuing research in the center.



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- Conclusions

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ABSTRACT

Lecture 1 covers the Introduction to Battlefield Communications Architecture of the future; Support of Multi-service Applications with Quality of Service Assurance; Identification of Time Critical and non-Time Critical Applications; Use of Mobile Ad Hoc Network (MANET) Architectures; and Challenges in Using MANET Architecture.

Lecture 2 covers the design of MANET Architecture and radios with spectral efficiency, bandwidth efficiency and power efficiency; and functional design of radios to support "automatic reconfiguration" for supporting interoperability with legacy radios; "dynamically changeable modulation" based on real time channel conditions to handle multi-path fading environment; and "use of cognitive radio principles to achieve spectral efficiency.

Lecture 3 covers introduction of "cognitive radio management design" using distributed management system that uses cross-layer controls. Both distributed management operations and cognitive radio management will be discussed.

Lecture 4 covers the design of cognitive radio based MANET and sensor networks and provide alternate solutions that allow each vendor implement the solution in their own native mode. A brief discussion of battlefield applications will also be presented.

Lecture 1: Overview of Battlefield Communications Architecture

Covers the Introduction to Battlefield Communications Architecture of the future; Support of Multi-service Applications with Quality of Service Assurance; Identification of Time Critical and non-Time Critical Applications; Use of Mobile Ad Hoc Network (MANET) Architectures; and Challenges in Using MANET Architecture.

Network Centric Warfare

Source:

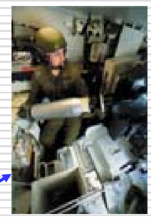
D.R. Vaman, "Work Complexity and Information Technology", **Key Note Speech, *The Eighth Annual Symposium on Human Interaction with Complex Systems (HICS 2008) – Second Topical Workshop on Sense Making,*** Norfolk, Virginia, April 3-4, 2008 [1]

Warfare History

High-Tech Army

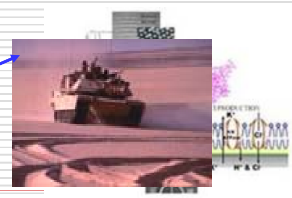
Robotic IED Detector

Highly Survivable Material for Future Warrior



Armored Vehicle

All Terrain Vehicle



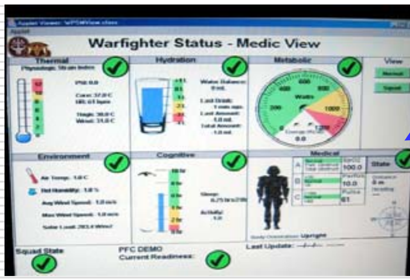
Future Warrior 2010 & 2020

Well Equipped

Future Warrior 2020

Future Warrior 2010

Situational Understanding of Future Warrior



This is a snapshot view of a computer screen future soldiers will see in a dropdown eyewear device attached to their helmets.

This particular screen view shows the physiological status of a given soldier.

A medic in the field can monitor another soldier's health status without physically seeing that particular soldier

Source: This was part of the Future Warrior exhibit for congressmen and their staff members to view on Soldier Modernization Day July 23 on Capitol Hill in Washington

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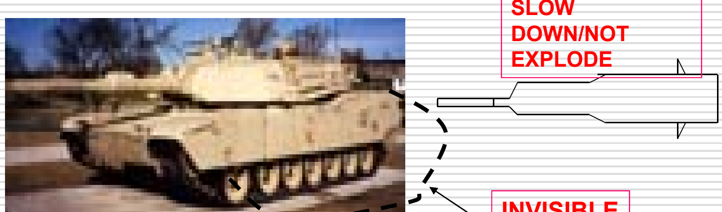
Armored Vehicle of the Future



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Today's Warrior Well Equipped with Network Centric Capability

Network Centric Battlefield

Tactical Operations

Communications and Remote Execution

Warrior Radios

Software Defined Radios with Great Flexibility and Dense Information

Information Dissemination of Actionable Sensor Information to Warrior Radios and Other Electronic Devices

Secure and Real time

Line of Sight and Beyond Line of Sight (LOS/BLOS) Lethality

Protect Warriors

"Fully Automated Battlefield Needs Constant Evolution to Maintain Preeminence"

Mobile Ad Hoc Network (MANET) and Sensor Networks

Under C4ISR – Sensor Networks and MANETs are deployable to provide:

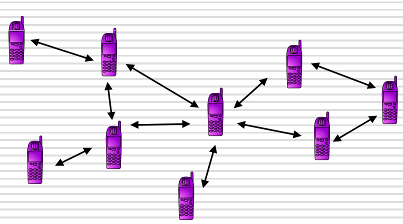
❖ Current, Accurate and Actionable Information for War Fighters from distributed SDRs and Unattended Ground Sensors and possibly Aerial Sensors.

❖ Data Fusion Centers are a reality to collect and integrate various information to form "*Actionable Information*" for Combat Lethality that supports:

- NLOS Launch Systems
- Dismounted Soldiers

❖ For Tactical needs, use of mixed MANET and Sensor Networks are also possible so that isolated dismounted soldier can be supported by sensor networks if MANET is not available.

MANET AND ITS FEATURE REQUIREMENTS



MANET

Both Battlefield and Emergency Disaster Management Applications Exploit Novel Solutions

1. Multi-hop Communications
2. Multi-service Provisioning
3. Quality of Service Assurance
4. Radio Power Efficiency
5. Network Bandwidth Efficiency
6. High Mobility
7. Process Efficient Distributed Management
8. Support Time Critical and Mission Critical Applications
9. Remote Situational Awareness Concept
10. Protect the Identity of the Node and Check for Malicious Node in the Path

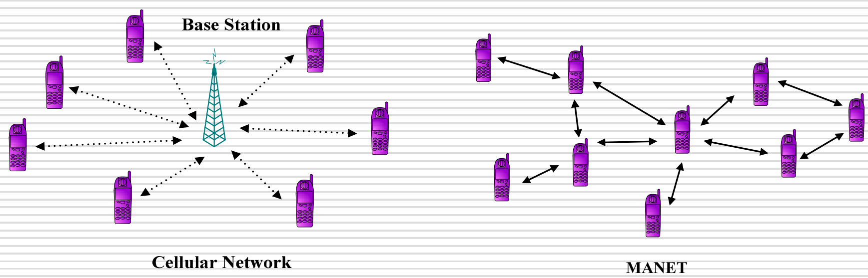
Key to Successful Deployment of MANET in Battlefield and Emergency Disaster Management

- ❖ Cloud Networking and Cloud Computing
- ❖ Pre-Determined MANET Fabric and On-Demand MANET Fabric Deployments
- ❖ Skillful Management of QoS Assurance for All Applications with High Probability of Success
- ❖ Efficient Use of Resources to Achieve:
  1. Processing Efficient Management
  2. Bandwidth Efficient Management
  3. Power Efficient Management
  4. Delivery of QoS Assurance

What is a MANET?

- MANET is a collection of mobile wireless radios and Sensors that are capable of communicating with each other without the aid of any established infrastructure such as Base stations and Tower.
- Advantages of MANET Architecture
  - Cost Effective, Easy and Fast Deployment
- Disadvantages of MANET Architecture
  - Complex Network Management (Unless Use Distributed Management)
  - Deal with Low Power Radios in the network
  - Bandwidth Constraint in the Network
- Applications
  - Battlefield Theater
  - Emergency Rescue Management and Wireless Sensor Networking

MANET VERSUS CELLULAR NETWORK



Architectural Differences between MANET and Cellular Network

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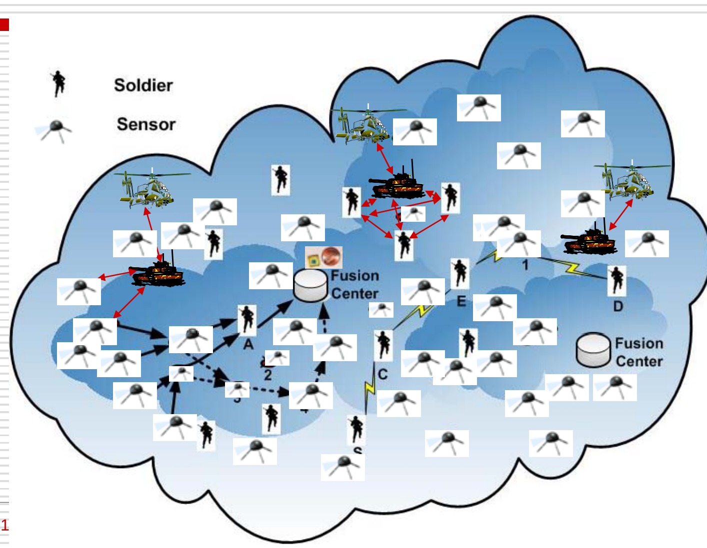
Conceptual MANET / Sensor Network / Mixed MANET-Sensor Network



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MANET and Sensor Networks – Limitations

- MANET and Sensor Networks are Highly Mobile
- Power is Limited for Each Node (Radio or Sensor)
- Bandwidth is Limited in the Network
  - Bandwidth Usage Needs to be Minimized for Overhead Transport
- Network Architecture has no Fixed Infrastructure
  - No Base Station or No Towers
  - They operate on the fly
- Needs to Communicate for Indoor and Outdoor Situational Awareness System Operations

Support of Multi-service Applications with Quality of Service Assurance

To Achieve Target Quality of Service Assurance with High Probability of Success, Modeling of Networks and Systems must be Based on:

- Specify Target Data Error Rate
- Dynamically Change Data Rate to Achieve Target Data Error Rate for all Conditions of the Network Connected Path
- Achieve Bounded Response Time Would Require Minimizing the Processing Time and Maintain Nearly Constant Delay (low standard deviation)

Multi-Service Applications

1. Video and Instantaneous Maps (128 – 384 kbit/s)
2. Sensor Data with Fusion (32 – 128 kbit/s)
3. VOIP (64 kbit/s)
4. Partial Video Distribution (1.024 Mbit/s)
5. Position, Location and Tracking (384 – 1.024 Mbit/s)
6. Management Information Base Elements Transmission (64 kbit/s)
7. Remote Situational Awareness Data (128 kbit/s)

'QoS Requirements are Based on Mission Critical Needs in the Battlefield and as such they vary based on Tactical Operations"

– A unique thing in Battlefield Architecture as opposed to the Commercial Network Designs

MANET and Sensor Networks – Tactical Applications

- Multi-Function / Multi-Frequency Radio and Sensor Capability in a Tactical Environment (Dynamic Re-configurability)
- Multi-hop Capability with Power / Energy Efficient Routing to Maintain Desired QoS for Each Application
- Design of Efficient (Power and Bandwidth) Management Function in Each Radio
- Minimal Disruption in Communications for High Priority Applications
- Efficient Use of Available Spectrum (Cognitive Radio)
- Maintain Communications even Under Multi-path Fading Interference with Variability of Information Transfer Rate

Identification of Time Critical Applications

- Execution of Indoor Situational Modeling Data Transport
  1. Sensors play a major role to map the indoor environment (video)
  2. Sequential Improvement of Video needs to be maintained to achieve rapid "executable actions"
- Indoor and Outdoor PL&T
  1. Robotic Imaging with Robot Tracking from outside the Building for Indoor PL&T Tracking
  2. UAV imaging and target hunting for outdoor PL&T Tracking
- Remote Situational Awareness System (RSAS) for Commander Execution
  1. RSAS Data to be transported to the Remote Command Center
  2. Creation of Executable Action to be Conveyed to the Theater.
- VOIP Calls, In-Vehicle Sensing Data and Mission Critical Data Delivery are to be achieved with desired QoS at all times.

