Tutorial

European Wireless 2002

February 25-28, 2002

Florence, Italy

Ad-hoc/Multi-hop Networking for Wireless Internet

Prof. Bijan Jabbari, PhD
George Mason University
Fairfax, VA 22030, USA

bjabbari@gmu.edu
http://mason.gmu.edu/~bjabbari

February 25, 2002

Outline

- Introduction
- Self-organization
- System modeling
- Wireless multi-hop networks overlaid with cellular structure
- Capacity enhancement techniques
- Network Throughput
- Concluding remarks

Updated Presentation Material

Soft copy of the presented material will be available at http://cnl.gmu.edu/SOPRANO, Username ew2002 and Password ew2002.

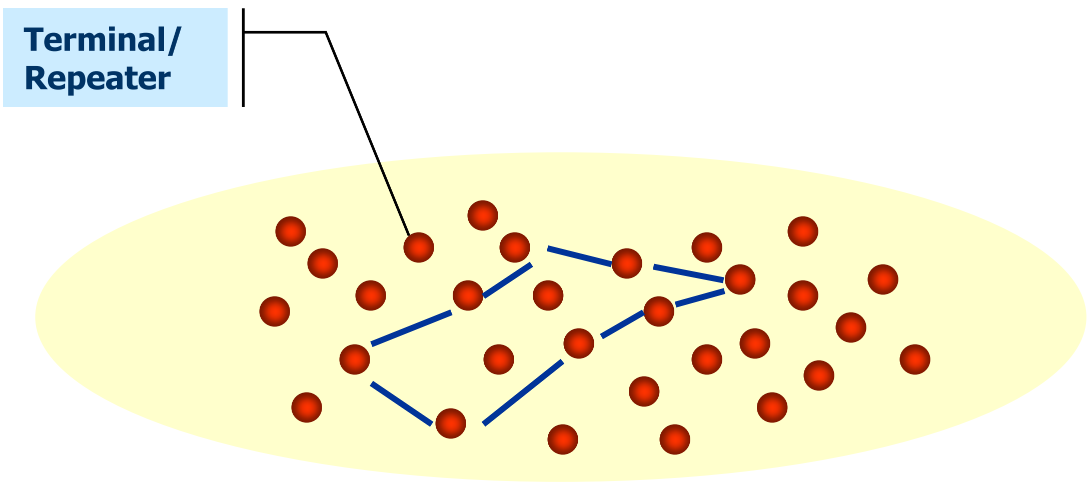
I wish to thank my doctoral students A. N. Zadeh and C. A. St Jean for their help with preparation of the material.

Wireless Ad hoc Networks

- A set of wireless devices/nodes which form a network with dynamic topologies
  - Not dependent on a pre-exiting infrastructure
- Properties
  - Topology may change randomly with time
  - Multi-hop and capability to relay traffic
  - Self-configuring/self-organizing capabilities
  - Bandwidth and energy constraints
  - Rapid and ease of deployment
  - Robust and survivable
  - Routing opportunity
  - Mobility support
  - Resource sharing in space, time, and frequency

Adhoc/Multi-hop Networks

- Routing is at the core of the problem
- Scalability is an important issue
- Realization needs to be addressed



Driving Forces

- Applications
  - Emergency/distress response units
  - Military/police/carabinieri
  - WPANs and WLANs
  - Conference/exhibit centers/stadiums
  - Public transportation
- Complementing local and cellular operators
- Potential in addressing COS/QOS
- Implementation
  - Low cost semiconductor implementation
  - Inherent economy of scale

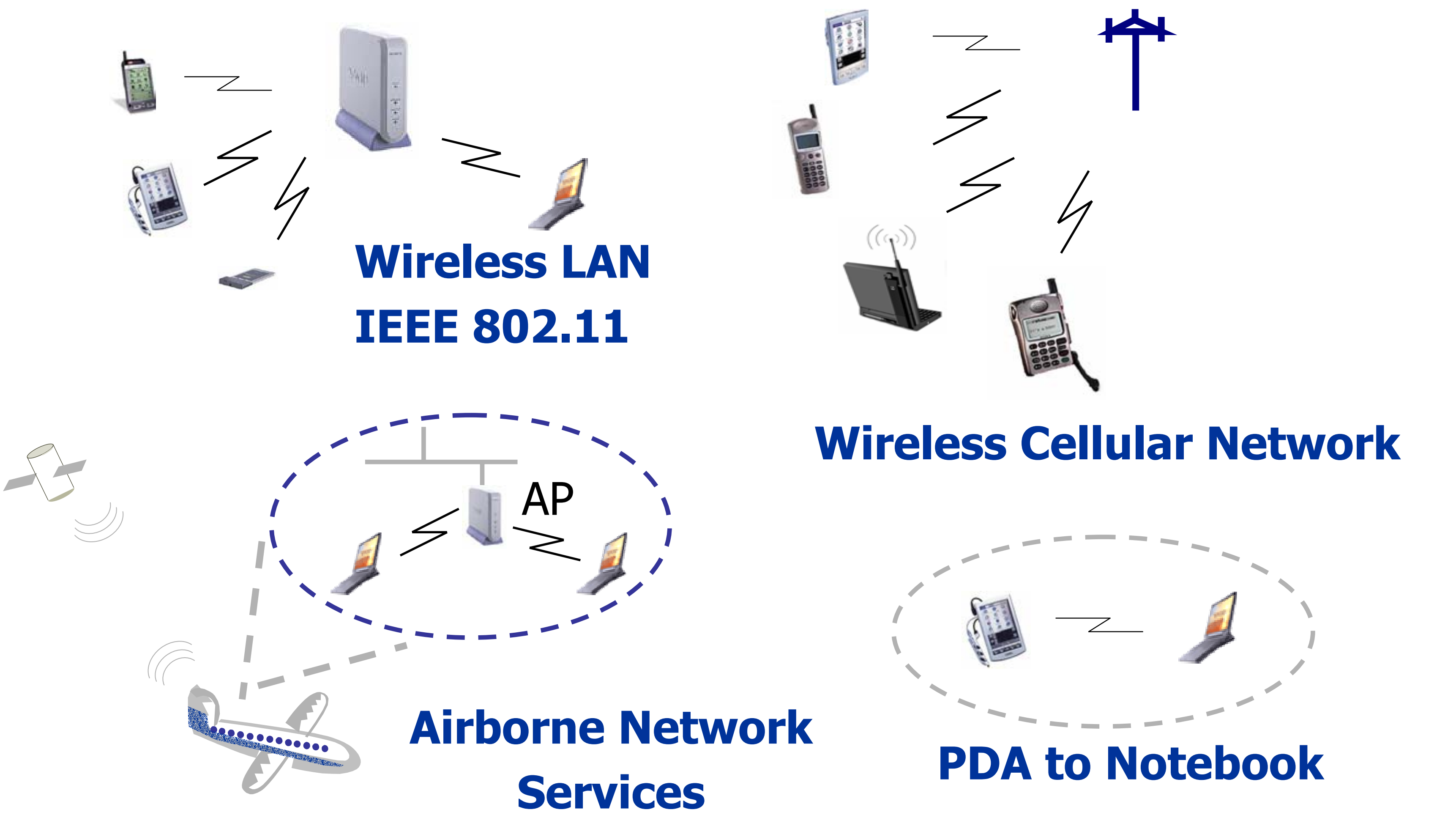
Part I - Introduction

Review of the packet radio and its use in Ad-hoc networks

Multi-hop Networks

- Originally intended to represent the extension of packet switching technology into mobile user environment
  - DARPA effort as part of Packet Radio Network Program
  - PRNET research effort initiated by DARPA in 1972
  - Several programs in 70's, 80's and 90's
    - Survivable radio networks
    - Instant Infrastructure program
  - Mobile Ad-hoc Networks (IETF MANET)
  - Opportunity Driven Multiple Access (ODMA)
    - Evaluation document by ETSI SMG2, Dec 97
  - IEEE802.11, Bluetooth, Wireless Internet, etc.
  - UWB

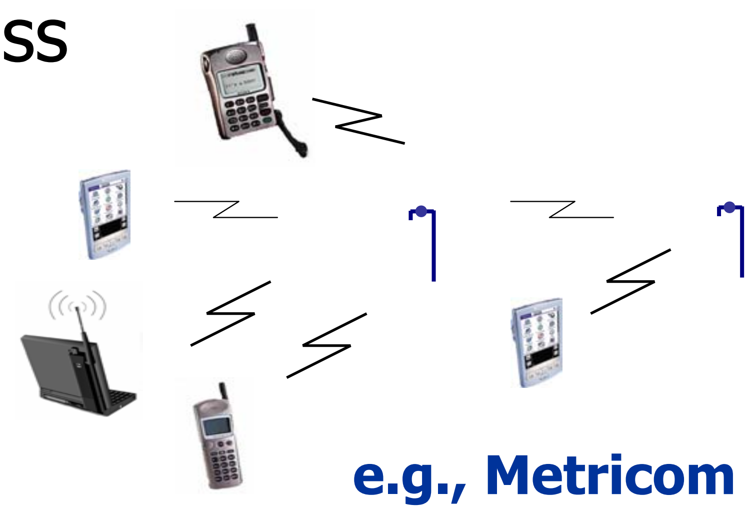
Single-hop Structure



Multi-hop Structure

- Local area wireless

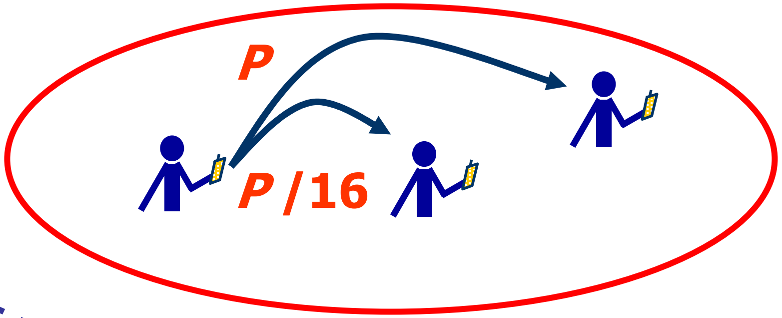
- Wide area wireless

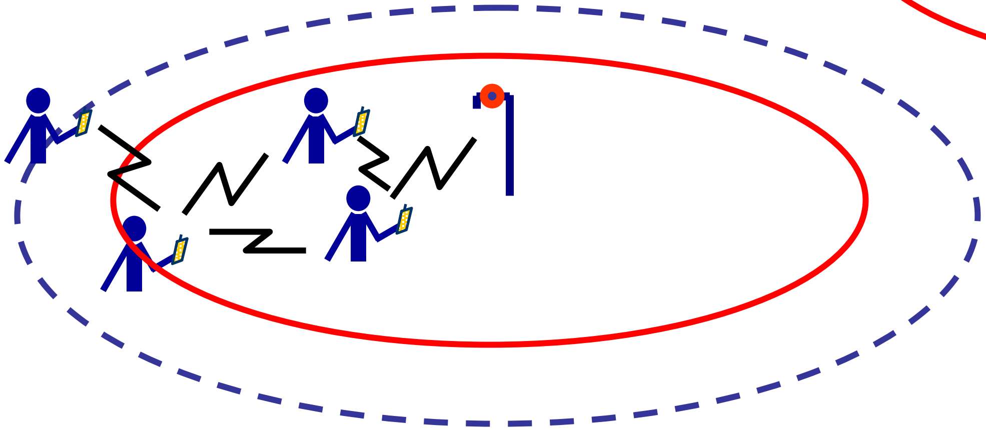


e.g., Metricom Ricochet

Why Multi-hop?

- Reduced terminal power
- Possibly less interference
- Coverage extension
- Dynamic topology through packet radio





CNL Communications & Networking Laboratory

The Wireless World and Mobility

Multi-hop Networks

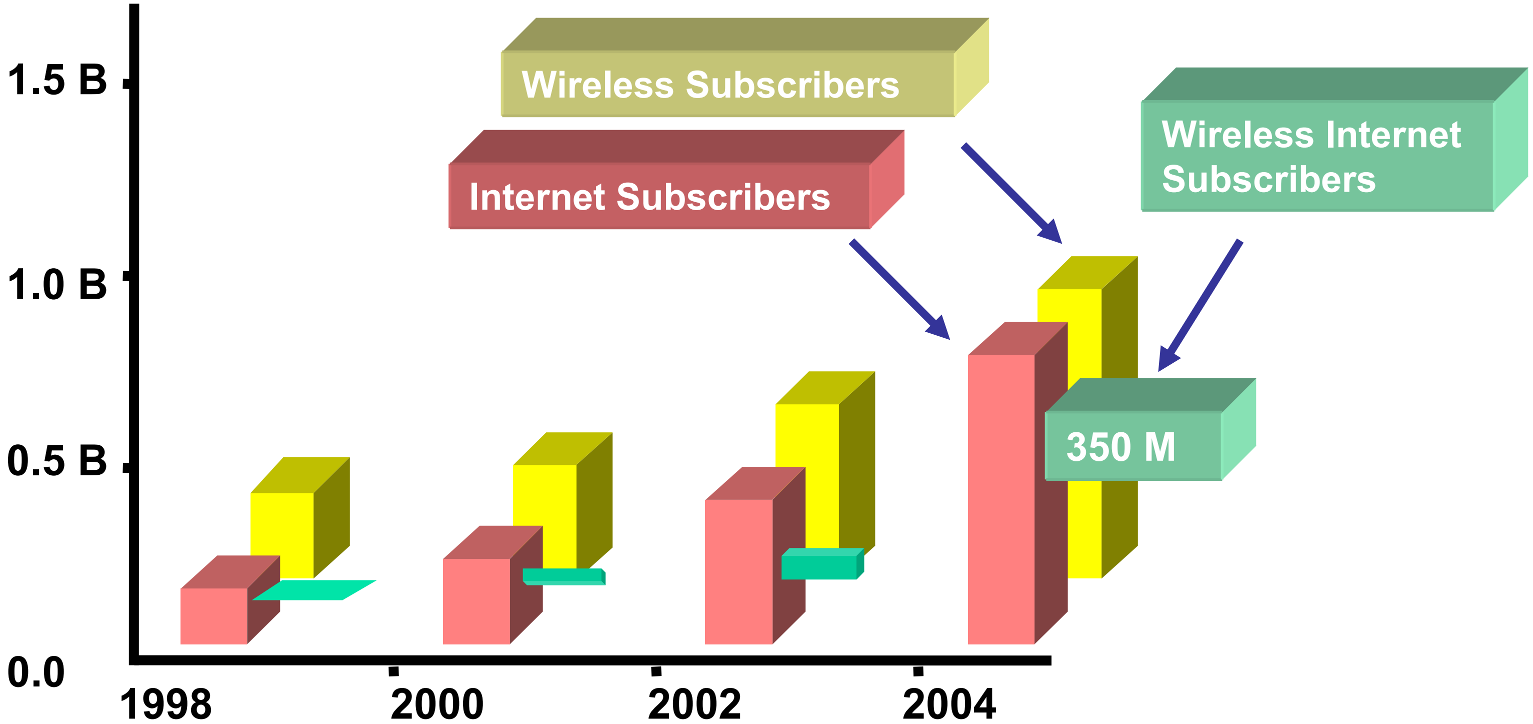
- No pre-existing infrastructure (Ad-hoc)
- Self-organizing
- Low power
- Wide-area & LAN
- Packet radio-based

Cellular Networks

- Fixed infrastructure
- Controlled interference
- Wide-area & LAN
- Packet and circuit-based

Wireless Internet

Projected Demand for Wireless Internet



Source: ITU, MWIF, ETSI, TIA, etc.