Use of Mobile Ad Hoc Network (MANET) Architectures

1. Allows Fast Deployment
2. Needs Dynamic Tracking and Re-Initialization
3. Multi-hop Communications for Intra-Cluster Fabric only for Power Efficiency
4. Multi-Hop Communications for Inter-Cluster Fabric only through Cluster Heads
5. Radio Anonymity and Security
6. If Software Defined Radio is Used, then Trust and Verification Software needs to be maintained
7. Distributed Management

Challenges in Using MANET Architecture

- Scalability of Architecture (To support large number of nodes; to add new nodes and still maintain the necessary path connectivity across the network).
  1. Pre-determined Fabric (Cluster Based), where Clusters are added to increase the size of the network instead of nodes (or radios) only added).
- Power Efficiency (Attempt to transmit with minimum power in order to sustain battery life in each radio).
  1. Minimum of sum of transmit power along multi-hop and maximize the balance energy.
- Bandwidth Efficiency (Attempt to ensure that the network capacity is maximally used for end user service provisioning.
  1. Minimize the impact of bandwidth greedy TCP or use only UDP
  2. Management Information Transport must be Efficient

Mobility Handling (to maintain path connectivity efficiently at all times).
  1. Continuous Path Connectivity using Joint Power Control and Scheduling
- Quality of Service (QoS) assurance (Attempt to provide QoS for each multi-service application end-to-end).
  1. KV Transform and QoS indexing using ensemble delay and its Variance.

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Challenges in Using MANET Architecture

- Synchronization (Two Levels)
  1. Level 1: Fast Peer-to-Peer Radio Synchronization
  2. Level 2: Fabric Synchronization for Optimal End-to-End Scheduling Time
- Network Life Time
  1. Sensors have one life time; and Radios have difficulty in re-charging frequently.
  2. Differentiated Services must be skillfully used to maximize the life time of radios and sensors.
- Multi-path Interference Handling for both Indoor and Outdoor Situational Modeling Applications
  1. Use Forward Error Correction to Recover Data at Low Eb/N0.
  2. KV Transform is realizable with the ability to dynamically change the data rate for each ensemble and allow nearly constant delay with a constrained data error rate.
- Mobility Handling (to maintain path connectivity efficiently at all times).
  1. Continuous Path Connectivity using " pre-emptive band aid on the fly"
- Quality of Service (QoS) assurance (Attempt to provide QoS for each multi-service application end-to-end).
  1. Dynamic Management of data rate, response time and data error rate must be done to maintain the QoS

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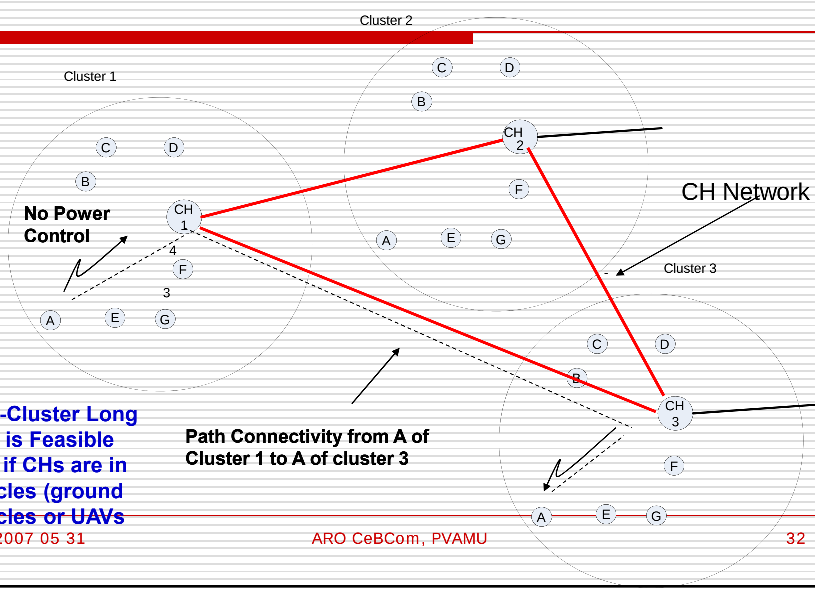
Lecture 2: Design of Ad Hoc Mobile Network (MANET) Architecture for Battlefield

Covers the design of MANET Architecture and radios with spectral efficiency, bandwidth efficiency and power efficiency; and functional design of radios to support "automatic reconfiguration" for supporting interoperability with legacy radios; "dynamically changeable modulation" based on real time channel conditions to handle multi-path fading environment; and "use of cognitive radio principles to achieve spectral efficiency.

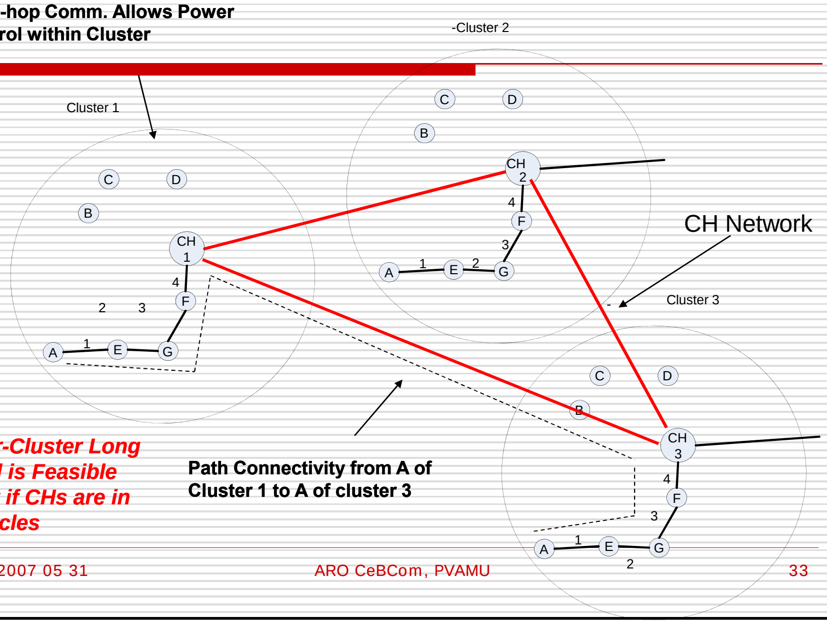
MANET Architecture 1: Intra-Cluster Broadcast Network for peer-to-peer operation between radios



Inter-Cluster Long Haul is Feasible only if CHs are in vehicles (ground vehicles or UAVs

MANET Architecture 2: CH network as a Backbone Network for Radios in Each Cluster

Multi-hop Comm. Allows Power Control within Cluster

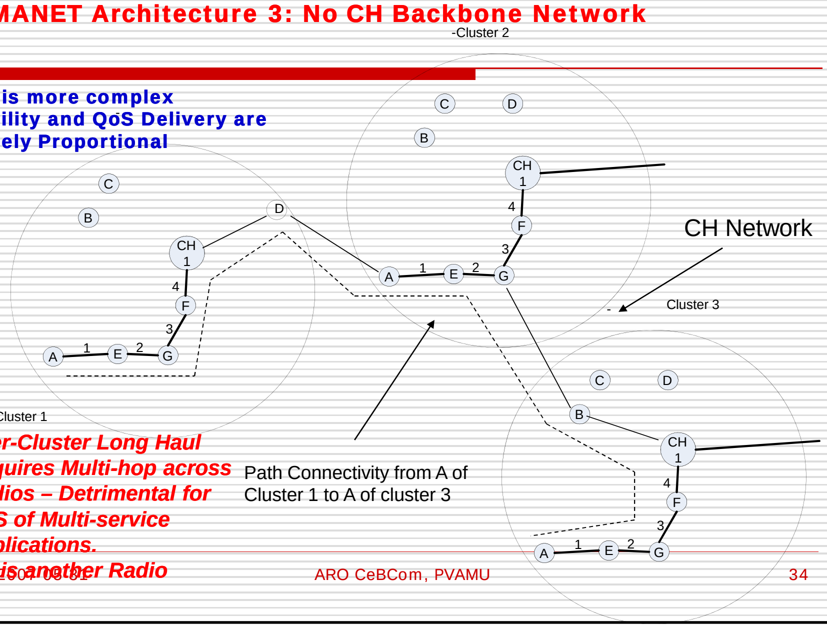


Inter-Cluster Long Haul is Feasible only if CHs are in vehicles

Path Connectivity from A of Cluster 1 to A of cluster 3

MANET Architecture 3: No CH Backbone Network

MGMT is more complex
Scalability and QoS Delivery are Inversely Proportional



Inter-Cluster Long Haul Requires Multi-hop across Radios – Detrimental for QoS of Multi-service Applications.
CH is another Radio

Path Connectivity from A of Cluster 1 to A of cluster 3

Uniqueness and Advantages

Uniqueness:

1. Cluster Head or Designated Alternate will have public IP addresses. All radios can be configured with private IP Addresses. Preferred over using radio Ids.
2. Distributed Management using Clusters and Cluster Heads
3. Allowing CH Backbone network capability will provide an option to US Army to consider either UAV or ground vehicles for CH.
4. Clustering provides bandwidth efficient management and control, yet support "Quality of Service (QoS) assurance" for Multi-service Applications.

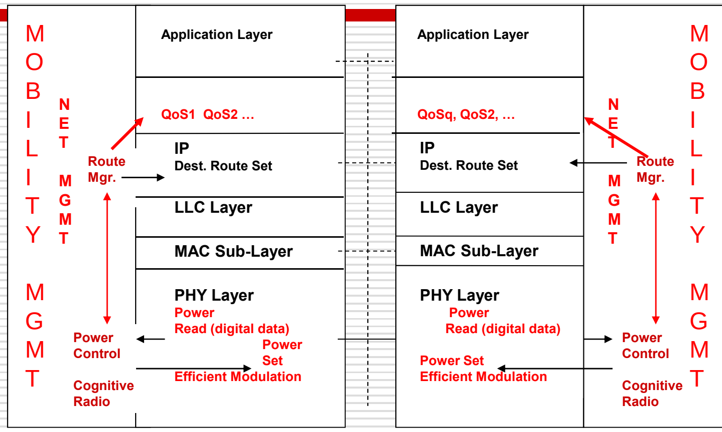
Advantages:

1. Scalable Network - Cluster based network is scalable to large physical battlefield system in terms of additions of squads, groups and battalions
2. Bandwidth Efficiency – Distributed management ensures small amounts of bandwidth used management and control.
3. Simplified Routing: There is no routing scheme required within the domain for intra-domain traffic. However, for radio mobility and non-disruptive communications, the multi-hop is required and a minimal routing is managed by the domain manager.
4. QoS Assurance for Multi-service applications: Controlled delays in managing the applications provides for support of QoS assurance.

Feature Radio Enhancements

- **Clustered Based MANET Fabric Design**
  1. Predetermined Cluster of Nodes
- **Distributed Network Management**
  1. Logical Operations and Management Information Base Elements
- **Power Control and Scheduling**
  1. Multi-Hop Connectivity with Cumulative Minimum Power & Minimum Cumulative Scheduling Time
- **Cognitive Radio and Cross Layer Power Control**
  1. Spectrum Access: Autonomous Identify-Resolve-Occupy Spectral Slots based on Need
  2. Real Time Cross-Layer Power Control Decisions
- **Dynamic Real Control Decision to Effect QoS for Multi-Services' Provisioning**
  1. Constrained Data Error Rate, Sustainable Data Rate and End-to-End Response Time

Ultimate Efficient Radio with QoS Differentiation



Soldier Radio *Remote Soldier Radio*

Design of Modular Radio and Sensor Nodes with Flexibility – Use of SDR [13, 15]

Software Defined Radio (SDR) Approach

◆Design a Power Efficient, Resource Efficient Multi-band, Multimode and Multi-role Tactical SDR capable of Flexible Configuration.