More Applications

- Sensors and embedded controllers
  - Automobile collision avoidance, remote sensor networks, weather conditions
  - Maintenance data from vehicles, high speed trains, airplanes
- Emergency response
  - Early transmission of patient data from ambulances
  - Fixed network infrastructure replacement in disaster relief such as fire, earthquake, and flood
- Mobile multimedia services and network capability responsive to applications
- Communications services for exhibit centers
- Education, multi-user games, entertainment
- Location and location-dependent information
- Wireless Internet: email, portals,.....and fridge-to-store

Ultra-WideBand (UWB) Standard

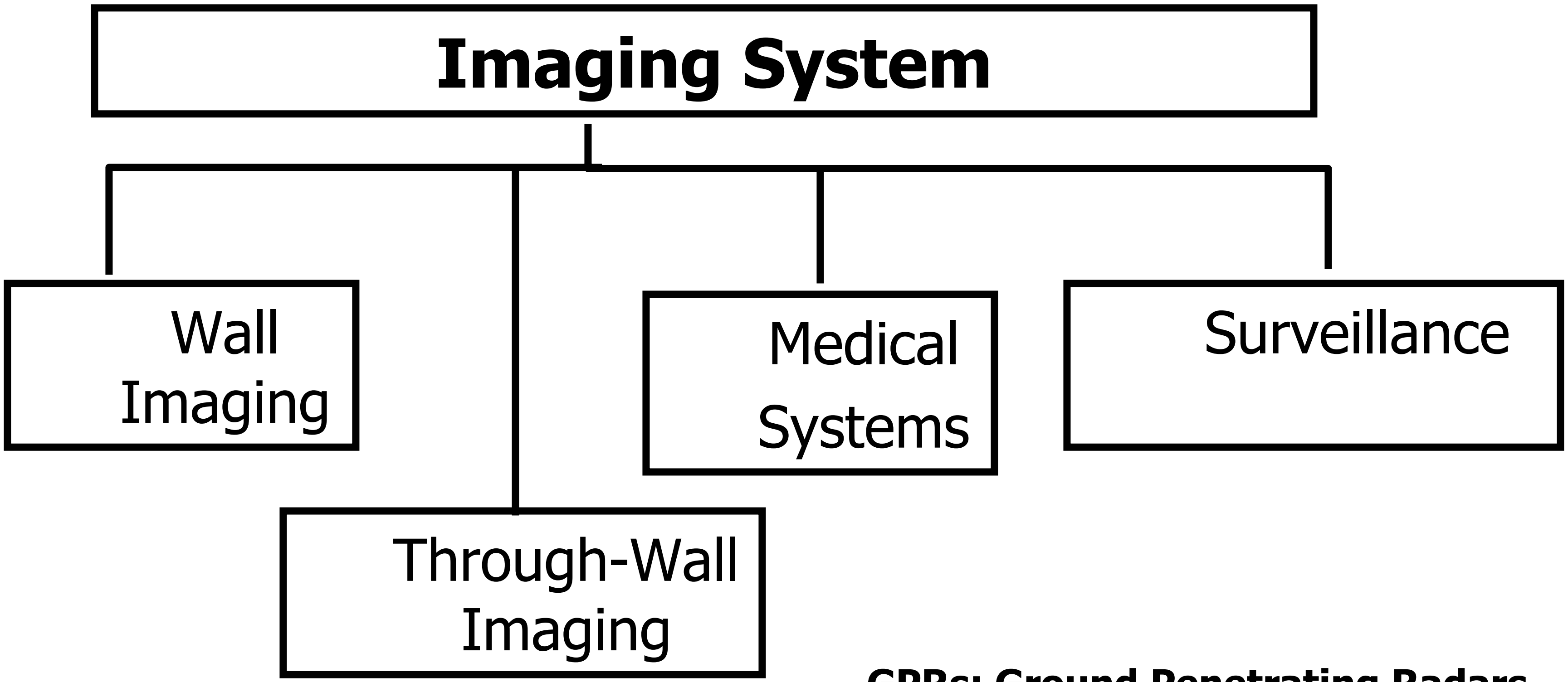
- On February 14, 2002 Federal Communications Commission (FCC) issued a new Order permitting marketing and operation of products incorporating Ultra-WideBand (UWB) Technology
- UWB devices operate by employing very narrow or short duration pulses, which results in very large transmission bandwidths
  - UWB shares the same spectrum as that occupied by existing radio services, thus increase the spectrum usage efficiency
  - The objective is to ensure the level of interference from operation of UWB devices is sufficiently low
  - Using the provided technical standards the radio services (particularly safety services) are adequately protected

Motivation for UWB and Technology Authorization

- New public safety applications and broadband internet access among uses envisioned by Recent FCC "Order"
- The Order establishes different technical standards and operating restrictions for three types of UWB devices based on their potential to cause interference
- The three types of UWB devices are:
  - 1) Imaging systems including Ground Penetrating Radars (GPRs), wall, through-wall, medical imaging, and surveillance devices
  - 2) Vehicular radar systems
  - 3) Communications and measurement systems

Imaging Systems

- Operation of GPRs and other imaging devices subject to certain frequency and power limitations



GPRs: Ground Penetrating Radars

Wall Imaging Systems

- Goal: Designed to detect the location of objects contained within a "wall,"
  - E.g., a concrete structure, the side of a bridge, or the wall of a mine
- Operating frequency band
  - below 960 MHz, or
  - in 3.1-10.6 GHz
- Restricted to
  - law enforcement
  - fire and rescue organizations,
  - scientific research institutions
  - commercial mining companies
  - construction companies

CNL Communications & Networking Laboratory

Through-Wall Imaging Systems

- Goal: Designed to detect the location or movement of persons or objects that are located on the other side of a structure such as a wall
- Operating frequency band
  - below 960 MHz, or
  - in 1.99-10.6 GHz
- Limited to
  - law enforcement
  - fire and rescue organizations

Medical Imaging Systems

- Goal: Used for a variety of health applications for example to help diagnose the human or animal anatomy (under health director supervision)
- Operating frequency band
  - 3.1-10.6 GHz

Surveillance Systems

- Goal: To provide security zones
  - Establishes a stationary RF perimeter field to detect the intruders (persons or objects) in that field
  - Treated in the same way as through-wall imaging
- Operating frequency band
  - 1.99-10.6 GHz
- Limited to
  - law enforcement
  - fire and rescue organizations
  - public utilities
  - industrial entities

CNL Communications & Networking Laboratory

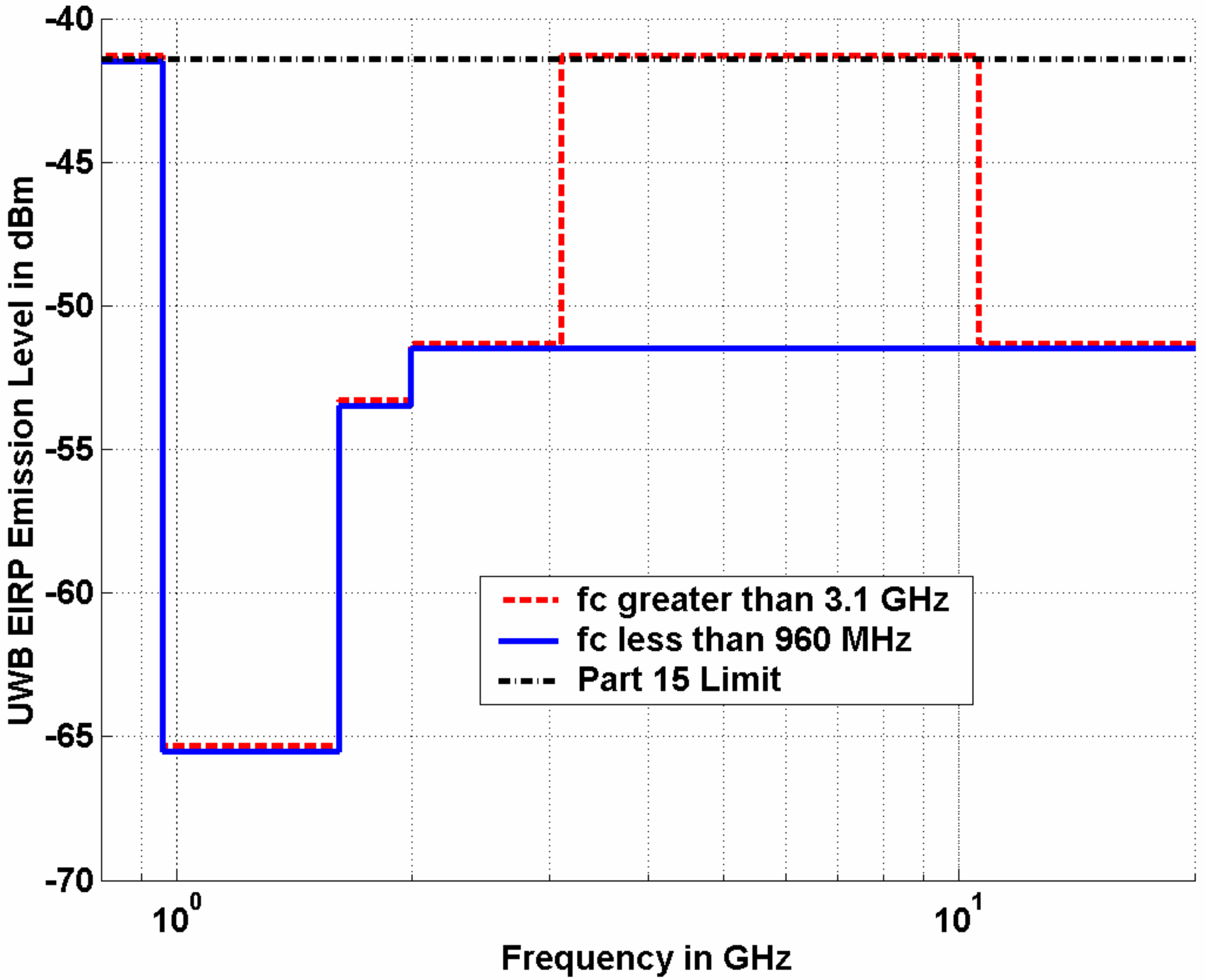
Vehicular Radar Systems

- Goal: Vehicular radar systems using directional antennas on terrestrial transportation vehicles
- Operating frequency band is 24 GHz
  - the center and the highest radiated emission frequency are greater than 24.075 GHz
- Capable of detecting the location and movement of objects near a vehicle
  - to enable features such as near collision avoidance
  - improved airbag activation
  - suspension systems with better response to road conditions

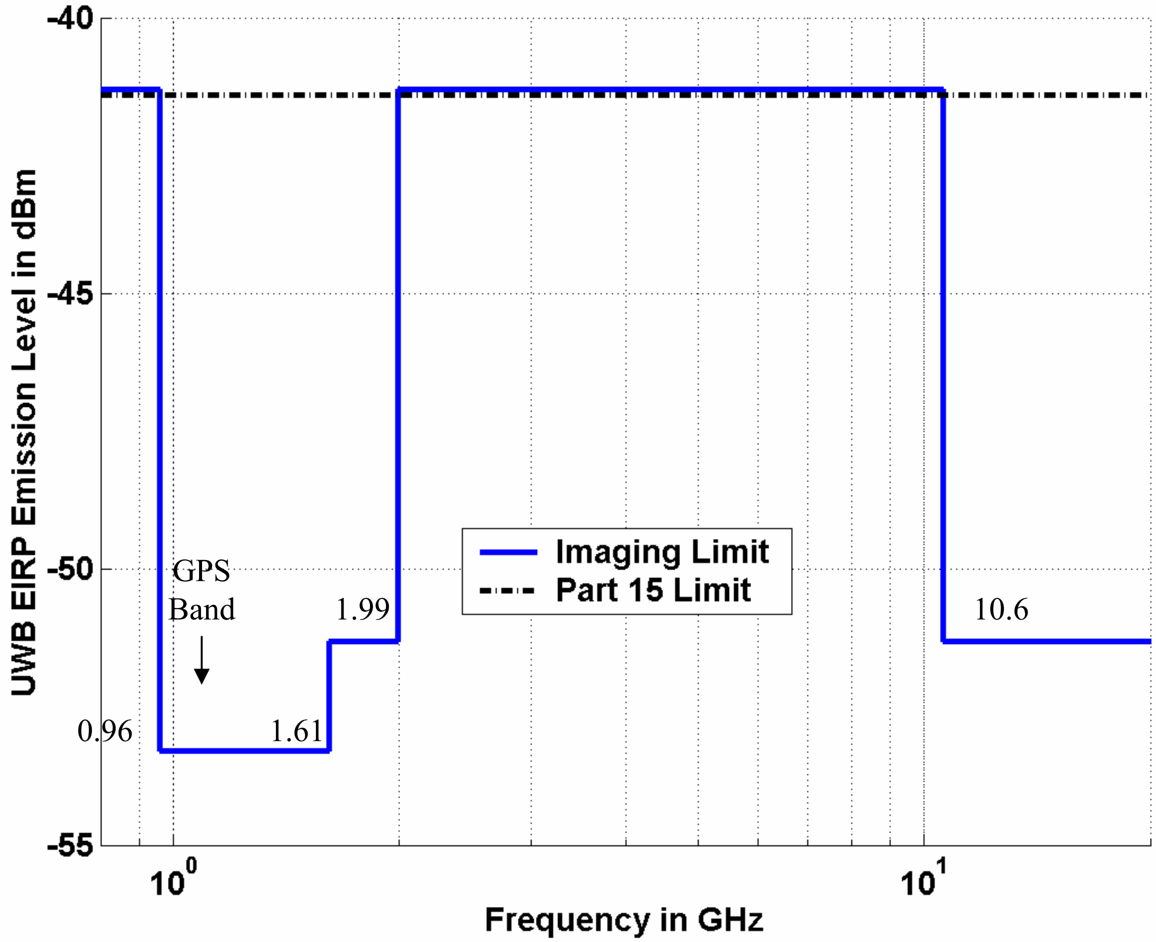
Communications and Measurement Systems

- Goal: A wide variety of other UWB devices, such as
  - high-speed home and business networking
  - storage tank measurement
- Operating frequency band
  - 3.1-10.6 GHz
- operation limited to
  - indoors, or
  - peer-to-peer operation using hand-held devices

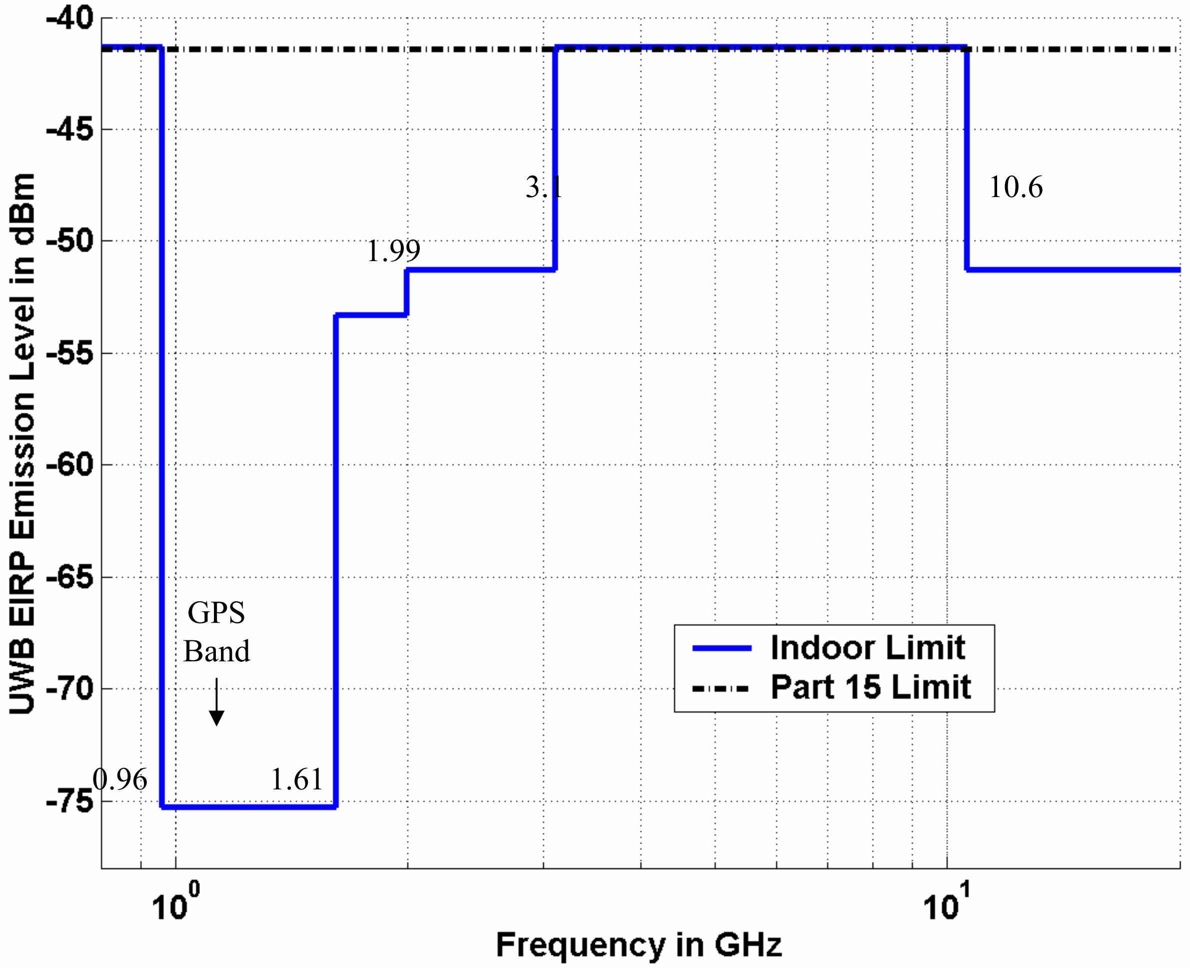
Emission Mask



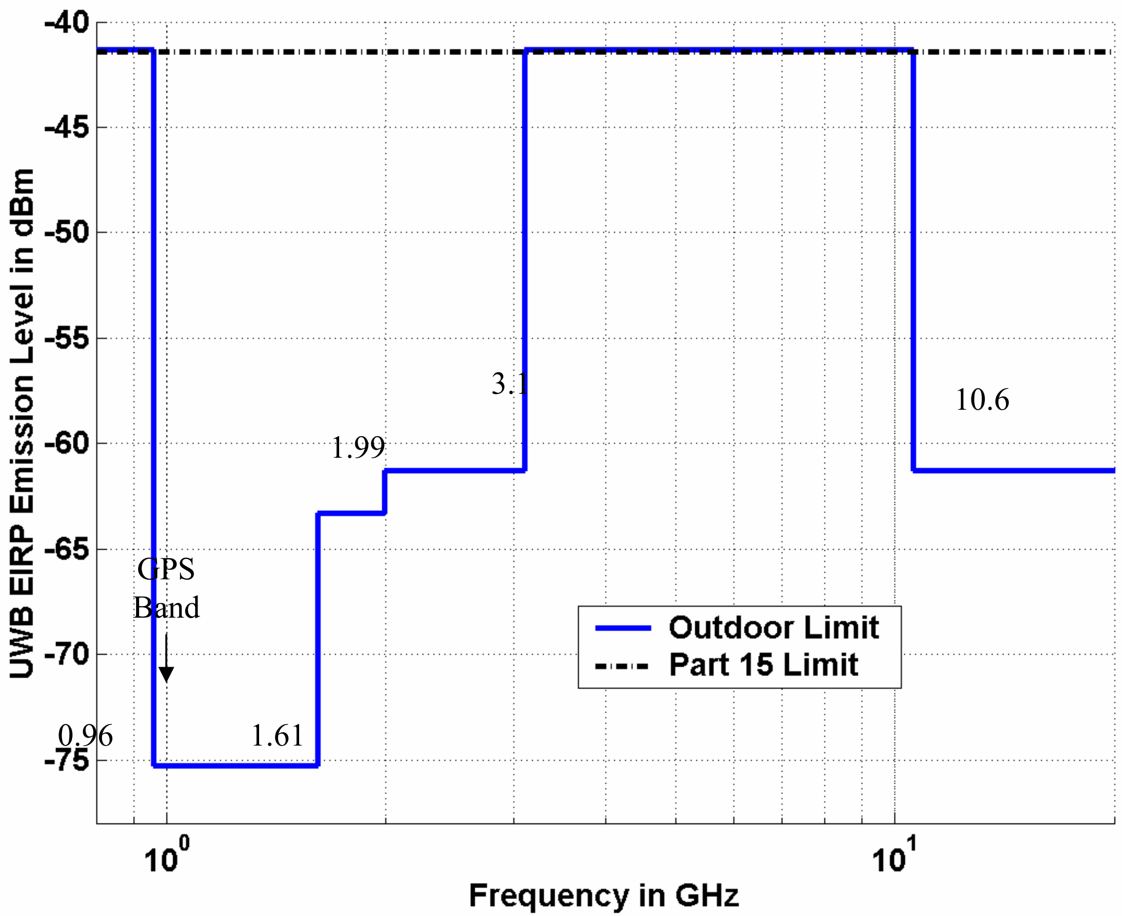
Emission Mask



Emission Mask



Emission Mask



B. Jabbari

Part II

Self Organization

Self Organization

- Self-Organization involves architecture, algorithms, configurations, and all those means which allow mobile terminals to obtain interconnection to the network and adapt to the environment as changes occur

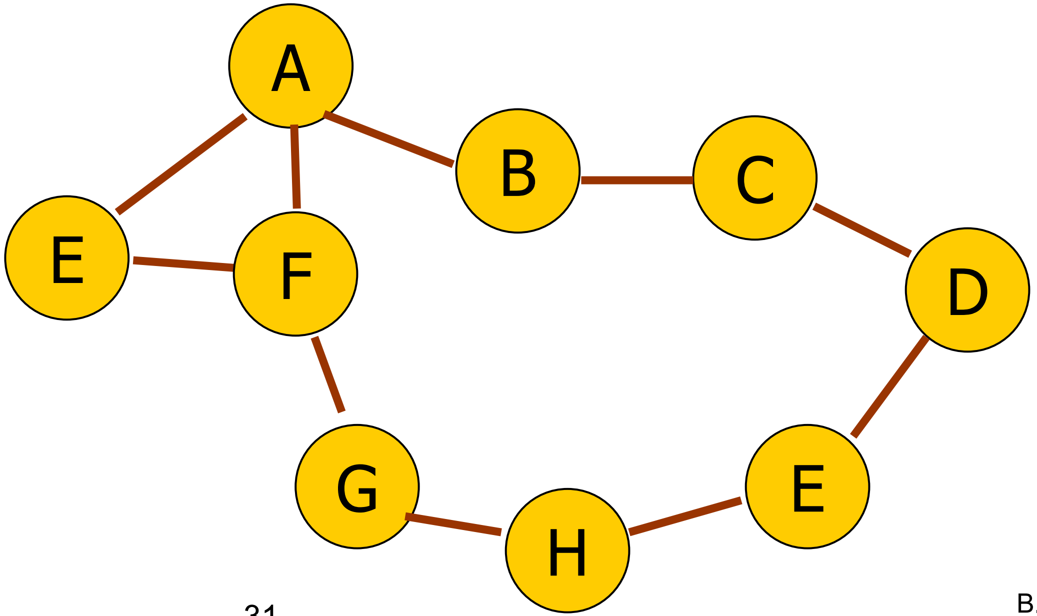
- This includes access, control and service aspects, routing, traffic control, profile management, self healing, etc.

Self Organization

- Neighbor discovery
- Channel setup
  - Spreading code assignment in CDMA
  - Frame structuring in TDMA
  - Frequency coordination in FDMA
- What and how control and routing information is exchanged
- Topology updating

Routing

- Flooding and traditional routing algorithms
- Routing tables and path computation algorithms
- Information in packet headers



A Taxonomy of Ad Hoc Routing

Ad Hoc Routing Protocols

- **Algorithms which do not consider signal propagation effects**
  - Minimize Hop Count
  - Stress Connectivity
- **Algorithms which consider signal propagation effects**
  - Minimize Interference
  - Maximize Signal Stability
  - Minimize Transmit Power
  - Maximize Mobile Station Lifetime
  - Maximize Capacity

Ad Hoc Routing Protocols: Propagation Effects Not Included

CNL Communications & Networking Laboratory

- Objectives:
  - Minimize hop count (usually with preference to minimum delay paths)
  - Insure node connectivity
  - Minimize overhead during topological changes
- Includes
  - Distance vector protocols (DSDV, AODV)
  - Source routing (DSR)
  - Associativity-based routing (ABR)
  - TORA

Acronyms

- DSDV: Destination-Sequenced Distance-Vector Routing
- AODV: Ad Hoc On-Demand Distance Vector Routing
- DSR: Dynamic Source Routing
- ABR: Associativity-based routing
- TORA: Temporally Ordered Routing Algorithm

Table vs. Demand -Driven Protocols

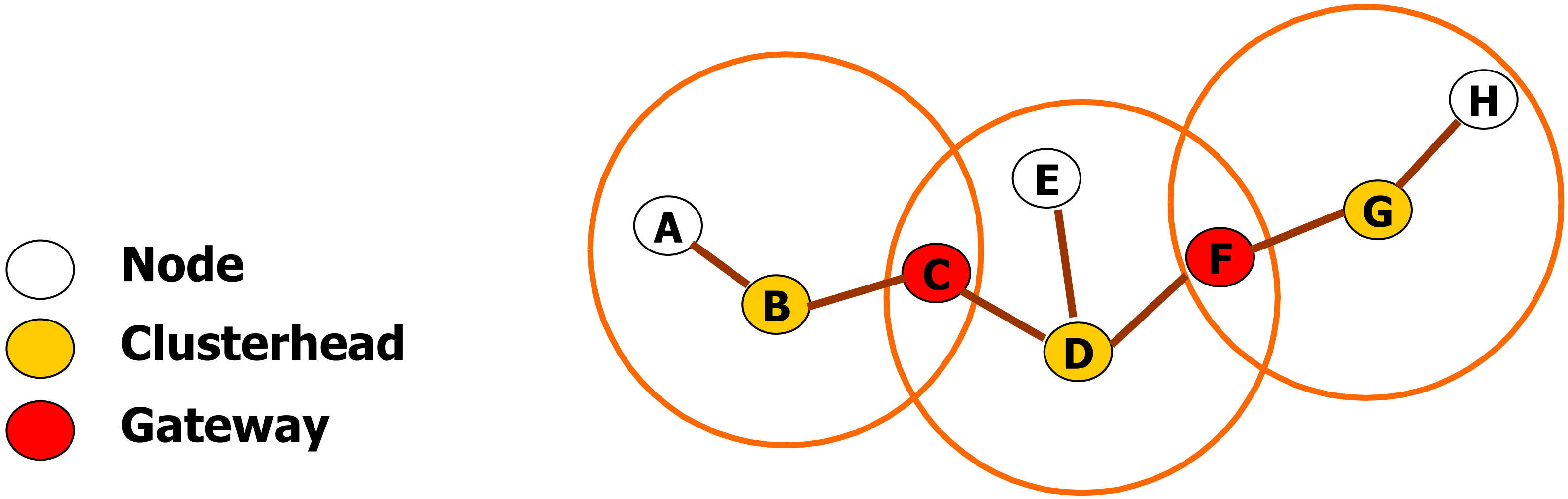
- Table-Driven
  - A route to every other node in the ad hoc network is always available, regardless of whether or not needed
  - Substantial signaling traffic and power consumption
- Source-initiated (demand-driven)
  - When a node desires a route to a new destination, it will have to wait until such a route can be found
  - Requires less signaling and power consumption but adds delay

Destination-Sequenced Distance-Vector Routing (DSDV)

- Basically enhanced classical Bellman-Ford routing mechanism (w/o looping)
- Each entry is marked with sequence number to distinguish stale routes from new ones
- Routing table updates are periodically transmitted throughout the network for consistency
- Delay implemented by the length of the settling time to reduce network traffic
- Brute force approach
  - It depends on correct operation on the periodic advertisement and global dissemination of connectivity information

Hierarchical Routing

- Important for scalability
  - Cluster head is used to control a group of ad hoc nodes
  - Hierarchical addressing scheme
  - e.g., Clusterhead Gateway Switch Routing where DSDV used as underlying routing scheme



Ad Hoc Routing Protocols: Propagation Effects Included

CNL Communications & Networking Laboratory

- Minimize Interference
  - Minimize the amount of interference encountered by a packet traversing a route (Least Resistance Routing)[1]
  - Minimize the amount of interference that a transmission will cause in a network[2, 3]