◆Trusted Software and System

◆ Distributed Embedded Network Management Design (with Simple Logical Operation) for reducing Processing Time and Processing Delay.

◆ Tactical configuration with dynamic Reconfiguration Capability

DESIGN FOCUS

◆Automatic reconfigurability for changing network environment
- ➢Interoperability with existing multi-legacy environment

◆Dynamically changeable channel conditions
- ➢Variable modulation and symbol constellations

◆Sustained data transmission in multi-path faded environment
- ➢Power efficiency in processing and transmission

◆Management of software trust functions

◆Spectrum Efficiency
- ➢Cognitive Radio

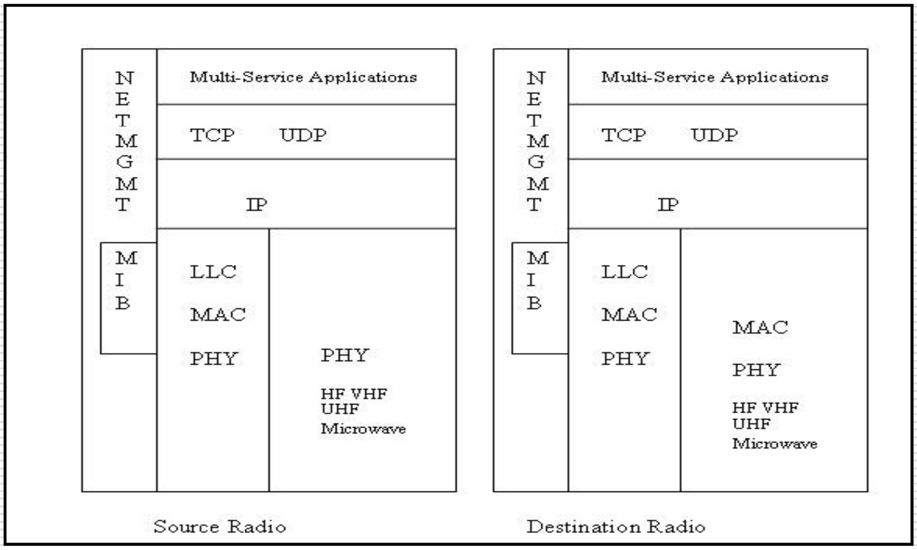
◆Distributed Management for manager – agent relationship
- ➢Cross layer function for trust software management
- ➢ Security and anonymity of nodes

SDR FEATURES

- Power Efficient Multi-band, Multimode and Multi-role SDR Flexibly Configured
- Multimode and Multi-role SDR Flexibly Configured
- Support of Different RF Transport (examples)
  - HF band (9.6kbit/s),
  - VHF band (28 kbit/s),
  - UHF band (256 kbit/s)
  - 10 Mbit/s Microwave Radios
- Standard Interfaces to fixed networks
- Efficient Distributed Network Management
- Embedded security and Key Management
- Provisioning of IP Transport
- Reprogrammable and Reconfigurable Architecture
- Support Selective Point-to-Point, Point-to-Multipoint and Broadcast through Dynamically Configurable Address Filtering
- Place holder for User Definable Encryption module

SDR ARCHITECTURE

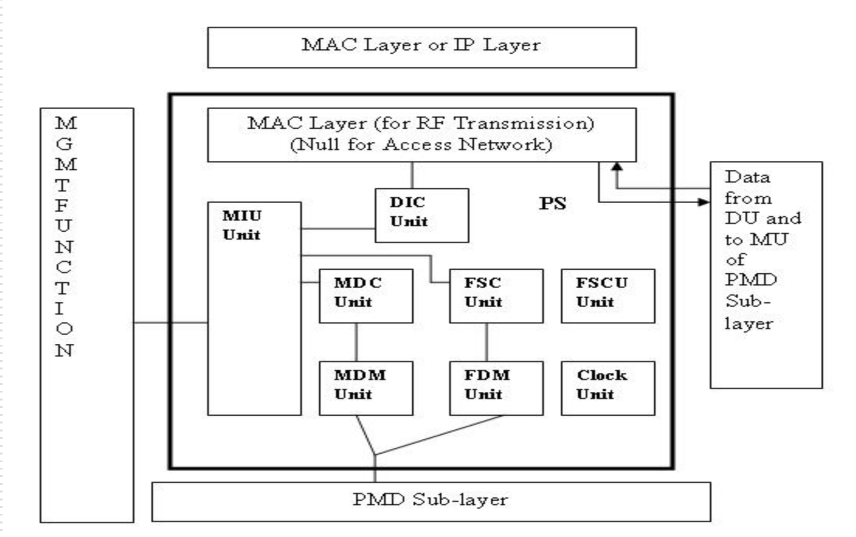
- Supports Layered Architecture of OSI Reference Model
- Each Layer has Unique Set of Functions
- Cross Layer Functionality is Achieved Through Management Plane
- For Flexibility, Use Distributed Network Management
- Embedded security and Key Management
- Provisioning of IP Transport
- Reprogrammable and Reconfigurable Architecture
- Support Selective Point-to-Point, Point-to-Multipoint and Broadcast through Dynamically Configurable Address Filtering
- Place holder for User Definable Encryption module



PHYSICAL LAYER

- **Physical Services (PS) Layer**
- **Physical Medium Dependent (PMD) Layer**

PS SUB-LAYER MODULES



PS SUB-LAYER FUNCTIONS

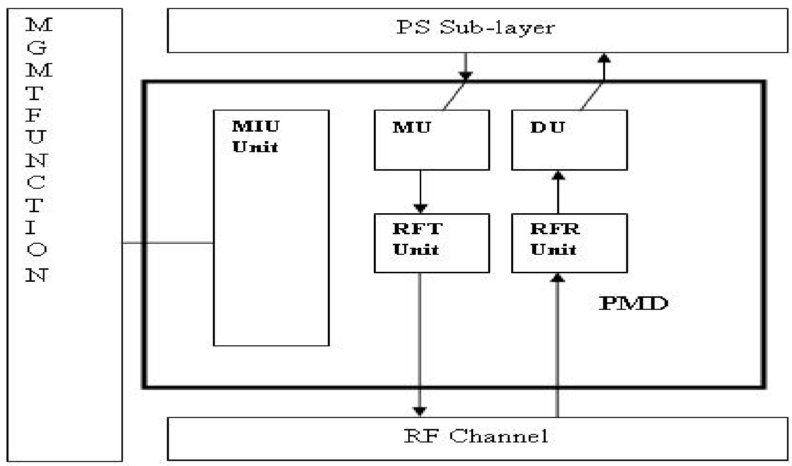
- **Data Interface Control (DIC) for IP Packets**
  - Exchange of valid IP Data for Transmission and Receiver
  - Priority Conditions for QoS over the Network
  - Data Rate for IP Transmission with Management Control
  - Cross Layer Information through Managementa
- **Modulation/Demodulation Control (MDC)**
  - Type of Modulation, Constellations, Data Rate setting for PMD
  - Collect knowledge of Radio Location (GPS, or Triangulation)), Real Time Channel Condition and Power Requirements for Transmission
- **Frequency Selection Control (FSC)**
  - Selection of Frequency and Frequency Slot (Spectrum) by PMD
- **Frequency Decision Module (FDM)**
  - FDM provides the control data to PMD for use of Spectrum

PS SUB-LAYER FUNCTIONS

- **Modulation/Demodulation Decision Module (MDM)**
  - Specify Modulation Type to PMD
- **Preamble Generator (PG)**
  - Local Preamble Generation for Asynchronous Transmission for Synchronization of Peer Radios
- **Frequency and Clock Synchronization Unit (FCSU)**
  - Achieves Frequency and Clock Synchronization for Receive Operation
- **Clock**
  - Specific Clock Rate
- **Management Interface Unit (MIU)**
  - Cross Layer Decision Rules and Control with Knowledge of PMD, PS, MAC, IP and Application Entities

PMD SUB-LAYER FUNCTIONS

- **Modulation Unit (MU)**
  - Different Modulators Programmed
  - Dynamic Selection of Constellations
  - Digital to Analog Converter
- **Demodulator Unit (DU)**
  - Different Demodulators are Programmed
  - Dynamic Selection of Constellations
  - Analog to Digital Converter
- **Type of Modulation supported**
  - AM, FM(NBFM & WBFM), QPSK, FSK, M-aray, PSK, OFDM, OFDMA, QAM etc.
- **RF Transmitter (RFT)**
  - IF to RF Converter
  - Transmitting Unit
- **RF Receiver (RFR)**
  - RF to IF Converter
  - Receiving Unit



MAC SUB-LAYER FUNCTIONS

- ARQ Functions
  - **Stop and Wait ARQ**
  - **Go Back N ARQ**
  - **Selective Reject ARQ**
- Embedded Transform Coding (Patent Protected)
  - **Orthogonal Transform Coding**
  - **Block Error Correction**
  - **Selective Single Retransmission**
  - **Sample Inter-leaving**

HIGHER LAYER FUNCTIONS

STANDARD FUNCTIONS

DISTRIBUTED MANAGEMENT FUNCTION

Management Function

MO_app {security_attr1 (trust level), sec_attr2 (trust_time_counter), sec_attr3 (count_thresh), sec_attr4 (counter_status);

QoS_attr1 (info_rate (integer), response time (integer), info_loss (integer);

Encryption_attr1 (level); Attr2 (Level_verification); Attr3 (session time lapse)

MIU Unit

LME/A - Application Layer

LME/T -Transport Layer

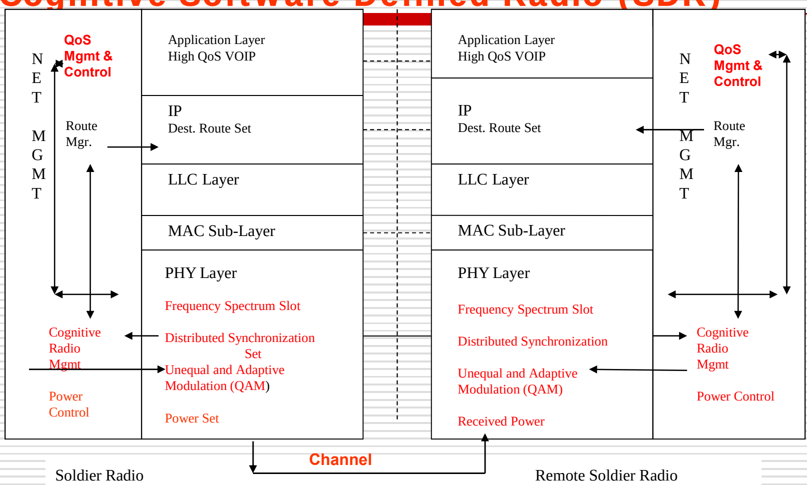
LME/N - IP

LME/M - MAC

MIU- PS

MIU - PMD

Cognitive Software Defined Radio (SDR)



FIRST KNOWN SDR IMPLEMENTATION

- SDR Designed and Implemented by Boeing (1997 – Current) – Funded by DOD.
- Software Programmable Multi-service Radio.
- Implemented Using Software Communications Architecture (SCA) Platform.
- Offers Interoperability with Legacy Radios.
- Currently in Technology Phase for Validation and Not in Final Implementation.
- Yet to Demonstrate in Heavy Multi-Path Fading for Indoor and Outdoor Situational Awareness System Crucial for Battlefield Theater.