---

1. Pursley and Russell, *IEEE Trans. Commun*
2. Stevens, *Proc. Tactical Commun. Conf.*
3. Tsudaka, Kawahara, Matsumoto, and Okada, *IEEE Glocom*

Ad Hoc Routing Protocols: Propagation Effects Included

- Maximize Signal Stability[4]
  - Categorize links in an ad hoc network as either "strong" or "weak" based on signal strength
  - Give preference in connection establishment to links with strong connections, avoiding weak links if possible

4. Dube et al., IEEE Pers. Commun.

Ad Hoc Routing Protocols: Propagation Effects Included

- Minimize Transmit Power
  - Minimize total power of each path subject to minimum SNR requirements[5]
  - Minimize the total amount of energy consumed by the network[6]

---

5. Singh and Raghavendra, *ACM Commun. Rev*
6. Michail and Ephremides, IEEE PMRC

Ad Hoc Routing Protocols: Propagation Effects Included

CNL Communications & Networking Laboratory

- Maximize Mobile Station Lifetime
  - Out of all globally available nodes for a path, choose path which includes nodes with greatest amount of residual power[7, 8]
  - Prevent nodes from participating in route establishment if remaining power is not above a threshold[9]

---

7. Toh, " *IEEE Comm. Mag.*
8. Stojmenovic and Lin, *IEEE Trans. on Parallel and Distributed Systems*
9. Woo, Yu, Lee, Youn, and B. Lee Symp Mod&Simul

Ad Hoc Routing Protocols: Propagation Effects Included

- Maximize Capacity
  - Least developed as a routing metric
  - One solution: determine the minimum transmit power strategy required to achieve a fixed amount of network capacity[10]

---

10. St. Jean, Zadeh, Jabbari, VTC02

Example Routing Protocol Details

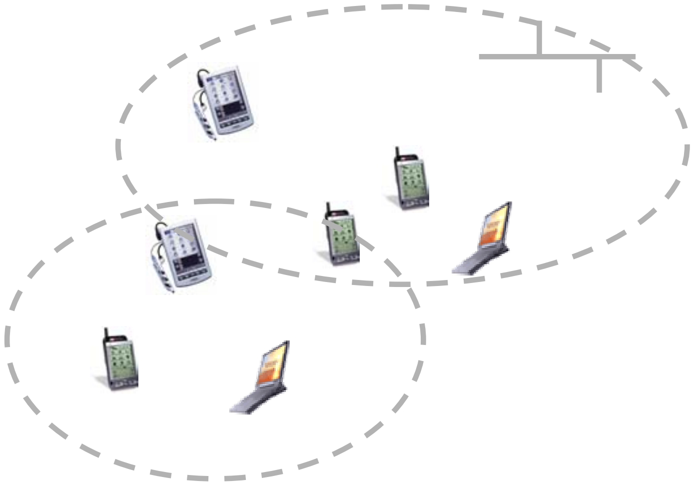
Protocol	Metric / Objective Function	Route Discovery	Response to Route Failure	Scalability	Notes
Signal Stability Routing (Dube et al.)[4]	Each link is assigned a signal stability of either "strong" or "weak." The routing path is (most likely) the shortest delay/ least congested path which includes only strong links.	Route selection is done by flooding route search packets but only on links that are deemed strong. A route reply is sent by the destination to the source along the path of the first received route search packet. If no strong paths exist, paths with one or more weak links are allowed.	Nodes upstream of the route failure send an error message to the source; a new route search is then initiated.	No hierarchical structure	
Minimum Total Transmission Power Routing (MTPR)[7]	Minimizes total transmit power in a distributed fashion by determining the minimum power required to transmit to each neighbor while insuring a minimum SNR. (Uses distributed Bellman-Ford.)	(Routing method is conceptual only, but would most likely include some flooding variant.)	(conceptual only)	No hierarchical structure	In its purest form, routes with a large number of hops may be chosen due to the r^{α} power dependence. Using total power (transmit plus receive) may help this.

Example Routing Protocol Details (cont.)

Protocol	Metric / Objective Function	Route Discovery	Response to Route Failure	Scalability	Notes
Minimum Battery Cost Routing (MBCR)[7]	A cost which reflects a node's unwillingness to forward a packet (because of low battery power) is assigned to each link. The path which minimizes this is chosen.	(Routing method is conceptual only, but would most likely include some flooding variant.)	(conceptual only)	No hierarchical structure	A variant includes choosing the path whose most energy-depleted node has the greatest residual energy reserves (min-max battery cost routing)
Local Energy-Aware Routing (LEAR)[9]	Similar to MBCR. However, here nodes chose whether or not to participate in route requests based upon their remaining battery lifetime.	Route selection is done by flooding route search packets. A node may not forward a route request, however, if the battery power remaining at a node is less than a predefined threshold. A route reply is sent by the destination to the source along the path of the first received route search packet. If no viable paths exist, the minimum battery power threshold is lowered.	The algorithm does make use a route cache for use in the event of link failures.	No hierarchical structure	Does not require full network topology

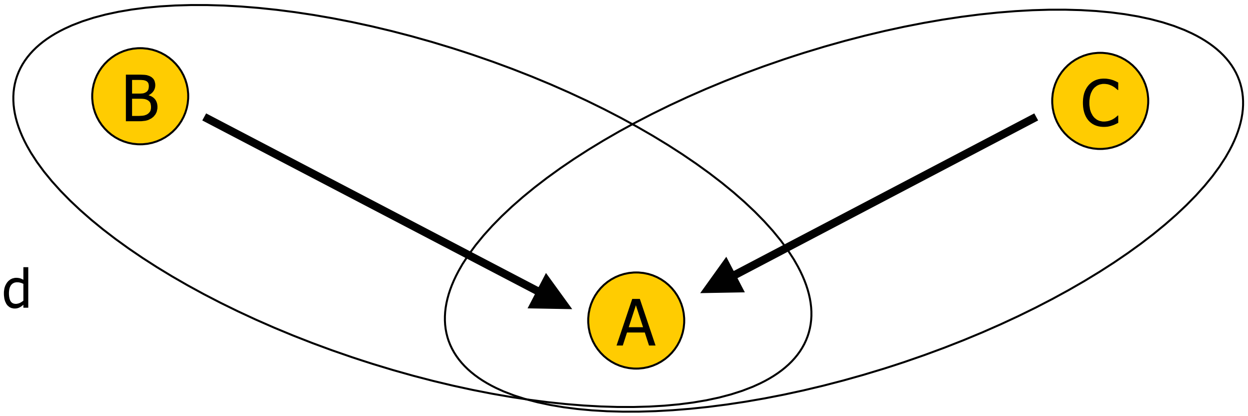
IEEE 802.11 DCF Mode Operation

- DCF (Distributed Coordination function) supports peer-to-peer ad-hoc/multi-hop networking
- It is CSMA-based with added functionality
  - RTS and CTS
  - ACK



Hidden Terminal Problem

- B and C can communicate with A
- But if both transmit in an overlapping time period to A, there will be collision
- Solution is Based on using RTS and CTS

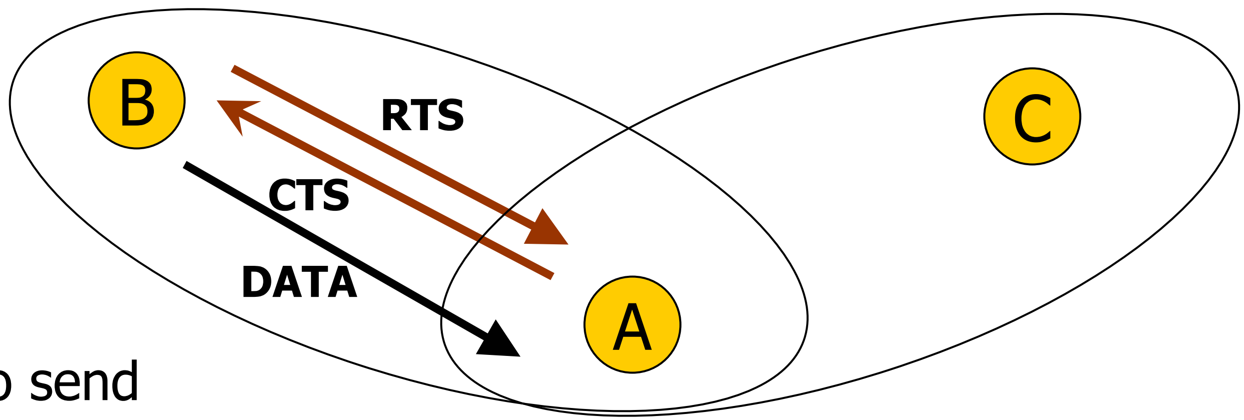


RTS: request to send

CTS: clear to send

RTS/CTS Operation

- Exchange of RTS and CTS before Data



RTS: request to send

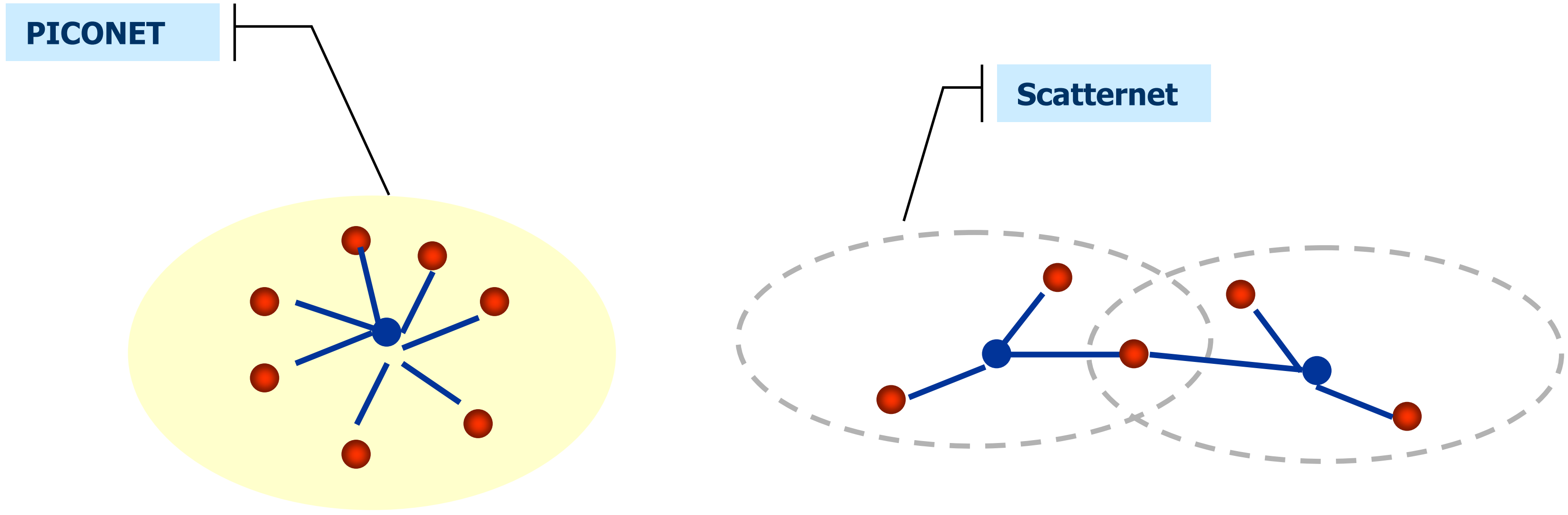
CTS: clear to send

CSMA Protocol

- CSMA
  - Wireless Medium Access protocol
  - Carrier Sense
- Collision Avoidance
- Congestion Avoidance

Bluetooth

- Piconet
- Scatternet



Bluetooth

- Developed through a consortium with many members
  - Original consortium comprised of Ericsson, Intel, IBM, Nokia, Toshiba
- Operates in 2.4 GHz band
- Ranges are 10 to 100 m
- GFSK modulation
- Frequency hopping
  - 79 hop carriers spaced 1 MHz apart
  - 1600 hops/sec
- TDD

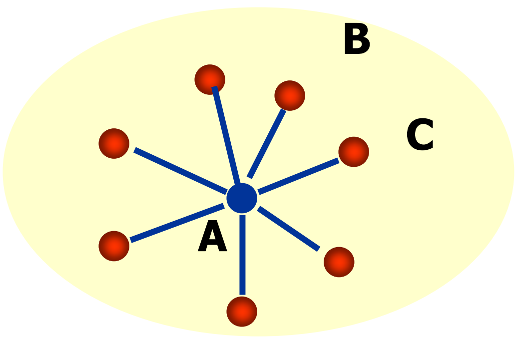
CNL Communications & Networking Laboratory

Bluetooth Piconet

- Up to 8 devices (1 Master and 7 Slave)
- Sharing the same hopping sequence
- Master determines the hopping sequence and provides synchronization
- Link types
  - ACL (Asynch Connectionless)
    - master polls
    - Up to 723 kpbs/57 kbps Asym or 440 Kbps Sym
  - SCO (Synch Connection- Oriented)
  - 64 kbps symm, Master reserves

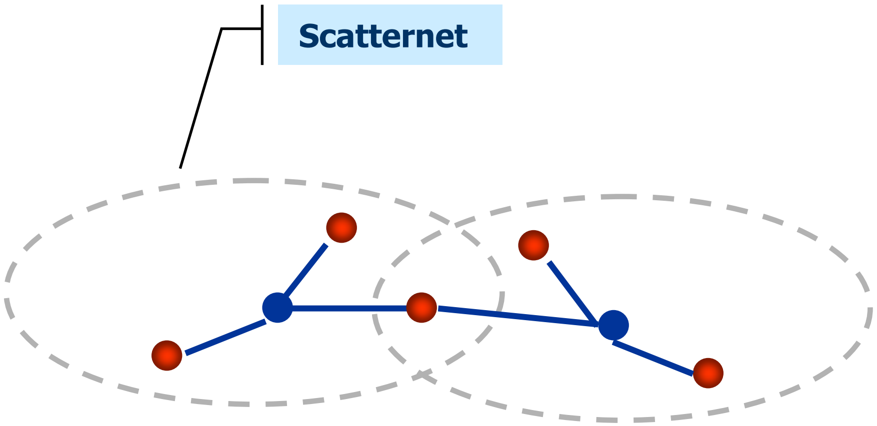
Piconet Formation

- Inquiry - A sends inquiry
- Response - Slaves B, C respond
- Page: A pages B
- Response: B Acks
- FHS: Set clock
- Response



Bluetooth Scatternet

- Multiple Piconets with Overlapping Coverage
- Synchronization to hopping sequence



Part III

System Modeling

Question:

How does multi-hop strategy affect the throughput and the total required transmit power?

Radio Propagation Model

The received signal is

$$y(t) = \int_{-\infty}^{\infty} h(t,\tau)x(t-\tau)d\tau$$

Where

$x(t)$ is the transmitted signal

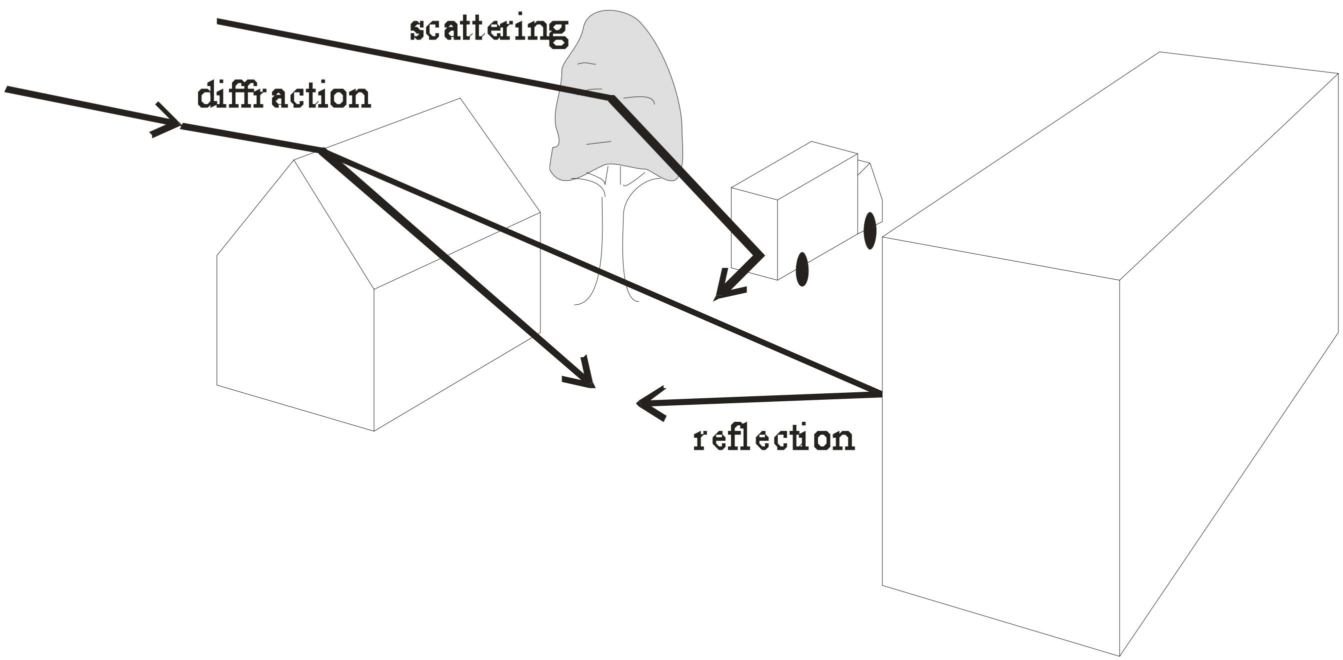
$h(t,\tau)$ is the channel impulse response

$$h(t,\tau) = h_o(t,\tau)h_1(t)$$

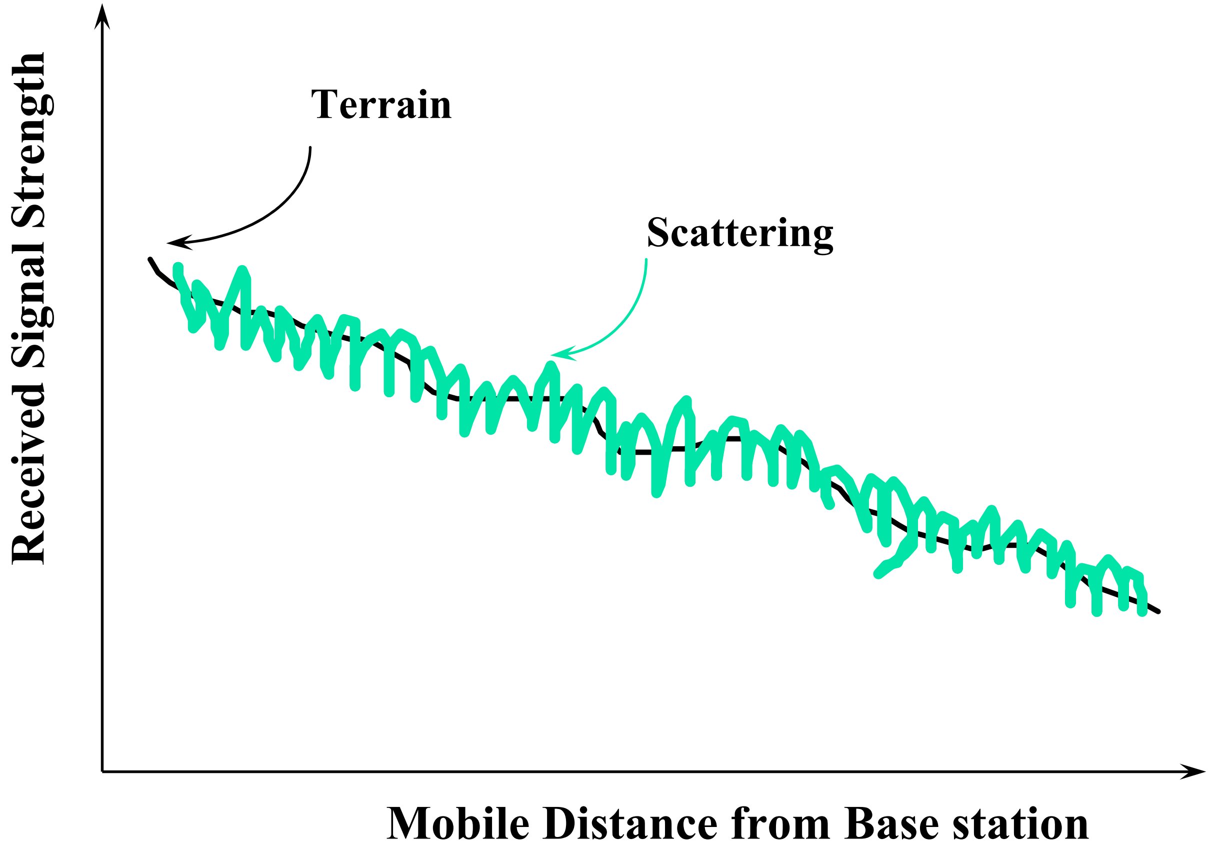
where

$h_0(t,\tau)$ is the short-term (Rayleigh or fast fading)

$h_1(t)$ is the long-term fading (shadow or slow fading)


scattering
diffraction
reflection

Radio Propagation Model



Radio Propagation Model- Slow Fading

- The stochastic process $|h_1(t)|^2$ contributes to the local mean of the received signal
- The random variable $|h_1(t_0)|^2$ can be modeled by a lognormal distribution
- Expressed in dB, this random variable follows a Gaussian distribution

Channel Model

- In general we characterize the channel with **path loss**, **long-term fading**, and **short-term fading** for analysis
- The effect of fast fading is considered in the design of encoder and performance of decoder while considering the required SNR
- Hence we use channel model based on path loss and Log-normal shadowing

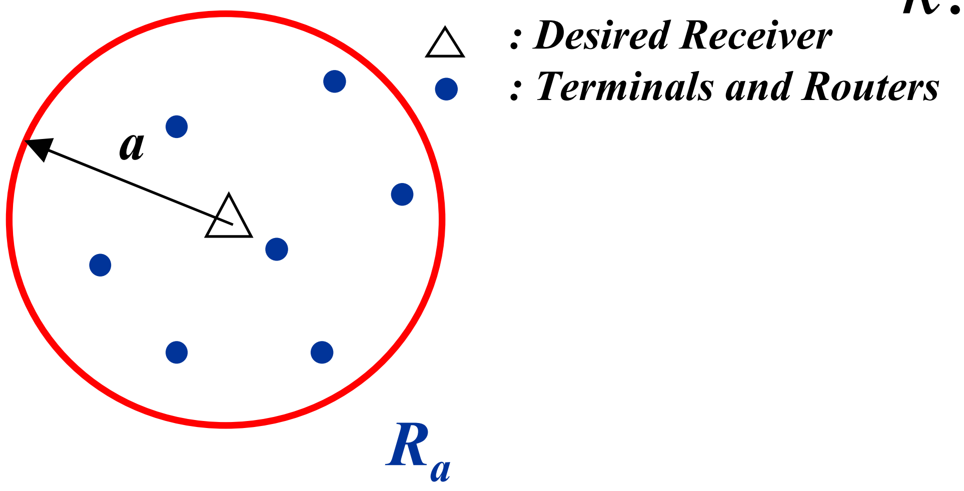
$$\alpha(r,\xi) = r^m 10^{\xi/10} \quad \text{for } m > 2$$

  - r is link length
  - propagation exponent m
  - ξ decibel attenuation with normal distribution

Network Structure

- Mobile stations and routers:
  - Distributed in the plane as a two dimensional Poisson point process with parameters λ_{MS} and λ_{R}, respectively

$$\Pr[k \text{ nodes in } R_a] = e^{-\lambda_x A_a} \frac{(\lambda_x A_a)^k}{k!}$$

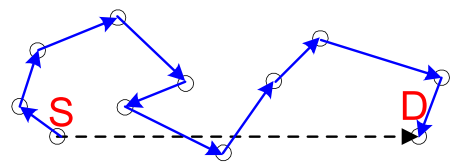


Network Structure (Cont'd)

- Assumption: For calculation of the received power, given the distribution of the number of packets at each node, for any receiver
  - mobiles and routers are distributed uniformly around it in infinite plane

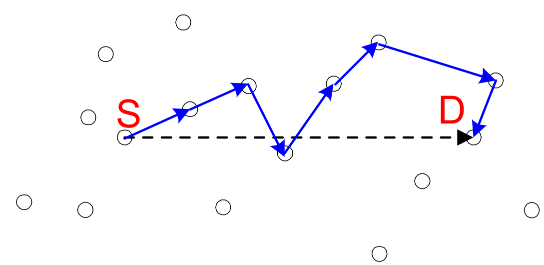
Forwarding Strategy

- Minimum Path Loss (MPL):
  - No priority on selecting a base station over a router
  - The average input rates to routers and base stations are the same



a) MPL

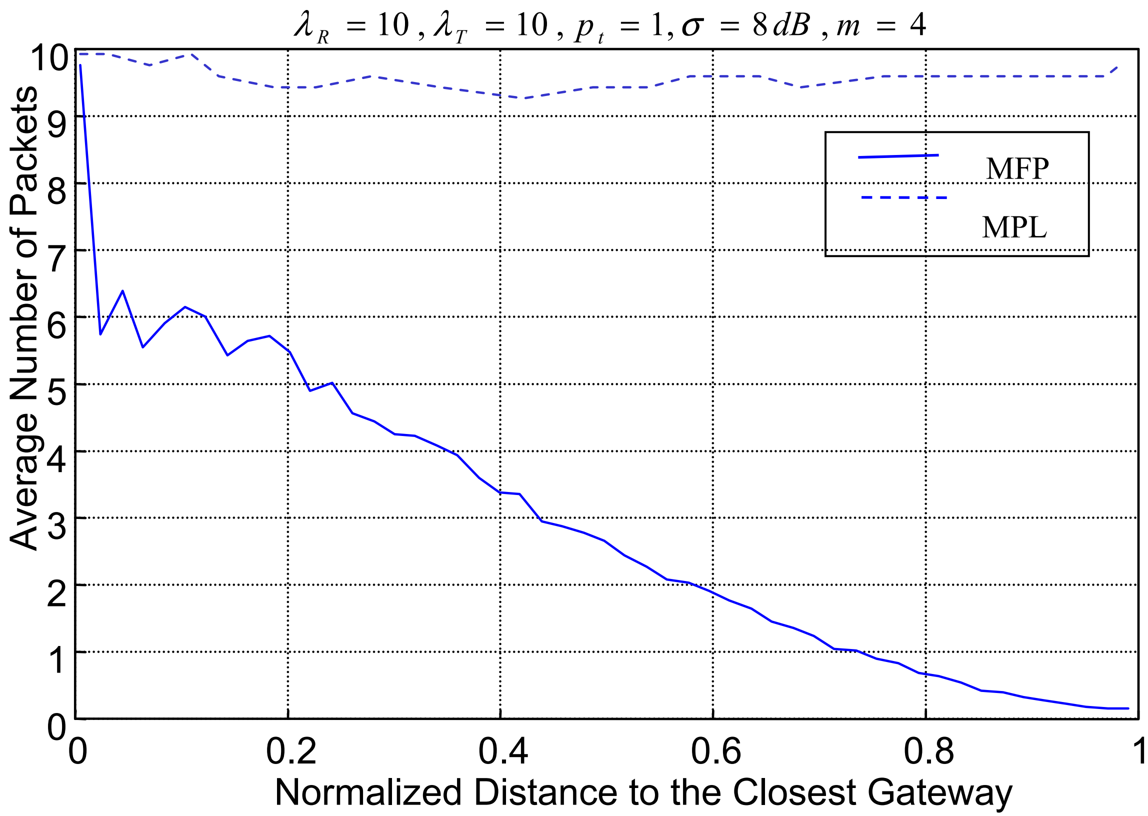
- Minimum path loss with Forward Progress (MFP):
  - Density of packets at routers decreases as their distances to the center of the cell increase



b) MFP

Traffic Density for MFP and MPL

- Density of packets at the gateway is equal to the average packet rate generated



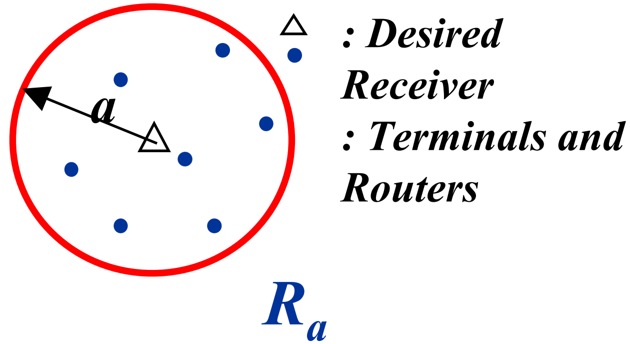
PDF of Received Power

- Steps
  1. Calculate the pdf of the received power due to a node located in a circular region with radius ***a*** around the receiver
  2. Calculate the moments
  3. Calculate characteristic function based on the moments
  4. Find characteristic function of the total received power in the limit as ***a*** goes to infinity
  5. Pdf of the total received power is obtained using inverse Fourier transform

PDF of Received Power (Cont'd)

- Received power from different nodes are assumed to be independent
  - Knowledge of the received power of a node gives some information about the network structure
    - Received power levels for different nodes are correlated
  - By increasing shadowing variance the correlation of received power to structure is reduced and the assumption becomes more accurate

PDF of Total Received Power



- A receiver centered in a circular region R_a with radius a

$$E(e^{sH_T}) = E(e^{\sum_i sH_i})$$

$$= \sum_{k=0}^{\infty} e^{-\pi a^2 \lambda_{Tx}} \frac{(\pi a^2 \lambda_{Tx})^k}{k!} E\left(e^{s\sum_i H_i} \middle| k \text{ in } R_a \right)$$