Lecture 3: Cognitive Management Radio Design for MANET

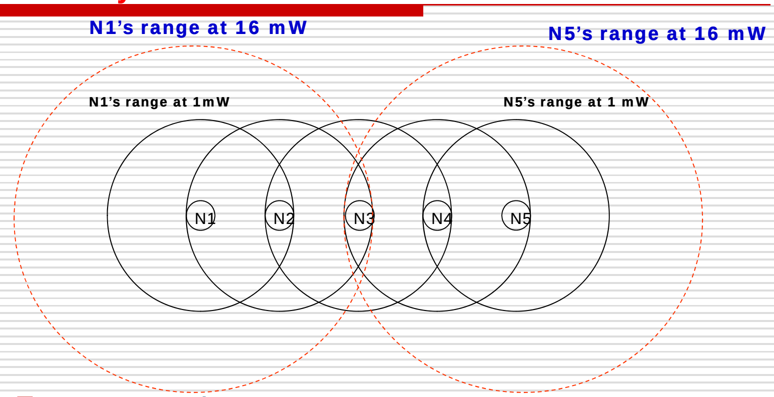
covers introduction of "cognitive radio management design" using distributed management system that uses cross-layer controls. Both distributed management operations and cognitive radio management will be discussed.

Brief Introduction to Power Control and Scheduling [4, 5, 6]

Power Control and Scheduling

- ❖ The Objective is to achieve transport QoS in MANET with Power Control, Scheduling and Routing – An Integrated Multi-Layer Design.
- ❖ We have implemented joint power control and scheduling with maximally disjoint path connectivity to handle mobility (OPNET Simulation).

Power Control Interacts with Data link Layer and Network Layer



- Route from N1→ N5:

  Transmitting at 1mw (all nodes) : N1 → N2 →N3 →N4 →N5

  Transmitting at 16 mw (all nodes) : N1 →N3 →N5

Joint Power Control and Maximally Disjoint Routing

Design Objectives

- **Energy efficiency**
- **"soft" Transport QoS (minimum rate assurance)**
- **Extended network lifetime (balanced traffic)**
- **Reliability (accommodate node mobility and/or node failures)**
- **Bandwidth efficiency**

Proposed Solution

- **Joint power control and routing design with minimum rate guarantee**
- **Maximally disjoint paths and dynamic traffic switching**

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Interference Model and Power Control

$$\underset{\vec{p}}{Min} \sum_i p_i \qquad i = 1,2,\cdots,N.$$

subject to the constraints :

$$\gamma_i = \frac{h_{ii} p_i}{\frac{1}{L}\sum_{j \neq i} h_{ij} p_j + \sigma^2} \geq \gamma_i^{tar}$$

Received power

Interference plus noise

AWGN

$$\gamma_i^{tar} \geq 2^{\frac{R_i^{tar}}{W_i}} - 1$$

This is only true if cumulative interference is Gaussian

$$0 \leq p_i \leq p_i^{\max}$$

W_i	Bandwidth
R_i^{tar}	Desired data rate
h_{ii}, h_{ij}	Link gains
p_i, p_j	Tx power
$p_i^{\max}$	Upper bound on Tx power

- **Minimize the total energy consumption**
- **Provide guaranteed data throughput**
- **Extend battery life**

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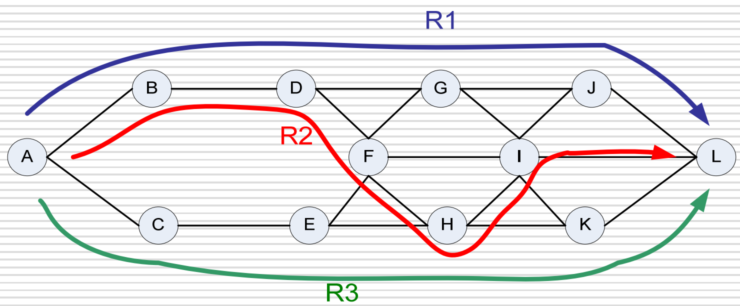
Node Disjoint Path vs. Link Disjoint path



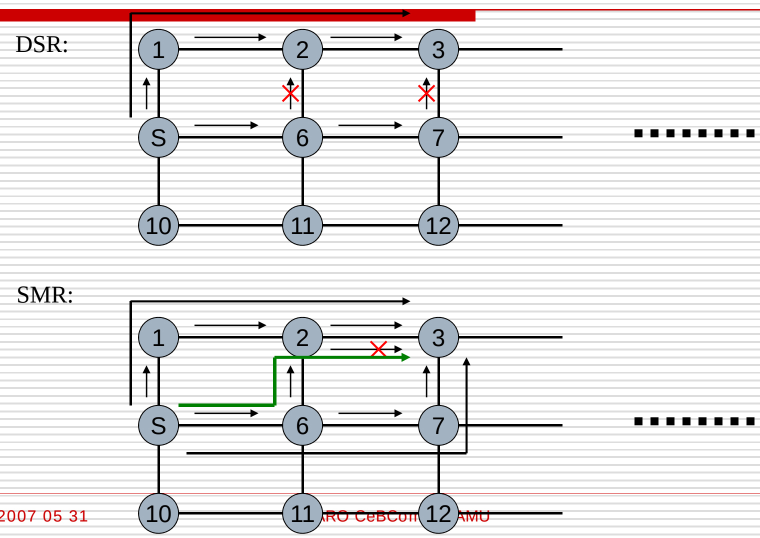
R1, R3 : node disjoint
R2, R3 : link disjoint

Routing Methods

- Split Multi-path Routing (SMR) used as the baseline for Comparison. (Proposed by Lee and Gerla)
  - Based on Dynamic Source Routing
  - Accept and forward duplicate RREQ if
  - RREQ from different upstream node
  - Hop count is no more than previous RREQ
- Our proposed modifications to SMR (above) Routing
  - Min Power Split Multi-path Routing (MPSMR)
    - ✓ Control Metric =Tx power
  - Balanced Energy Split Multi-path Routing (BESMR)
    - ✓ Control Metric = Tx power / remaining energy

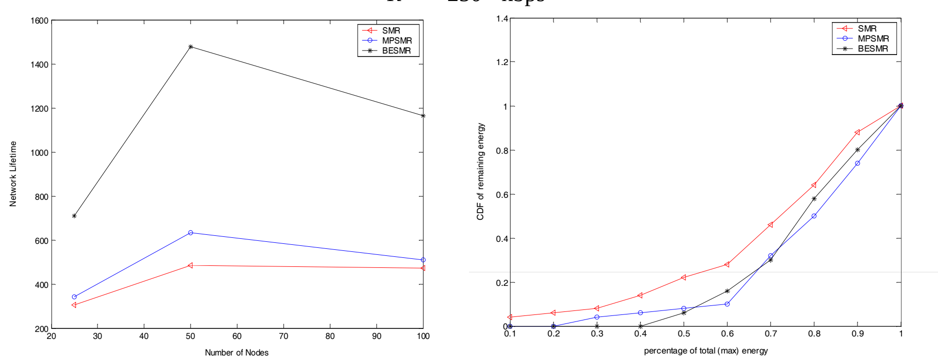
Objective is to consider "tradeoff of TX power and remaining energy of a node", thus maximize network lifetime

Dynamic Source Routing vs. Split Multi-path Routing (SMR)



Simulation Results Using OPNET

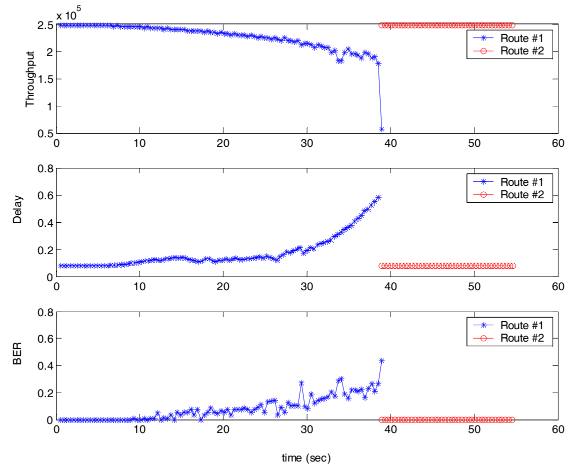
$R^{tar} = 250$ kbps



Network Lifetime CDF of remaining energy

Network lifetime: the time when the first node run out of energy

Simulation Results (contd.)



Performance during Traffic Switching

Advantages

- Almost no disturbance/delay when primary path is broken
- Simple implementation: only source and destination nodes are involved
- Bandwidth efficiency

Cognitive Radio With Cross Layer Power Control [2, 3, 7]

The objective of cognitive radio is to improve spectral and power efficiencies in MANET for multi-user communications, by locating unused spectrum.

System Description

- Multi-carrier modulation (DS-CDMA) used with cognitive radio
- The wireless channel is modeled as a frequency selective Raleigh Fading Channel.
- Entire spectrum is divided into M subcarriers, each with bandwidth B
- Each Sub-carrier experiences a flat fading.
- No interference between different subcarriers
- A CR user has a specified data rate requirement, R_i and a BER requirement, BER_i
- A CR user has a free subcarrier set F_i with A_i subcarriers ($A_i \leq M$)
- A user may experience NBI with probability P_{NBI}
- MQAM modulation and coherent demodulation

Problem Formulation

- Scenario
  - *N* CR users want to share the common spectrum with existing primary users
- Goal
  - Avoid interference to primary users and minimize the total power consumption
- Each CR user detects the availability of each subcarrier, and employs subcarriers from its free subcarrier set F_i
- Definitions:
  - Primary users: existing users + CR users who have successfully accessed the system (with its SINR satisfied)
  - CR users: New users who want to access the system

Problem Formulation (2)

- Mathematically, the problem can be addressed as

$$\min\left(\sum_{i=1}^{N}\sum_{k=1}^{A_i} P_i^{(k)}\right), \quad \textit{subject to}$$

Transmit Power of transmitter i of the kth available sub-carrier

N Cognitive Radio Users

$$\textbf{C1:} \quad \sum_{k=1}^{A_i} P_i^{(k)} \le P_{\max}, \; i = 1,\ldots,N. \qquad \textbf{C2:} \quad \sum_{k=1}^{A_i} b_i^{(k)} \ge R_i, \; i = 1,\ldots,N.$$

No. of bits / symbol of user i

C3: The detected available subcarrier set F_i has A_i subcarriers, $i = 1,\ldots,N$.

  - To find the appropriate subcarrier assignment and power/bit allocation for each CR user
  - Required information: free subcarriers, noise power, channel gain
  - Ai is the total sub-carriers of which Fi is the available free sub-carriers' set

Detection of Subcarrier Availability

- Use of multi-taper spectrum estimation method (MTM) and singular value decomposition (SVD)
- For the *j*-th subcarrier of user *i*, we first compute the expansion coefficients, $y_n(f)$, $n = 0,..,K-1$.
- We then form an *H*x*K* matrix by accounting for spatial variations of spectrum

$$\underline{\underline{A}}(f)=\begin{bmatrix} y_0^{(1)}(f) & y_1^{(1)}(f) & \cdots & y_{K-1}^{(1)}(f) \\ y_0^{(2)}(f) & y_1^{(2)}(f) & \cdots & y_{K-1}^{(2)}(f) \\ \vdots & \vdots & & \vdots \\ y_0^{(H)}(f) & y_1^{(H)}(f) & \cdots & y_{K-1}^{(H)}(f) \end{bmatrix}$$

Detection of Subcarrier Availability (2)

- SVD is then performed [2]

$$\underline{\underline{A}}(f)=\sum_{k=0}^{K-1}\eta_k(f)\underline{u}_k(f)^{+}\underline{v}_k(f)$$

$\eta_k^2(f)$ is the *k*-th eigenvalue with $\eta_0^2(f)\ge\eta_1^2(f)\ge...\ge\eta_{K-1}^2(f)$

- Finally, the detection statistic $D(t)$ at time *t* for the *j*-th subcarrier of user *i* can be computed as

$$D(t)=\int_B\left|\eta_0(f,t)\right|^2 df$$

- A threshold comparison is then carried out to declare a particular subcarrier available or not
- Partially cooperative scheme: each CR user will broadcast its available subcarrier set F_i to its neighbors, and then majority logic is used to determine the status of each subcarrier

Noise Power Estimation

- Noise power is due to a combination of thermal noise, possible NBI, and interference from primary users when detection error occurs, and assumed to be Gaussian.
- The noise PSD of k-th subcarrier of user i is:

$$S_i^{(k)}(f) = \frac{1}{K}\sum_{n=0}^{K-1}\left|y_n(f)\right|^2$$

- Then, the noise power is

$$N_i^{(k)} = \int_B S_i^{(k)}(f)\,df$$

Channel Estimation

- Consider the effect of Doppler spread, i.e., coherence time, T_c
- The channel estimate is assumed to be

$$\hat{\alpha} = \alpha + e,$$

$$where\; e \in N(0, \sigma_e^2)$$

- The variance of the estimation error can be computed as a function of Doppler spread, i.e., coherence time T_c.

Spectrum and Power Allocation (1)

- For each CR user, only "local" information is available, i.e., available subcarrier set, channel gain, and noise power
- Define a quality indicator $Q_i^{(k)}$ for the k-th free subcarrier of user i

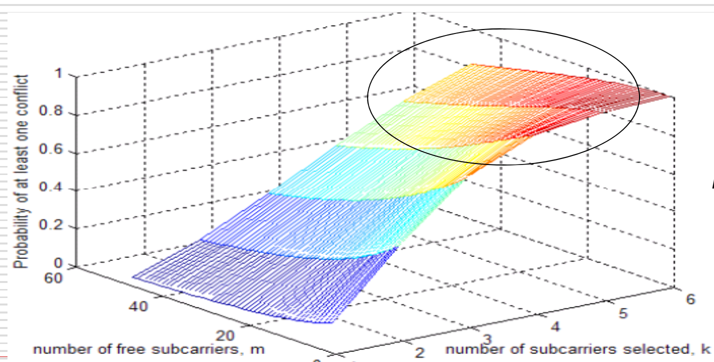
$$Q_i^{(k)} = \frac{\alpha_{ii}^{(k)}}{N_i^{(k)}}$$

- Each CR user performs resource allocation individually
  - Assumes no others sharing the resources with it
  - Employs its free subcarriers sequentially from the best to the worst
- Conflicts can occur!
  - Multiple users may pick the same subcarrier!

Spectrum and Power Allocation (2)

- If we have N CR users, and each of them selects k subcarriers from the available subcarrier set of size m, the probability of conflict is

$$\Pr\{\textit{at least one conflict is found}\} \geq 1 - e^{-\frac{\binom{N}{2}k^2}{m}}$$



N = 3

Spectrum and Power Allocation (3)

- Consider a conflicting subcarrier where Q users are simultaneously overlaid
  - How to protect active users
  - What if there is no optimal power allocation for all the Q users
- The first question can be solved by [6]

$$P_i(k+1)=\begin{cases}\dfrac{\delta\cdot\zeta_i}{SINR_i(k)}P_i(k), & if\ i\in \mathrm{X}(k)\\ \delta\cdot P_i(k), & if\ i\in \mathrm{Y}(k)\end{cases}$$

User i is in the active user set $X(k)$ during the k-th step *iff* it is originally a primary user or it is a CR user with $SINR_i(k)\geq\zeta$

User i is in the transition user set $Y(k)$ during the k-th step *iff* it is a CR user with $SINR_i(k)<\zeta$

Spectrum and Power Allocation (4)

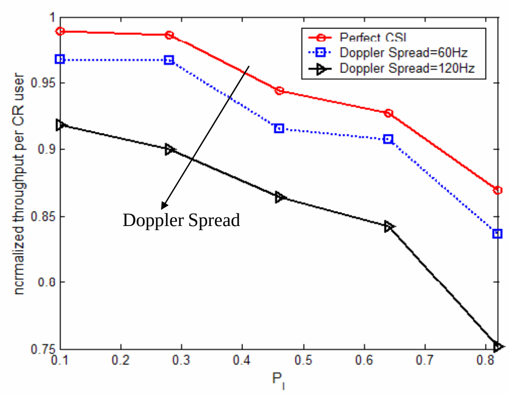
- If there is no optimal solution for all the Q users with current data rate requirements, a rate control scheme is employed
- Each CR user pre-sets a time duration T_i, during which it tries to access the system
- If it does not gain access, it will compute a time control interval ΔT_i
- If after $T_i+\Delta T_i$, it still cannot gain access, it will decrease its data rate by ΔB, and repeat the process

$$\Delta T_i = f\left(\zeta_i - SINR_i(T_i)\right) = \left\lfloor A\exp\left(-\beta(\zeta_i - SINR_i(T_i))\right)\right\rfloor$$

Performance Analysis (1)

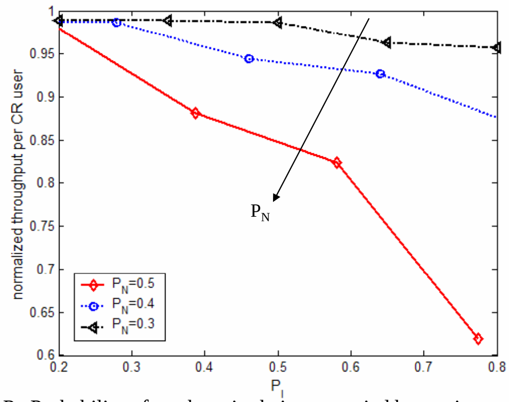
- 30 users in 200 x 200 m^2 area
- 64 subcarriers where each experience flat Rayleigh fading
- Maximum QAM constellation is 128
- BER requirement is 10^{-4}
- Consider the impact of
  - Primary users
  - Doppler spread
  - NBI
  - Cooperation

Performance Analysis (2)



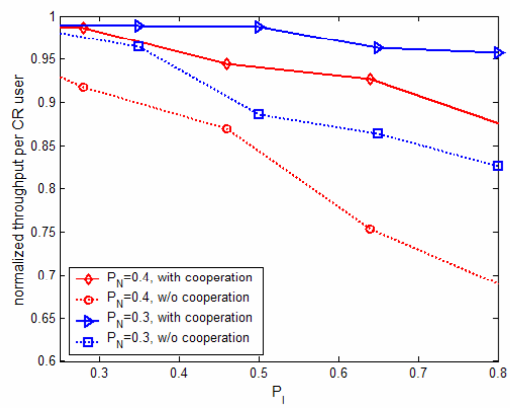
P_I: Probability of a subcarrier being occupied by a primary user.

Performance Analysis (3)



P_I: Probability of a subcarrier being occupied by a primary user.
P_N: Probability of NBI overlaying a subcarrier of a user.

Performance Analysis (4)



P_I: Probability of a subcarrier being occupied by a primary user.
P_N: Probability of NBI overlaying a subcarrier of a user.

Cognitive Radio in MANET - Summary

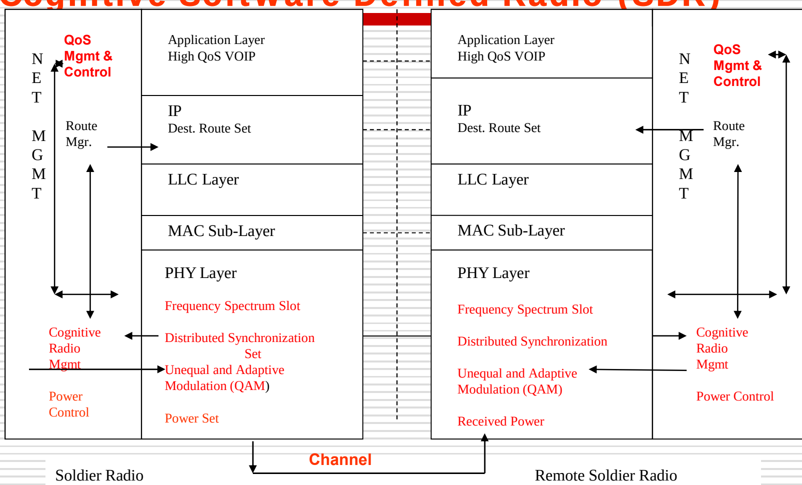
- Cognitive Radio detection of which spectral bands are occupied
- Cooperation among CR users to improve the detection performance
- Distributed spectrum allocation and conflict resolution if spectrum allocation errors occur
- Distributed power control and rate control
- Performance in the presence of interference from active users, intentional jamming, and cooperation

Lecture 4: Design of MANET with Cognitive Radio for Spectrum Efficiency [13, 15]

covers the design of cognitive radio based MANET and sensor networks and provide alternate solutions that allow each vendor implement the solution in their own native mode. A brief discussion of battlefield applications will also be presented.

We use the SDR Implementation to Demonstrate Feature Functions of Cognitive Radio.

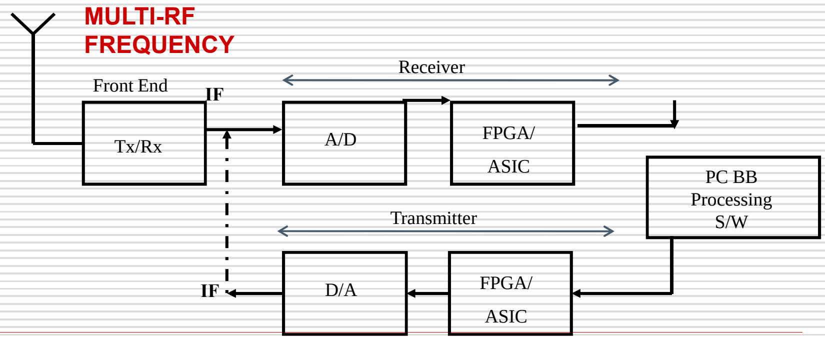
Cognitive Software Defined Radio (SDR)



INITIAL SDR DESIGN AND IMPLEMENTATION

SOFTWARE DEFINED RADIO

- Physical layer functions are implemented in Software
- Easy to reprogram, replace and/or add new functions.
- Extends lifecycle of the radio
- Facilitate adaptation to technology changes



Block Diagram of an SDR

AUTOMATIC RECONFIGURABILITY

AUTOMATIC RECONFIGURABILITY

- SDR adapts to different legacy environment to interoperate with existing radios.
  - RF needs to be changed when required
  - Require dynamically changeable modulation technique with minimal management and control operation.

DYNAMICALLY CHANGEABLE MODULATIONS

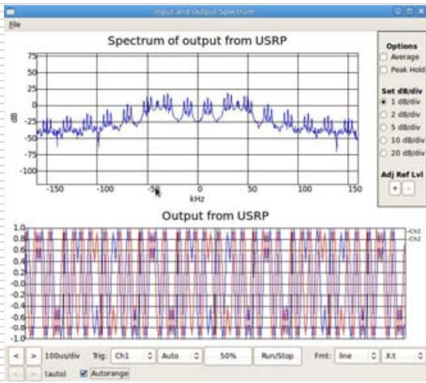
DYNAMICALLY CHANGEABLE MODULATIONS

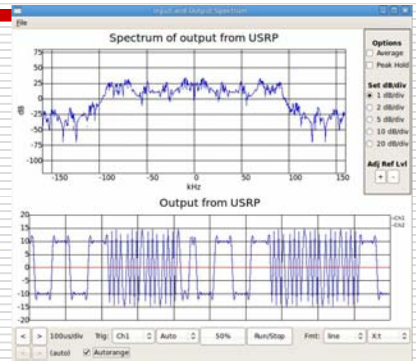
- Modulation Type
- Adaptive Constellations to Vary Symbol Rate Based on Real Time Channel Conditions

MODULATORS

- CRs capable of Multi-mode operation
  - Demonstrated using GMSK, DBPSK, DQPSK as Examples
  - Transceiver pair decides on the type of modulation during frequency synchronization
  - A default modulation scheme is chosen for the first control message.(GMSK in this demonstration)
- Dynamic switching between modulators
  - Control message exchanged requesting change in modulator (using existing modulation scheme).
  - A request from the receiver is included in the acknowledgement packet.
- Securing waveforms with user control
  - A user can port any new modulation scheme to existing SDR design.
  - Allows ability to secure waveforms using trusted software.