Where "k in R_a" is the event that there are k transmitting nodes in region R_a and λ_{tx} is the average number of transmitting nodes per unit area

PDF of Total Received Power (Cont'd)

- By independence assumption we have

$$E\left(e^{s\sum_i H_i} \middle| k \text{ in } R_a \right) = \left(E(e^{sH_i}) \right)^k$$

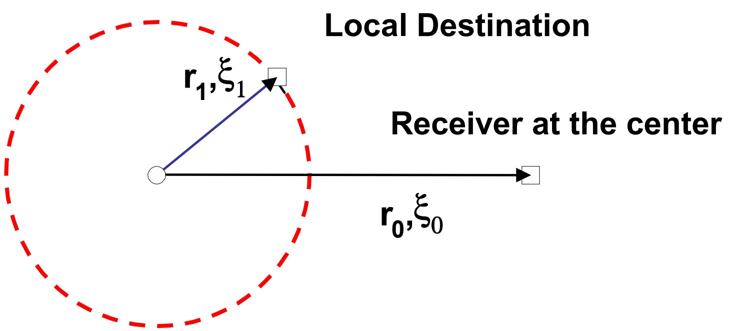
→ $$E(e^{sH_T}) = \sum_{k=0}^{\infty} e^{-\pi a^2 \lambda_{Tx}} \frac{\left(\pi a^2 \lambda_{Tx} E(e^{sH_i})\right)^k}{k!}$$

$$= \exp\left(\pi a^2 \lambda_{Tx} (E(e^{sH_i}) - 1)\right)$$

PDF of Received Power from One User

$$f(r_0,\xi_0,r_1,\xi_1) = f(r_0)f(\xi_0)f(\xi_1)f(r_1 | r_0,\xi_0,\xi_1)$$

$$H_i = \alpha(r_1,\xi_1)/\alpha(r_0,\xi_0)$$



- For uniform traffic the terms that contribute to the calculation of moments are obtained as

$$f_{H_i}(h) \cong \frac{2}{mNh^{(1+2/m)}} + \frac{1}{N}\delta(h-1)$$

Where

$$N = \lambda_{Rx} \pi a^2$$

Characteristic Function of the Received Power from One User

- Calculating moments $\lim_{N\to\infty} N\int_0^1 h^k f_{H_i}(h)dh =$

$$1+\frac{1}{mk/2-1} \text{ for k} \geq 1 \text{ and m} > 2$$

- Calculating characteristic function

$$\mathrm{E}(\mathrm{e}^{\mathrm{sH_i}}) = \mathrm{E}\left(\sum_{k=0}^{\infty}\frac{(\mathrm{sH_i})^k}{k!}\right) = \sum_{k=0}^{\infty}\frac{\mathrm{s}^k}{k!}E(H_i^k)$$

$$= 1+\frac{1}{N}\sum_{k=0}^{\infty}\frac{\mathrm{s}^k}{k!}(1+\frac{1}{(mk/2-1)})+o(\frac{1}{N})$$

$$= 1-\frac{i\sqrt{\pi s}\cdot erf(i\sqrt{s})}{N}+o(\frac{1}{N}) \text{ for m} = 4$$

in which o(k(n)) is equivalent to $\lim_{n\to\infty}\frac{o(k(n))}{k(n)} \to 0$

Characteristic Function of the Total Received Power

CNL Communications & Networking Laboratory

$$E(e^{sH_T}) = \exp\left(\pi a^2 \lambda_{Tx} (E(e^{sH_i}) - 1)\right)$$

$$E(e^{-i\omega H_T}) = \exp\left(-\frac{\lambda_{Tx}}{\lambda_{Rx}}\sqrt{i\pi\omega}\, erf(\sqrt{i\omega})\right) = M(\omega)$$

$$M(\omega) = M^*(-\omega)$$

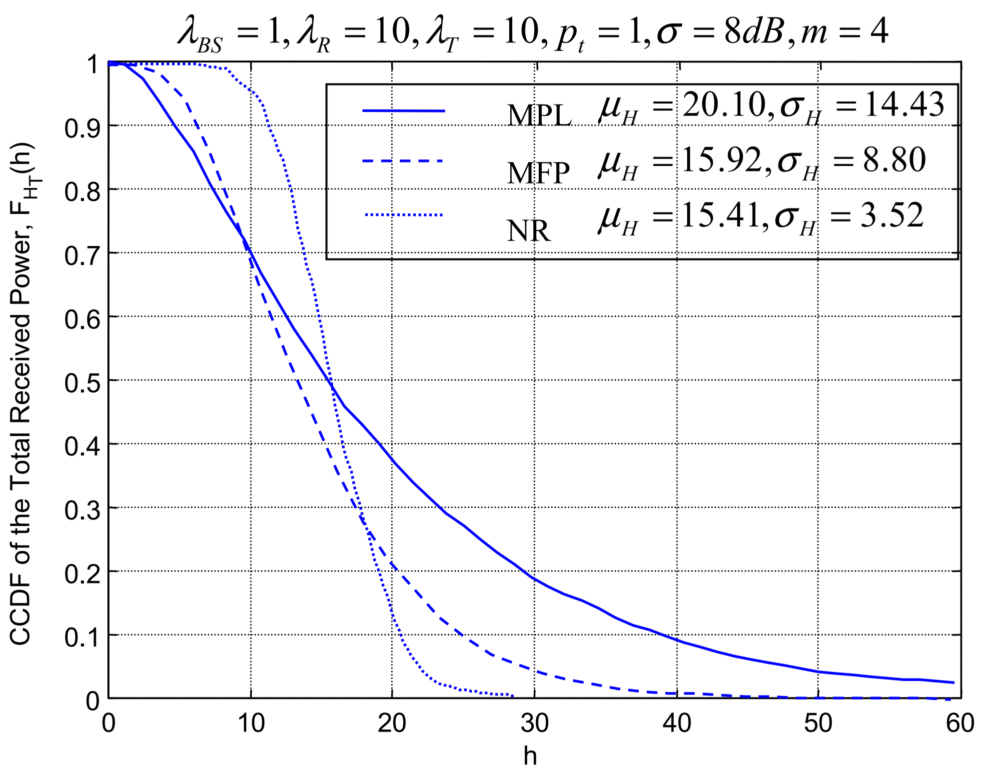
λ_{Tx} : Density of transmit packets

λ_{Rx} : Density of receivers

- Pdf of the total received power can now readily be obtained using FFT

Simulation/Analytical Results

- Average of interference for the two cases of MFP and NR (No Routers) are almost equal
- Due to randomness in locations of routers and also variance in the number of packets which routers relay MFP has much higher interference variance



Observation

- Without using capacity enhancement techniques multi-hop systems result in
  - Lower system throughput
  - Decreased total power consumption

Part IV

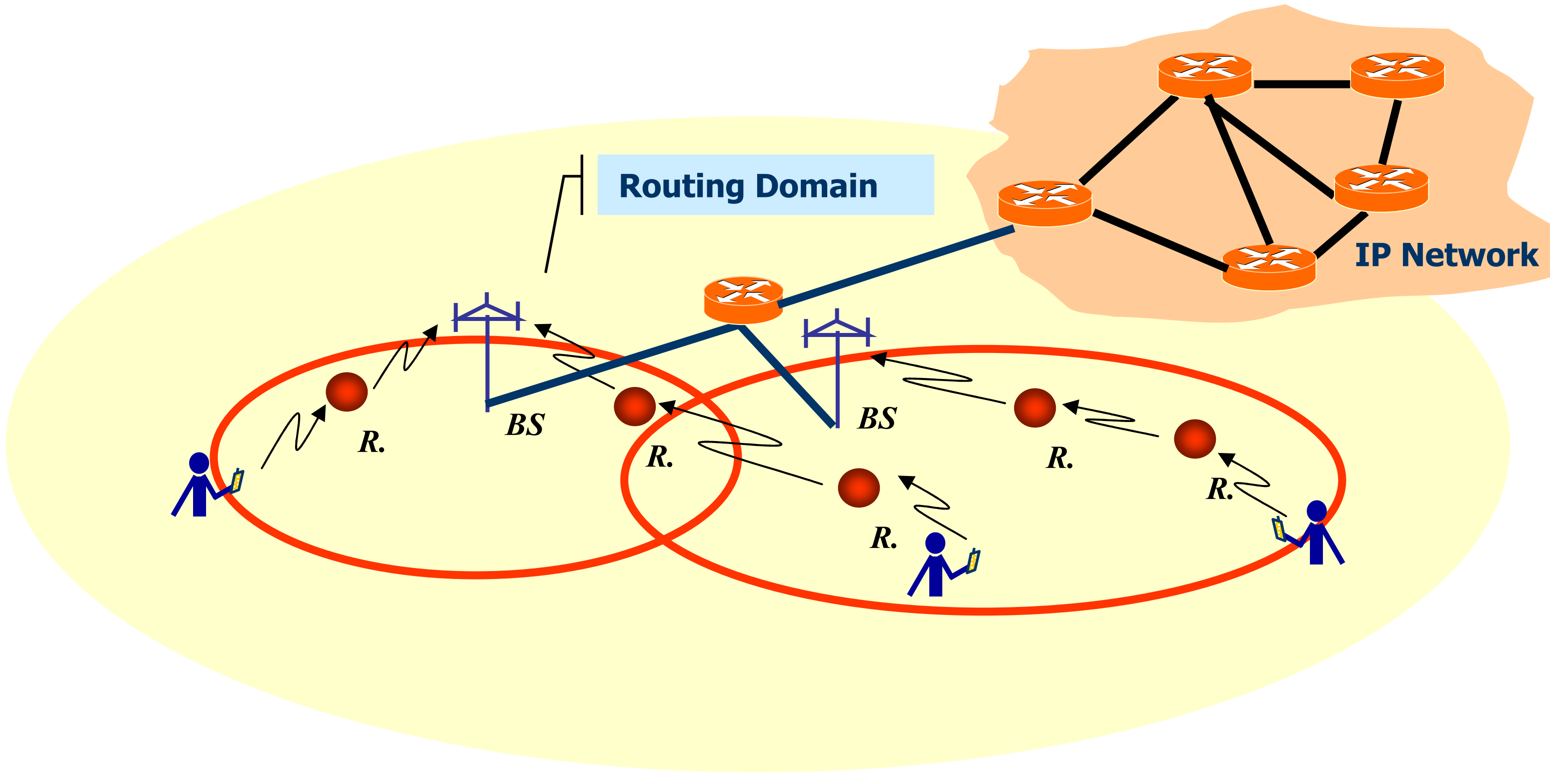
Wireless multi-hop networks overlaid with cellular structure

Project SOPRANO

SOPRANO – Self-Organizing Packet Radio Ad-hoc Networks with Overlay

Applying multi-hop to cellular networks

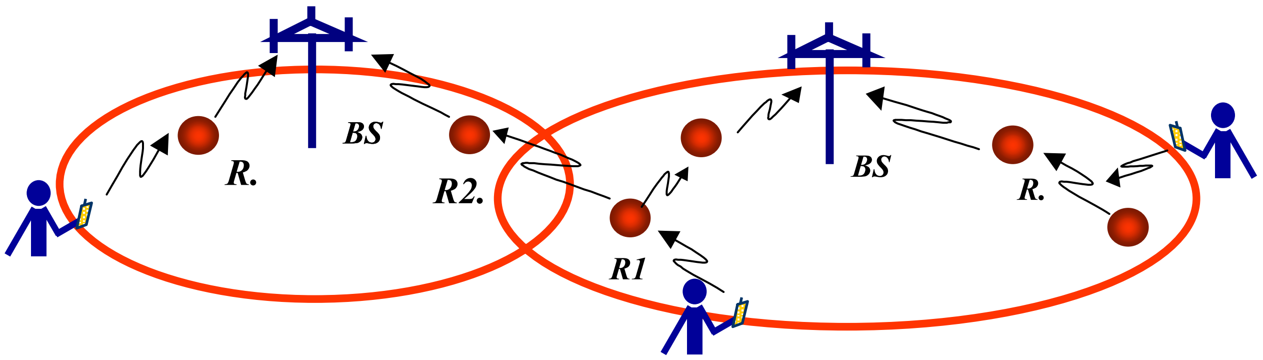
Network Architecture



A cellular overlaid network with dynamic, random and multi-hop topology with routers and terminals

Benefits and disadvantages

- Advantages
  - Transmitted power reduction
  - Further power reduction due to change for propagation model from $1/r^4 \sim 1/r^2$ for short links
  - Potential reduction in intercell interference
  - Spatial distribution of traffic and interference through routers
- Disadvantages
  - Terminal complexity
  - Privacy



B. Jabbari

CNL Communications & Networking Laboratory

Spectrum of Problems to be Addressed

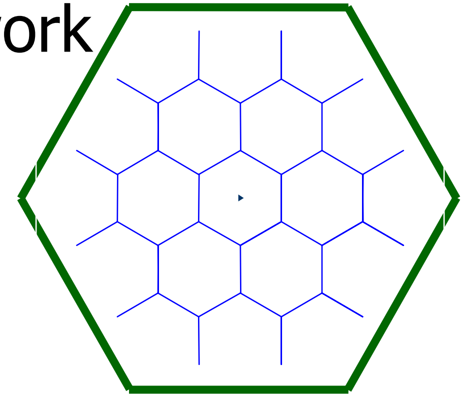
- Does reducing the transmit power result in higher capacity?
- Capacity enhancement techniques
- Performance modeling (capacity and throughput)
- Routing table build-up and updating
- Control channel usage optimization
- Integrating channel/link/network layer characteristics
- Degree of the scalability of the architecture
- Radio link aggregation for heterogeneous mobile end-users' traffic
- How to model a network of uniformly distributed base stations, repeaters and terminals?
- What are the efficient routing algorithms

Cell Splitting vs. Multi-hop

- Cell splitting in cellular networks
  - Increase in number of available channels

  → Will result in linear increase of capacity
  - Power loss reduction

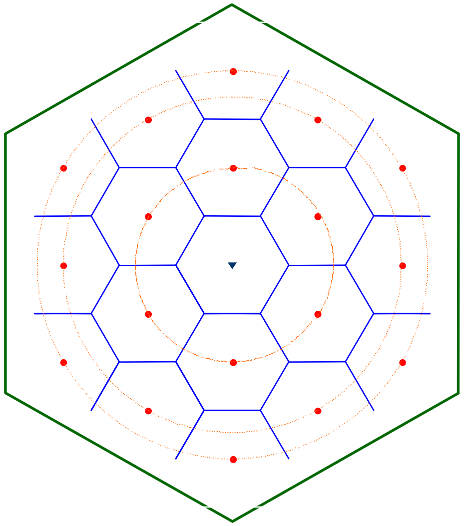
  → Can result in capacity increase, however, in interference-limited networks power scaling will not result in any increase in the maximum network throughput