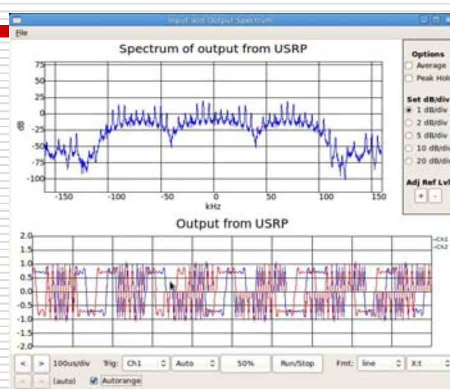
SPECTRUM OF OUTPUT OF MODULATORS WITH SINE WAVE





❖*GMSK Modulation*

❖*DBPSK Modulation*



❖*DQPSK Modulation*

HANDLING OF MULTI-PATH FADING

HANDLING OF MULTI-PATH FADING

- **Continuity of Data Transfer at varied Eb/N0.**
- **Maintain Sustainable Response Time and Data Error Rate.**
- **Use Koay – Vaman (KV) Transform to Maintain Low BER at Low Eb/N0 [Vaman, et. al [5]]**

We have implemented it in SDR, will not be presented here

MANAGEMENT OF SOFTWARE TRUST FUNCTIONS

MANAGEMENT OF SOFTWARE TRUST FUNCTIONS

- Owner of Network Must Have Flexibility of Changing the Secure Waveforms away from SDR Designer.
- Embedded Software Must meet the issues of trust and verification.

COGNITIVE RADIO FUNCTION IN SDR

WHAT IS COGNITIVE RADIO?

- **Cognitive Radio:**
  "*is a goal –driven frame work in which the radio autonomously observes the radio environment, infers context, assesses alternatives, generates* plans, *supervises multimedia services and learns from mistakes*"*- J.Mitola [13]*

In a nutshell, Cognitive radio is a thinking radio capable of efficiently configuring its elements to adapt to changes in tactical operations and environment Vaman [14].

SPECTRUM EFFICIENCY

- **Cognitive Radio (CR) Functions are Managed by the Agent at the Physical Layer.**

COMPONENTS OF CR FUNCTION

- **Components of Implementation:**
  - **Dynamic Spectrum Management**
  - **Multimode Operation**
  - **KV Transform for Minimizing the Impact of Multi-Path Fading (will not be covered)**

WHY CR?

- **Inefficient Spectrum Utilization**
  - Ensure maximal use of available spectrum.
  - Desire to increase capacity usage of the bandwidth starved MANET and Sensor networks.
- **Design Challenges**
  - MANET and Sensor Networks are being used in "Asymmetrical Theaters" Today.
  - Same network fabric is also becoming important for "Emergency Disaster Management".
  - Radio unable to operate in fixed frequency for dynamically changing tactical operations or application requirements.
  - Operate in multi-mode/use multiple waveforms to interwork & interoperate with legacy radios.

CR FEATURES

- Physical Layer Sensing of Available Spectrum
- Transceiver Frequency Synchronization
- Use of KV Transform for Multi-Path Fading Environment (Not Covered)

PHYSICAL LAYER SENSING [*D.Cabric et al.* [16]]

Spectrum hole (Unused spectrum) detection

- **Energy Detection : Measures energy/power of signal**
  - ✓ **Advantages:**
    - a. **Low computational cost/ processing power**
    - b. **Does not require any prior information about the type of primary user signal**
    - c. **Easier Implementation**
  - ✓ **Shortcomings:**
    - a. **"Probability of error (POE) in detection" is high in Fading channels**
    - b. **POE can be decreased by using cooperative sensing [F.F Digham *et al*. [3]]**

TRANSCEIVER FREQUENCY SYNCHRONIZATION [Y.R.K. Reddy, et. al [18]]

- ❖ Use of Dedicated Control Channel
  - Dedicated Bandwidth is Assigned for Control Channel
    - ✓ Advantages:
      - a. **Assured Channel for Control**
      - b. **Lower Complexity**
    - ✓ Shortcomings:
      - a. **Additional Bandwidth Required**
      - b. **Congestion in Control Channel**
      - c. **Network can be disabled by jamming the control channel**
  - Use of Distributed Listening Channels
    - ✓ **Multiple Data Channels for Listening**
    - ✓ **Overcomes the Shortcomings of Dedicated Control Channel**
    - ✓ **Increases Complexity at MAC Layer**

HANDLING OF MULTI-PATH FADING USING KV TRANSFORM (Vaman, etal [17])

- Achieves better BER performance at low SNRs
- Block error rate measured is an indicator of real time channel condition
- At lower SNRs BER can be decreased by decreasing number of bits/input sample(n)

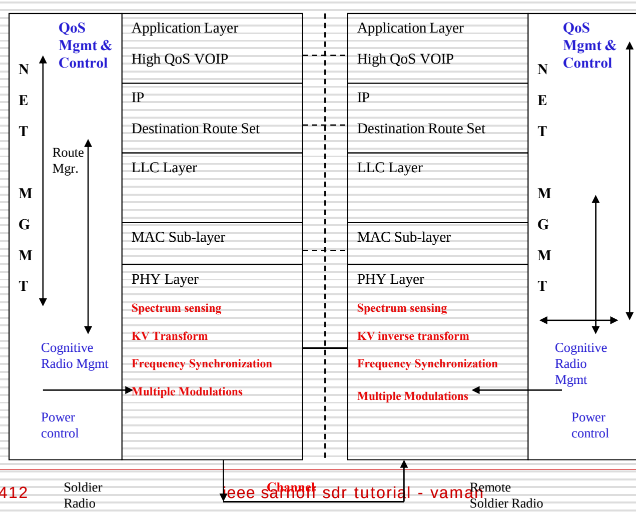
Design and Implementation of Power and Resource Efficient SDR Architecture for Cognitive Radio MANET

FEATURES OF PROPOSED SDR IMPLEMENTATION FOR MANET

- ❖ **Energy detection for spectrum sensing**
- ❖ **Distributed listening channels for frequency synchronization**
- ❖ **KV Transform for Multi-path error handling and real time channel condition measurements.**
- ❖ **Multiple modulation schemes**

SDR ARCHITECTURE

BASIC SDR ARCHITECTURE FOR CR BASED MANET



COGNITIVE RADIO FOR DYNAMIC SPECTRUM ACCESS

- **Significance**
  - Improves Spectral efficiency
  - Significant in battlefield ad hoc networks
    - ✓ Spectrum unavailability due to environmental and operational conditions
- **Key Features:**
  - Radio Spectrum Sensing
  - Dynamic Channel Allocation
  - Transceiver Frequency Synchronization
  - Transmission/Reception of Data
  - Reconfiguration

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SYSTEM DEFINITION

- **Cognitive radio system for battlefield ad hoc network**
  - Each node is equipped with two radios:
    - ✓ data radio and listening radio
  - Each node is uniquely identified using a radio id.
- **Definition of Cognitive Radio Users for given Network [Qi Qu, Milstein, Vaman [6]]**
  - *Primary User:*
    - ✓ An existing Cognitive radio Users (Radios currently transmitting and Receiving)
  - *Secondary User:*
    - ✓ A new Cognitive radio user which has to be accommodated in the network (also referred to as CRU)
  - *Priority User:*
    - ✓ A cognitive radio User with a certain degree of priority for channel access over other secondary users.

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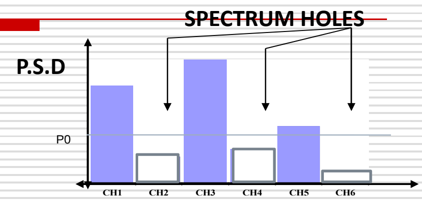
WIDEBAND SPECTRUM SENSING WITH ENERGY DETECTION



- ❖ Wideband spectrum is divided into smaller sub channels (programmable bandwidth)
- ❖ Antenna is iteratively tuned to the center frequency of each sub-channel
- ❖ Power Spectral Density is obtained for each channel using N-point (512,1024) FFT.
- ❖ Average PSD (Pc) for the channel is the calculated.
- ❖ Pc is compared to Threshold P_0
  - a. Pc > P_0 channel is declared busy
  - b. Pc < P_0 channel is declared free

Channel Status

Channel *Busy*

Channel *Free*

WIDEBAND SPECTRUM SENSING WITH ENERGY DETECTION (CONTD.)

- ❖ **Determination of Sensing threshold P0**
  - ➢ Sense the spectrum in the absence of signals during network initialization
    - a. Tune to center frequency of each channel
    - b. Perform FFT on the observed signal
    - c. Find the power spectral density for each channel.
  - ➢ Find average (μ) and standard deviation (σ) of PSD over several iterations.
  - ➢ The threshold $P0 = \mu + 3\sigma$

TX-RX FREQUENCY SYNCHRONIZATION

a) Initial Handshake   b) Dynamic Spectrum Switching during Transmission

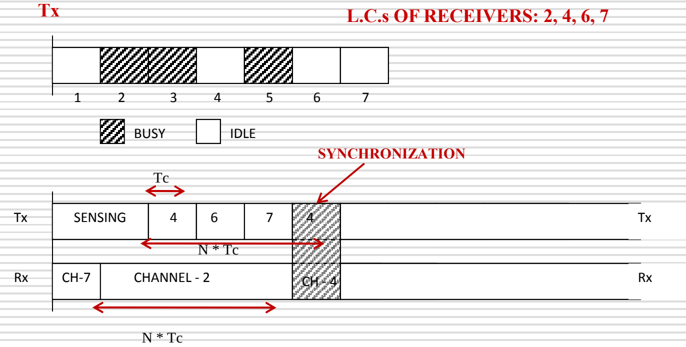
- ***Initial handshake***
  - **Every node has a set of pre –assigned listening channels (LC)**
- **Transmitter**
  - **Aware of the LCs of other nodes**
  - **Senses entire spectrum**
  - **Identifies *free* channels**
  - **Sends control signal in *free* LCs of intended receiver iteratively.**
  - **Remains on Each L.C for a time Tc**
- **Receiver**
  - **Each node in idle state listens on its LCs**
  - **Listens in each L.C for a duration N * Tc,**
    - ✓ **N = Total number of listening channels for that receiver.**
  - **If no control signal is received in the duration N * Tc switches to next LC**
  - **Once control signal is exchanged Transmitter and Receiver reconfigures for data transmission.**

TX-RX FREQUENCY SYNCHRONIZATION (2)

Spectrum sensing Output at Tx

TOTAL NUMBER OF CHANNELS = 7

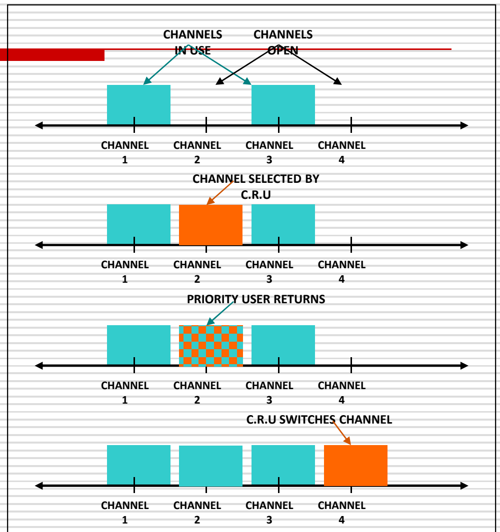
L.C.s OF RECEIVERS: 2, 4, 6, 7



DYNAMIC SPECTRUM SWITCHING

Two cases of dynamic spectrum switching:

- ❖Detection of a priority user
  - ➢ Certain users are assigned priority over others in a channel
  - ➢ CRU recognize priority users by their radio ids.
- ❖Unfavorable channel conditions
  - ➢ Due to mobility or environment conditions a channel can become unsuitable for data transmission



DYNAMIC SPECTRUM SWITCHING

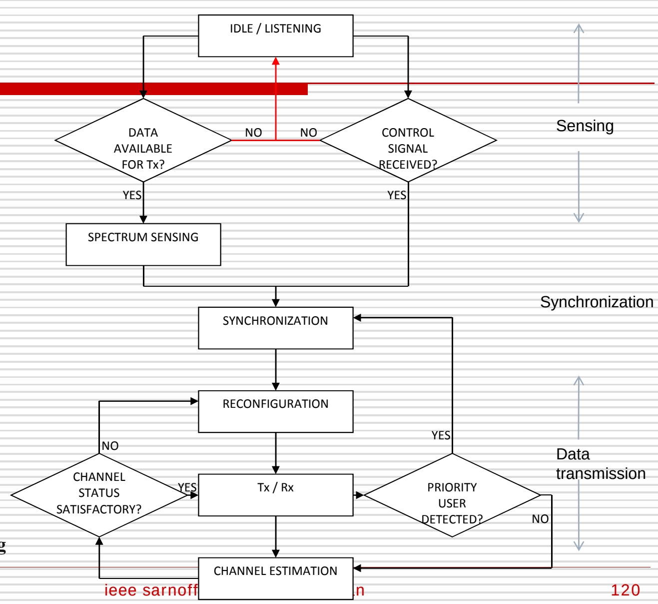
DYNAMIC SPECTRUM SWITCHING:

Cognitive Radio Test Bed

TX-RX FREQUENCY SYNCHRONIZATION – DYNAMIC SPECTRUM SWITCHING

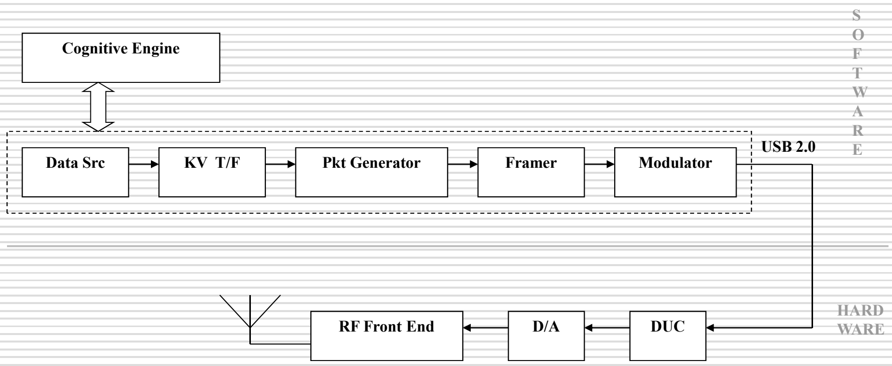
- **Priority user detection:**
  - Each node has a data radio and a listening radio tuned to same channel during transmission.
  - Priority User sends a Pilot signal requesting to vacate channel in the data channel
  - Cognitive Radio Users(C.R.U s) negotiates(in the same channel) to switch to a different frequency.
  - P.U waits for C.R.Us to negotiate and vacate channel.
- **Unfavorable Channel condition**
  - Transceivers dynamically vary radio parameters to account for noisy channel.
    - ✓ error rate is not acceptable after reconfiguration: CRUs switch to a new channel after negotiation on same channel.

SYSTEM IMPLEMENTATION



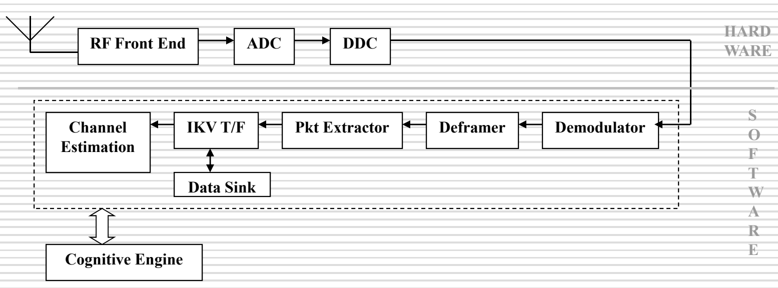
Basic Flow Chart showing CR System operation

DATA TRANSMISSION



BLOCK DIAGRAM: TRANSMITTER

DATA TRANSMISSION (CONTD..)

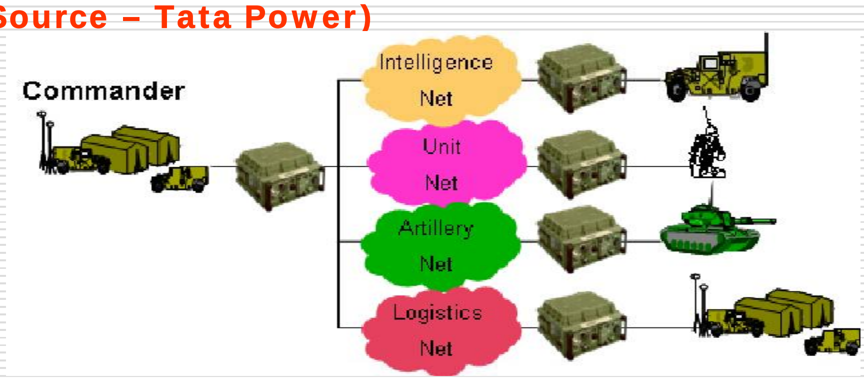


BLOCK DIAGRAM: RECEIVER

DISTRIBUTED MANAGEMENT FUNCTION

- Dynamic Management of Trust Software
- Cross Layer Security Function
- Cross Layer Management of QoS
- Automatic Reconfigurability Management of SDR
- Multi-path Fading Management
- Cognitive Radio Management

Mobile Adhoc Radio Nets (Source – Tata Power)



- Tanks/B-vehicles with high power radios
- Infantry soldier with low power radios
- Possible to send real time UAV data direct to Man-pack Radio

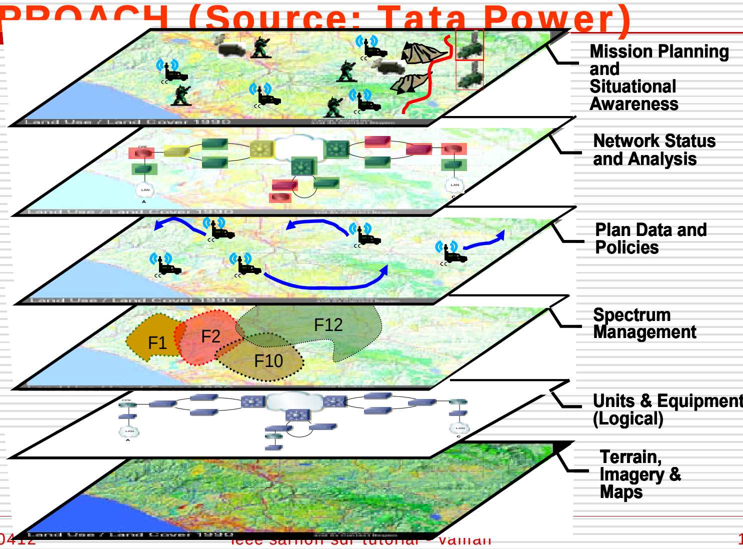
Edge of Battlefield Solutions
(Source - Tata Power)

- Tactical Access Router Switch (TARS)
  - All IP
  - Integrated Routing and Switching functionality supporting standard Protocol
  - Multi interfaces
  - Open source based
- Digital Control Harness (DCH)
  - All IP
  - Intra Tank Voice communication
  - Integration with onboard Radio for voice / data
  - Audible alarm annunciation of tank parameters
- Tactical Field Computer (TFC)
  - JSS 55555 and MIL STD 461E compliant
  - Ballistic Computer / Man Machine Interface for Artillery Applications
  - Battle Management System (BMS) Node

Next Generation Edge of Battlefield Solutions (Src: Tata Power)

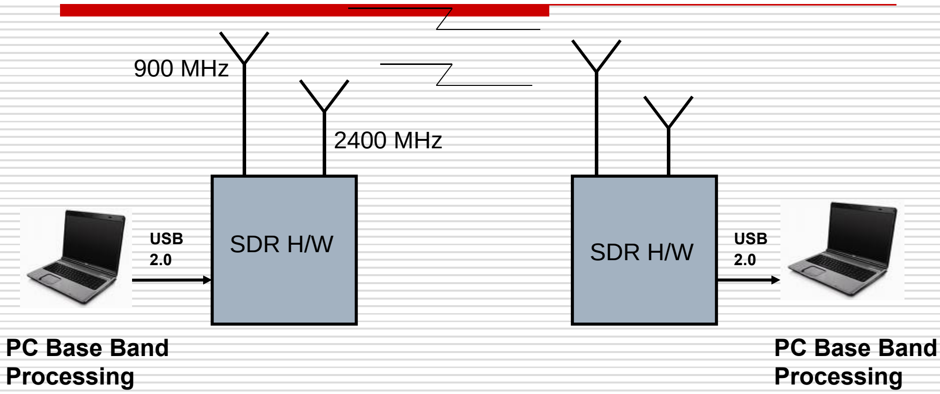
- Platform based for multi-role, multi-function deployment
  - SAMVAD as platform for Digital Control Harness, Intra Ship Communication
- Distributed Architecture
  - No single point of failure
  - Lesser power consumption
- Modular
  - Scalability based on addition of modules only from low to heavy deployment
  - Software upgrade only

LAYERED NETWORK MANAGEMENT APPROACH (Source: Tata Power)



INITIAL DEVELOPMENT OF SDR

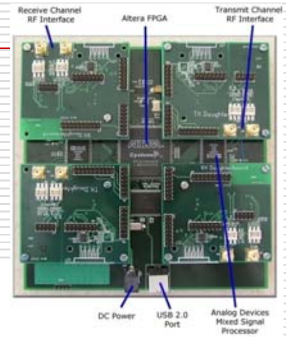
INITIAL SDR DEVELOPMENT SYSTEM



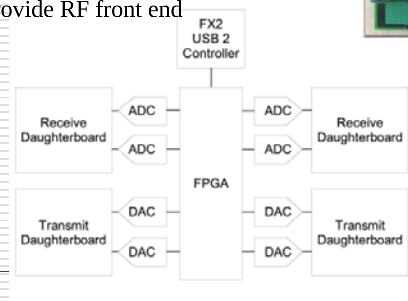
GNU RADIO AND UNIVERSAL SOFTWARE RADIO PERIPHERAL(USRP)

- **A low cost SDR Platform combing GNU radio and USRP**
- **GNU Software radio(GSR): [7]**
  - **Open source Software radio Development Kit**
  - **Flow graphs and applications in PYTHON**
  - **Critical signal processing blocks in C++**
  - **Reasonably Hardware Independent**
  - **A dedicated host computer is required per radio to run GSR.**