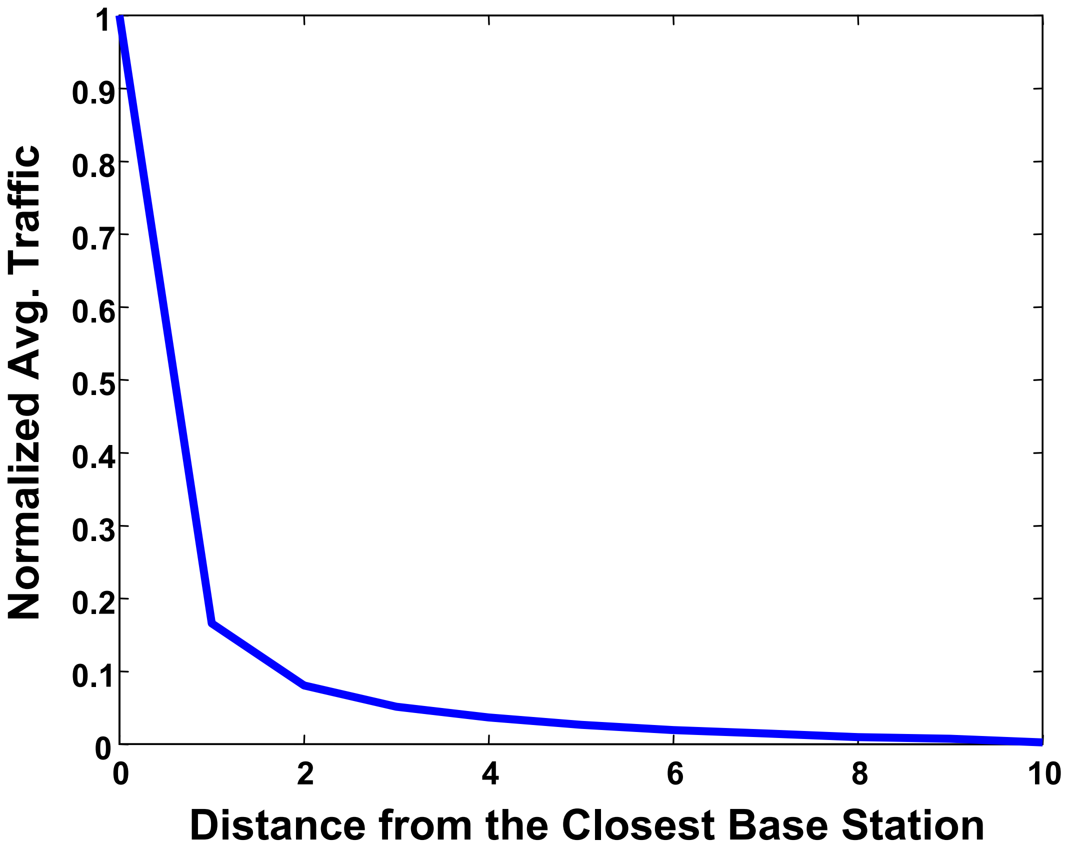
Cell Splitting vs. Multi-hop

- In multi-hop topology routers are replacing the new base stations
- Same as cell-splitting except that all packets must be relayed towards the base station
  - Traffic increases towards the base station
  - throughput bottleneck is at the base stations

→ Specific techniques are needed to benefit from the two issues of cell splitting to increase capacity



Traffic Concentration at Base Station



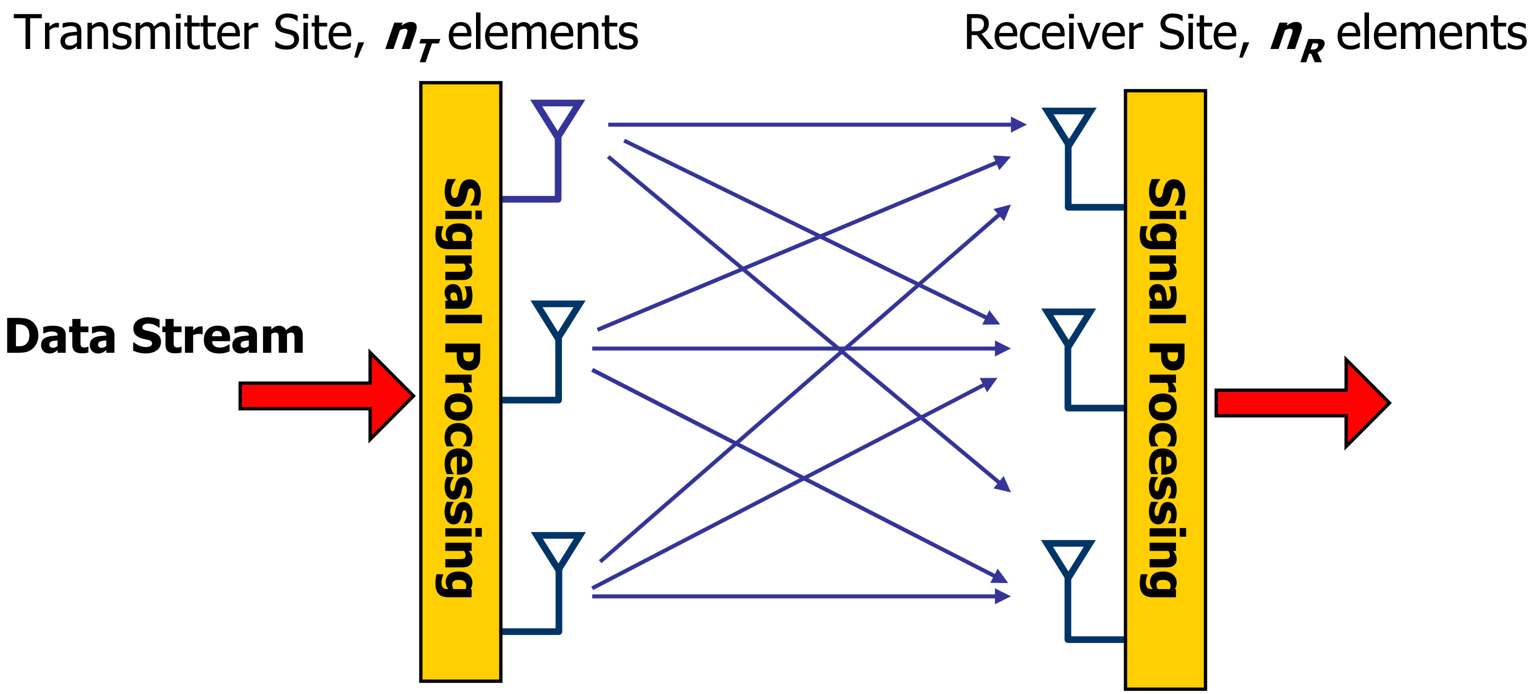
Part V

Capacity Enhancement Techniques

Capacity Enhancement Techniques

- Physical Layer
  - Diversity Techniques
  - Multiple-Input Multiple-Output Channels
  - Smart Antennas/Interference Cancellation
  - Multi-User Detection
- Data Link Layer
  - Medium access protocol: channel scheduling
- Network Layer
  - Routing strategy: i) the optimum transmission power ii) to whom the transmission should be addressed
  - Reduce the excess traffic/interference due to relaying

MIMO Radio Channels



- Input bit-stream is coded and demultiplexed to n_T sub-streams, each is sent over a different antenna
- Signal processing is used to unscramble different replicas of all signals and remultiplex them to original input stream

MIMO Radio Channels (Cont'd)

- Increased capacity in this link is due to two effects
  - By increasing the number of channels, mean capacity is increased almost linearly with the number of antenna elements
  - By providing temporal, transmit, and receive diversity channel reliability will be highly improved for higher data rates

MIMO Radio Channels (Cont’d)

- Adding multiple antennas for small devices is expensive and sometimes not practical
- Routers which are normally mounted on larger devices with better power supplies can afford better space time codes
- Connection of routers together and to the base stations using highly efficient codes is like connecting them by wire
- Outage capacity of 40 b/s/Hz has been reported
  - 95% availability
  - signal to noise ratio of 10 dB
  - eight elements at both transmitter and receiver

Increasing Link Efficiency

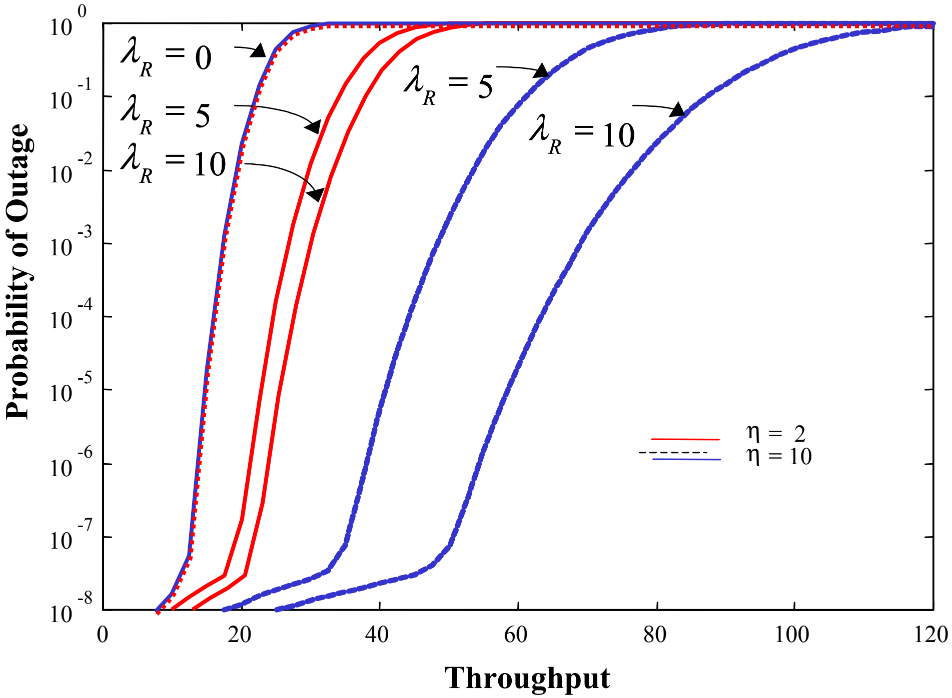
- Multi-hop relaying increases interference
- Improve router functionality to approach equivalent of wire-line connectivity
- Increasing Link efficiency
  - Directly increases capacity
  - Reduces the interference

Throughput Increase Using Efficient Links

- Throughput: Total number of generated packets per base station
- Ideal power control, fixed required received power at all receivers

λ_R: density of routers/density of base stations

η: Efficiency factor for links among base stations and route



CNL Communications & Networking Laboratory

Capacity Formulas - SUD & MUD

- σ_x^2 (σ_n^2): Signal (noise) energy per dimension
- N : Number of packets destined to a receiver, received with power P_i
- M : Number of packets interfering, received with power I_j
- W_s (W_c): Data bandwidth before (after) spreading
- $L=W_c/W_s$: Processing gain
- Capacity in bits/sec/Hz

$$SNR = \frac{P_i}{2W_s\sigma_n^2}$$

$$C = \log_2\left(1 + \frac{\sigma_x^2}{\sigma_n^2}\right)$$

Single User Detection (SUD)

- In SUD, for each packet when all others are considered as noise,

$$C_T = \sum_i \frac{W_s}{W_c} \log_2 \left(1 + \frac{P_i}{2W_s \sigma_n{}^2 + \frac{W_s}{W_c} (\sum_j I_j + \sum_{k \neq i} P_k - 1)} \right) \text{ bits/sec/Hz}$$

- For equal power case, $P_i = P_o = 1$

$$C_T = \frac{N}{L} \log_2 \left(1 + \frac{L}{L/\mu_0 + \sum_j I_j + N - 1} \right) \text{ bits/sec/Hz}$$

Multi User Detection (MUD)

- In MUD, *N* users are sharing the total BW of W_c, therefore, we must consider noise power for this BW

$$C_T = \log_2\left(1 + \frac{\sum_i P_i}{2W_c\sigma_n^2 + \sum_j I_j}\right) \text{ bits/sec/Hz}$$

- For equal power case and using normalized values, $P_i = P_o = 1$

$$C_T = \log_2\left(1 + \frac{N}{L/\mu_0 + \sum_j I_j}\right) \text{ bits/sec/Hz}$$

Comparison

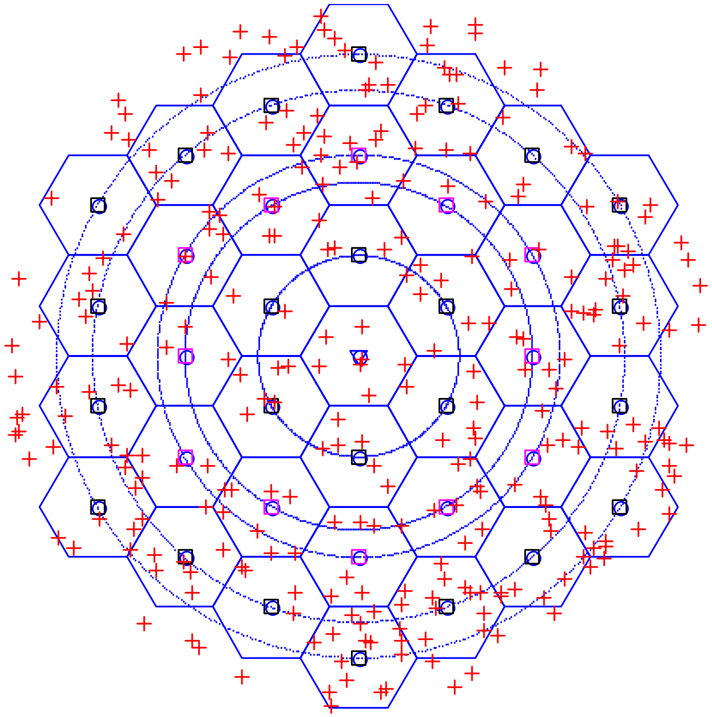
- We compare the two formulas for the simple case where *N=L*