UNIVERSAL SOFTWARE RADIO PERIPHERAL



- Four 12 bit per sample, 64MS/s ADCs
- Four14 bit per sample 128MS/s DACs
- Field Programmable Gate Array (FPGA)
- Programmable USB2.0 interface
- Transceiver boards provide RF front end



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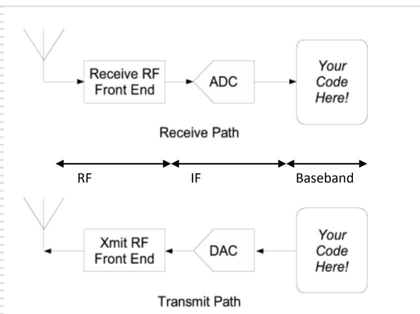

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STRUCTURE OF MESSAGES EXCHANGED BETWEEN TRANSMITTER AND RECEIVER

•Control Message from transmitter

Message Type	Destination Address	Source Address	Center Freq	Bandwidth	Modulation	KV parameters

•Control Message acknowledgement from transmitter

Message Type	Destination Address	Source Address	ACK	Accept/Reject chosen channel

•Packet payload

Length of retransmitted blocks	Retransmitted blocks	M	Kv1,1	Kv1, 2	… …	Kv1, 16	Kv2 ,1	…. .	Kv4, M	Ov1,1 to Ov1, M	Ov2,1 to Ov2,M

•Data message from Transmitter

Message Type	Destination Address	Source Address	Sequence Number	Packet Payload

•Data Message Acknowledgement from receiver

Message Type	Destination Address	Source Address	No: of Blks in error	Blks to be retransmitted	Preferred modulation	Preferred Reconfiguration parameters (optional)

FUNCTIONAL MODULES DEVELOPED

- Dynamic Modulation
  - Switching of GMSK, DBPSK, DQPSK

  (Other modulations such as AM, FM are available)
- Spectrum Sensing, Dynamic Channel Allocation and Switching of Channels, Dynamic frequency switching during transmission
  - Spectrum Search
  - Detection
  - Dynamic Channel Allocation
- Transmit and Receive simultaneously on Different Frequencies using MIMO

EXPERIMENTAL SETUP

- Implemented Cognitive radio operation is demonstrated using two CR nodes operating as transmitter and receiver.
- A third node serves as priority user to demonstrate dynamic switching of spectrum
- A single Node is implemented using:
  - A Linux PC running GNU Software radio Platform
  - A USRP Board (version 1)for RF front end and A/D-D/A Conversion
  - Two transceiver boards serving as (RFX900)
    - a) Data Radio b) Listening radio
  - Two 800MHz – 1000MHz antennas

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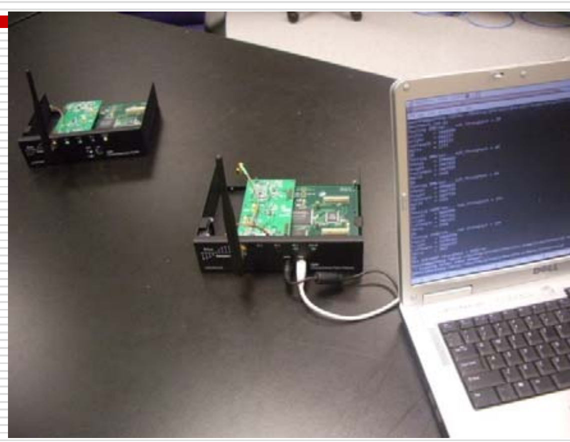

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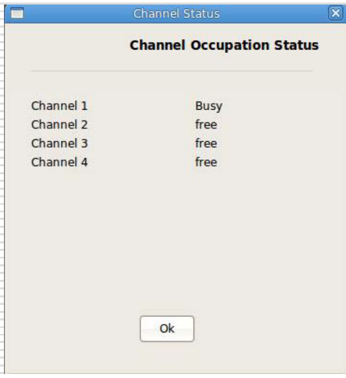
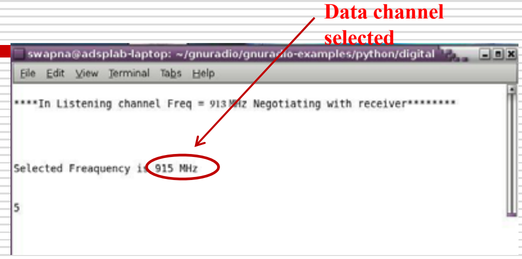
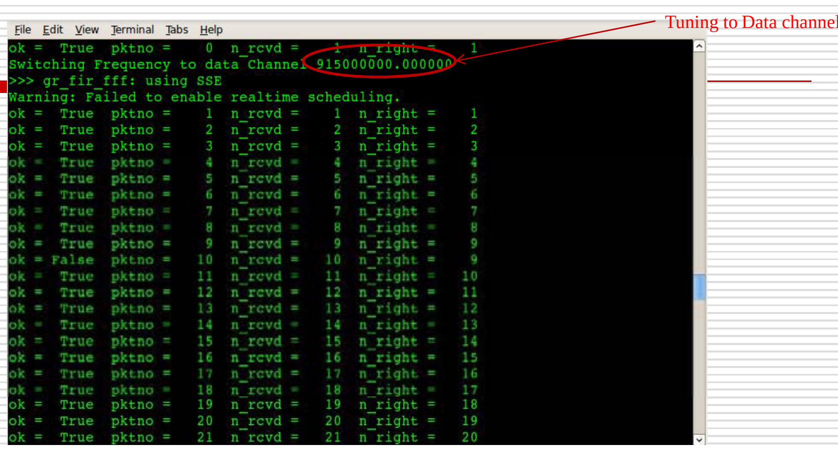
RESULTS



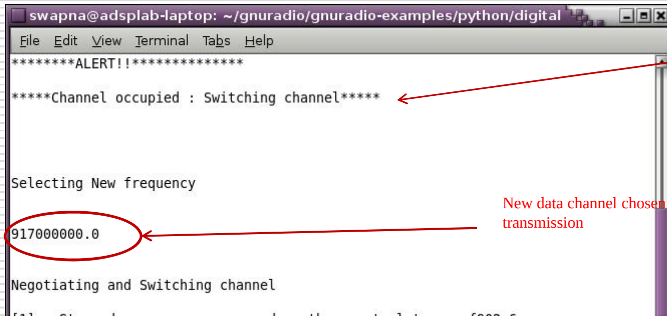


❖ ***Frequency Synchronization: Transmission of Control message in Listening Channel***

❖ ***Channel status: Spectrum sensing output***



❖ *Data Reception :output at receiver*

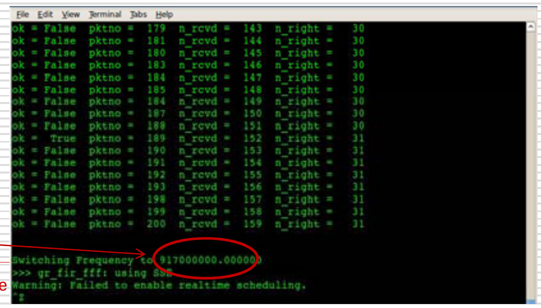


Transmitter senses Priority user

New data channel chosen for transmission

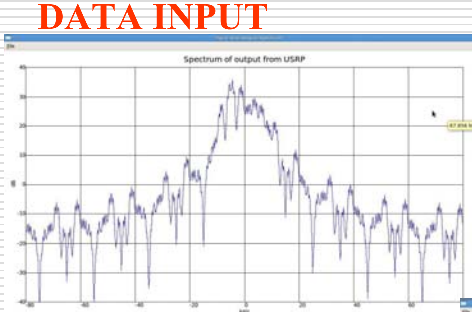
❖*Dynamic Frequency Switching at Transmitter*

❖*Dynamic Frequency Switching at receiver*



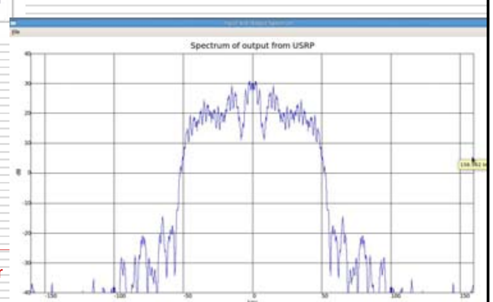
Receiver Synchronization to selected frequency

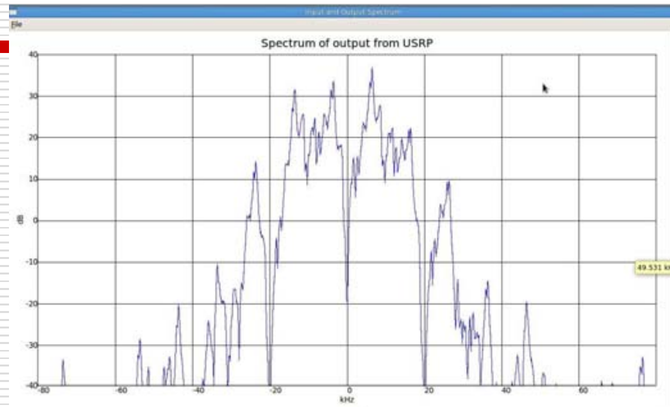
SPECTRUM OUTPUT FOR MODULATORS WITH DATA INPUT



GMSK Modulator

DBPSK Modulator

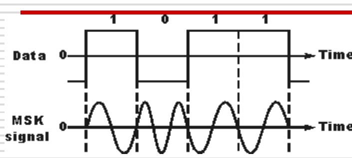




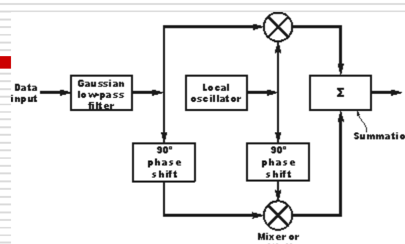
DQPSK Modulator

MODULATORS IMPLEMENTATION

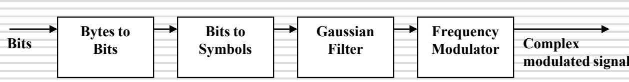
GMSK



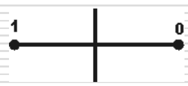
MSK Modulated signal



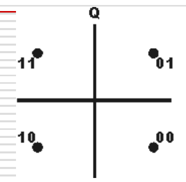
Block diagram :Generating GMSK Modulated signal



PSK CONSTELLATION DIAGRAMS

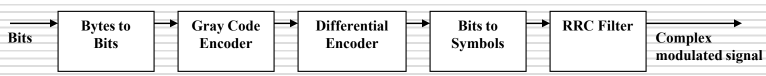


BPSK



QPSK

PSK Software Implementation



CONCLUSION

- Presented the evolution of Cognitive Radio in Battlefield MANET and Dynamic Variability of Different Functional Components in Layered SDR Approach:
  - Cognitive Radio Capabilities: Spectrum sensing, transmitter receiver frequency synchronization, dynamic switching of frequencies
  - Multiple modulation schemes and dynamic switching of modulations
  - KV transform coding for multipath error handling and channel estimation and dynamic variation of number of bits/input sample to maintain target BER.
- Cognitive Radio MANET Design using Distributed Slot Selection Process

CAUTION ON THE USE OF COGNITIVE RADIO

While Engineers who are in R&D working on Cognitive Radio provide ever optimistic opinion – "it is coming", there are still larger issues that concern users and developers.

Battlefield is very different from commercial environment in the sense of security and theater constraints.

The users feel unsecure of making distributed decisions on selecting the slots due to potential intruders or malicious radios. Any solution to identify malicious radios should not make radios and networks inefficient with respect to power and bandwidth.

Challenge is to find the solution for spectral efficiency while maintaining power and bandwidth efficiency.

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PEACE