$$C_{SUD} = \log_2\left(1 + \frac{N}{L/\mu_0 + \sum_j I_j + N - 1}\right)$$

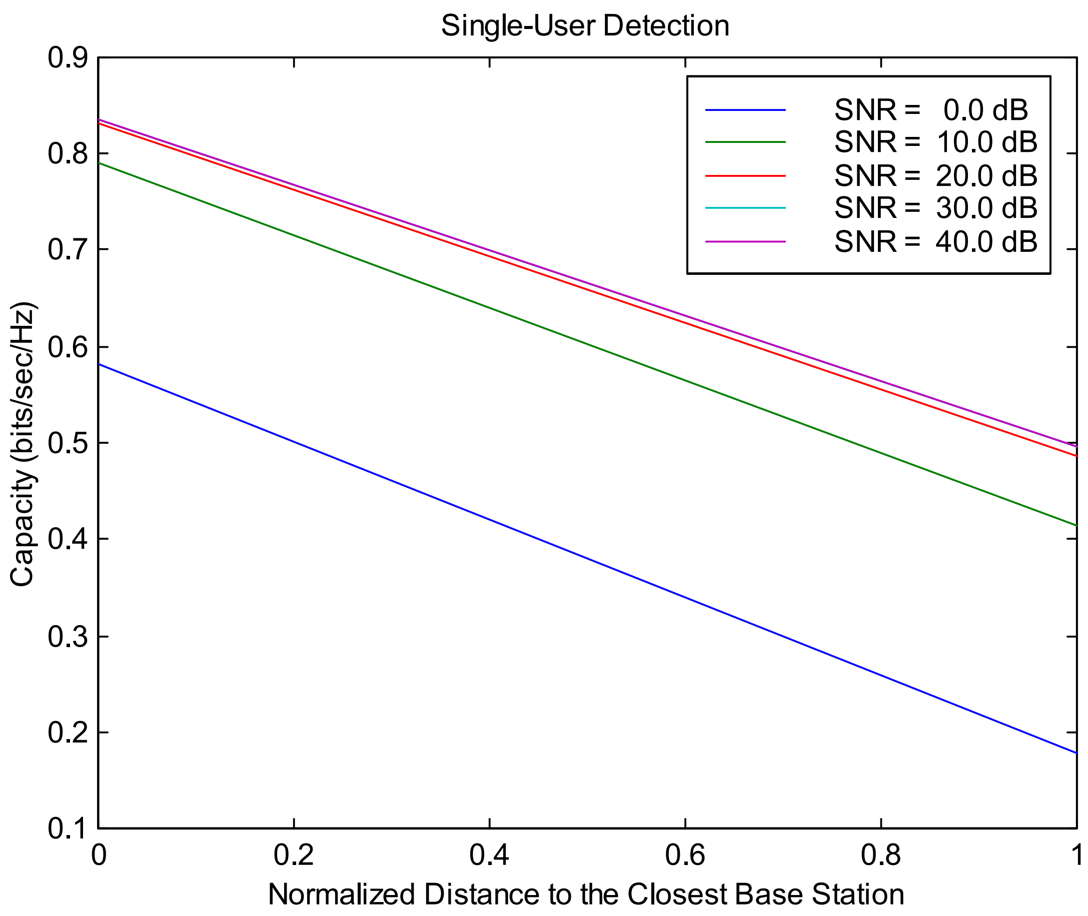
$$C_{MUD} = \log_2\left(1 + \frac{N}{L/\mu_0 + \sum_j I_j}\right)$$

- Reducing intercell interference, when using MUD can highly increase the capacity

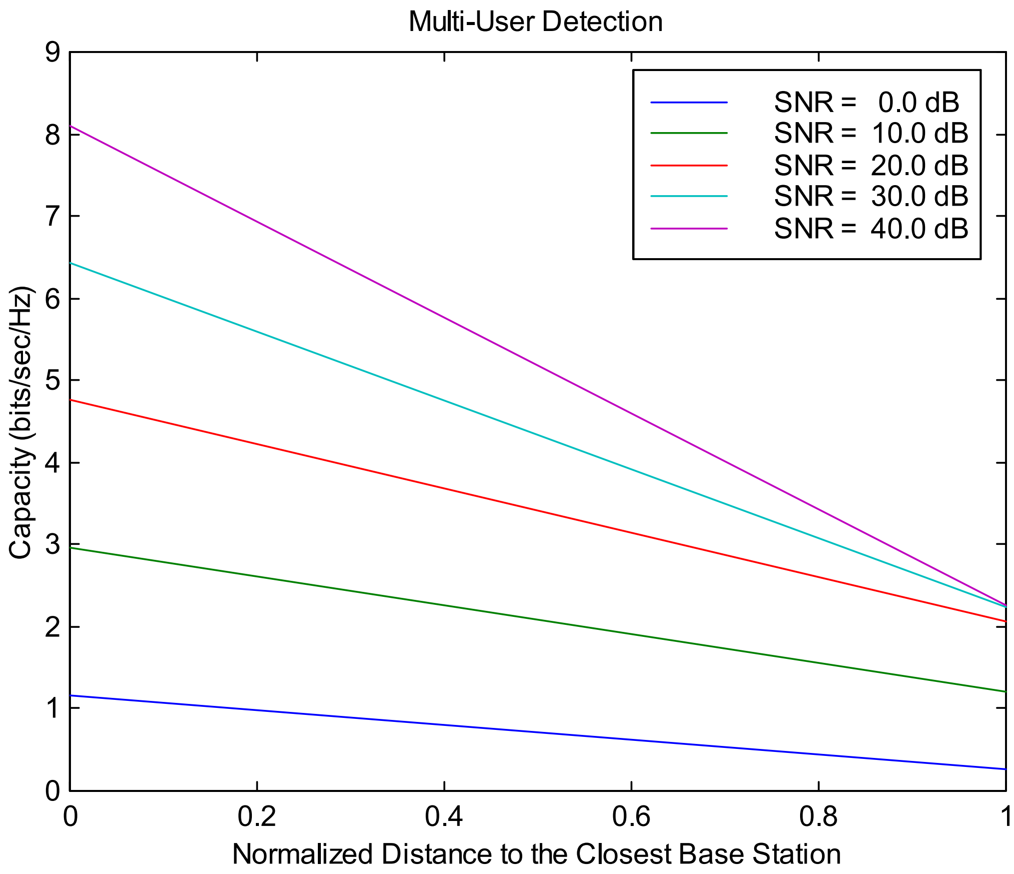
System for Capacity Evaluation



Power Scaling Does not Increase Capacity



Capacity Increase Through MUD and Scheduling



Part VI

Network Throughput

CNL Communications & Networking Laboratory

Network Capacity

- A set of channels must be shared between different network nodes
- Performance of each channel is highly affected by transmission on other channels
- Channel scheduling is part of medium access protocol
- Routing strategy: how to direct a packet toward the destination

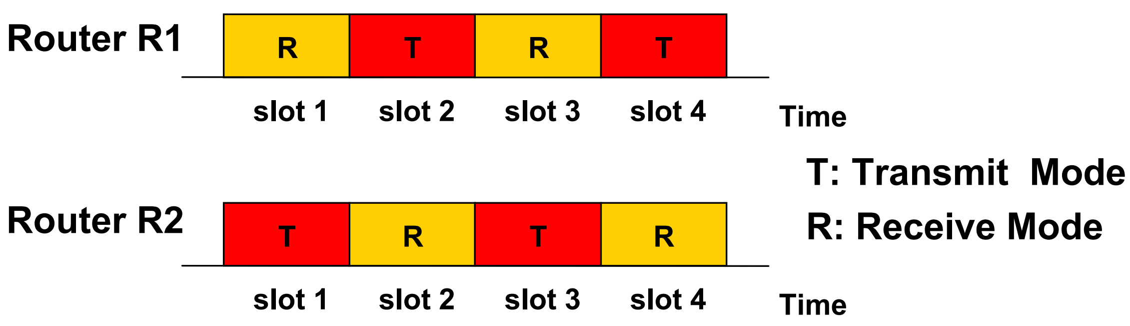
CNL Communications & Networking Laboratory

Access Technique Assumptions

- Each terminal sends and receives on one channel (spreading sequence)
- Two frequency bands carry the information on upstream and downstream independently (FDD Mode)
- Routers may send and receive on several channels, dynamically allocated by base station
- In each frequency band
  - Simultaneous transmission and reception is not practical
  - Routers use TDD mode to send and receive data
  - They select their modes randomly
- In each slot, nodes transmit one packet with probability *p*

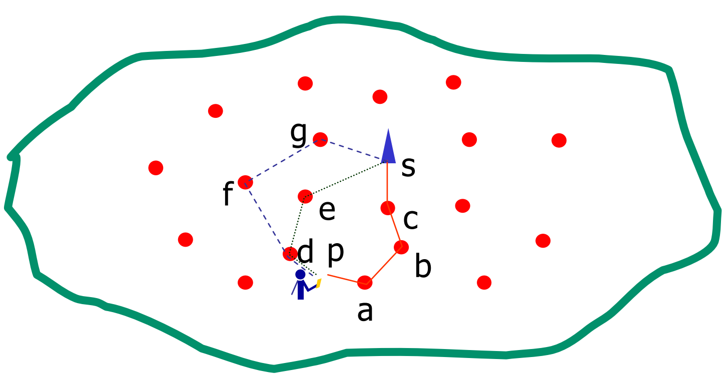
Transmit-Receive Modes

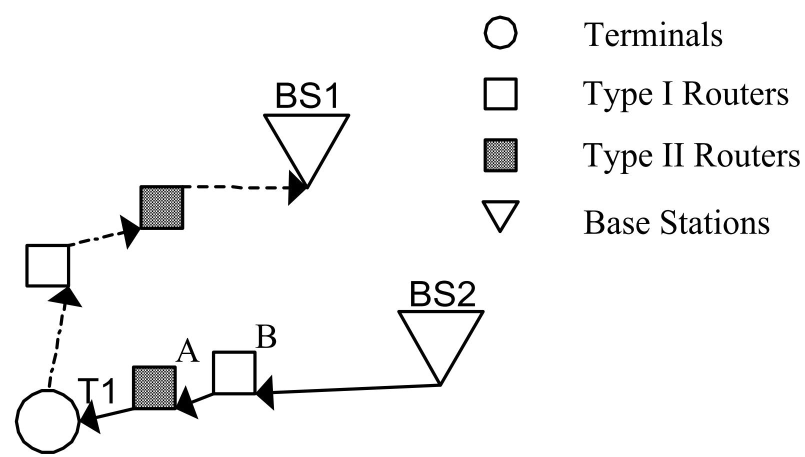
- Each router receives some packets in one time slot and relays them all in the following time slot using different spreading codes



Network Capacity (Cont'd)

- Routing assumptions
  - In uplink, each base station can be the final destination
  - In downlink, several base stations can send the data to one terminal
  - Loop free
  - Asymmetric links





Power-Constraint Channel Capacity

- Assume the channel state *s*
  - a stationary and ergodic stochastic process
  - takes values on a finite or infinite set S of discrete memoryless channels
- To each state *s*
  - there is an associate capacity C_s and
  - a probability or fraction of time $p(s)$ which channel stays in this state
- The capacity of this time-varying channel is then given by:

$$C = \sum_{s \in S} C_s p(s)$$

Power-Constraint Channel Capacity (Cont'd)

P_n : average power of AWGN at the receiver

Γ : fading coefficient, $\gamma = \Gamma / P_n$

P_{T_avg} : average transmit signal power

$P_T(\gamma)$: instantaneous transmit power

$$C(P_{T\_avg}) = \max_{P_T(\gamma):\int_\gamma P_T(\gamma)p(\gamma)d\gamma = P_{T\_avg}} \int_\gamma \log_2(1 + P_T(\gamma)\gamma)p(\gamma)d\gamma$$

$$P_T(\gamma) = \begin{cases} \dfrac{1}{\gamma_0} - \dfrac{1}{\gamma} & \gamma \geq \gamma_0 \\ 0 & \gamma < \gamma_0 \end{cases}$$

$$P_{T\_avg} = \int_{\gamma_0}^{\infty} \left(\frac{1}{\gamma_0} - \frac{1}{\gamma}\right)p(\gamma)d\gamma, \qquad C(P_{T\_avg}) = \int_{\gamma_0}^{\infty} \log_2\left(\frac{\gamma}{\gamma_0}\right)p(\gamma)d\gamma$$

CNL Communications & Networking Laboratory

Optimal Transmission Strategy

- The general problem of maximizing throughput can be decomposed into two related sub-problems:
  - maximizing the total amount of information that can be carried through all links and
  - minimizing the number of hops that the information must take to reach the destinations
- The optimum solution for this problem is a strategy which jointly designs techniques and algorithms for physical, data link, and network layers.

Optimal Transmission Strategy (Cont'd)

- More specifically, this strategy determines the following:
  - the techniques and technologies to be used in receivers and transmitters
  - to whom the transmission should be addressed
  - amount of information to be transmitted
  - on which channels to transmit their data
  - which channels to listen to
  - the transmit power level

Methodology

- The optimum solution for these decision variables depends on:
  - the available information on the network
  - system constraints
  - defined objective function
- Available information to receivers and transmitters:
  - traffic characteristics may be known completely or partially
  - statistics of the interference or exact value of the interference
  - propagation losses between different nodes
  - number of packets in the buffers

Methodology (Cont'd)

- Constraints may include:
  - maximum transmit power of each node
  - maximum acceptable delay for different types of traffic
  - complexity of algorithms
  - maximum probability of error
  - minimum guaranteed information rate
- Objective function can be defined in several ways:
  - minimizing network resources, e.g., total transmit power
  - maximizing system throughput
  - minimizing interference
  - maximizing total expected forward progress

Some Remarks

- As more information on the network is considered to find the optimum strategy, a better performance can be obtained
- System constraints reduce the flexibility of the algorithms and hence degrade the performance of the system
- By describing the problem in this way, we can formulate the problem based on dynamic programming

Definition

- Based on all the constraints and the nodes' knowledge of the network, the optimum transmission strategy is defined as:
  - *the strategy which satisfies all the constraints while it consumes minimum resources*

Dynamic Programming

- The capacity calculation based on Shannon's formula is equivalent to having the following constraints and objectives:
  - Considering C bits/sec as the average required capacity, the constraint is to transmit CT bits of information in T sec when T goes to infinity
  - The only system resource is the total transmit power
  - Objective is to minimize the total transmit power to empty the buffer
- In the classical approach
  - Maximizing the total information transfer with a fixed amount of power
- New statement of the problem
  - Minimizing the total transmit power for a fixed amount of information transfer
- If power and capacity has a one-to-one relationship, the two are equivalent

Dynamic Programming (Cont'd)

- Each packet is transmitted in one slot duration and time slots are indexed by n = { 1,2,...}
- Transmit power in each time slot is considered as the cost function
- Let J(b, γ) be the minimal average cost until the queue is empty, given that currently,
  - the queue has backlog *b* and
  - fading coefficient is γ

CNL Communications & Networking Laboratory

Dynamic Programming (Cont'd)

For heavy trafic model:

$$J_n(b_n,\gamma_n) = \min_{P_T(b_n,\gamma_n)}\left\{P_T(b_n,\gamma_n) + \int_0^\infty J_{n+1}\left(\max\left(0, b_n - \frac{1}{2}\log_2\left(1+P_T(b_n,\gamma_n)\gamma_n\right)\right),\alpha\right) f(\alpha)d\alpha\right\}$$

$J_N(b,\gamma) = \dfrac{2^{2b}-1}{\gamma}$ to empty the buffer in one slot based on Shannon's formula

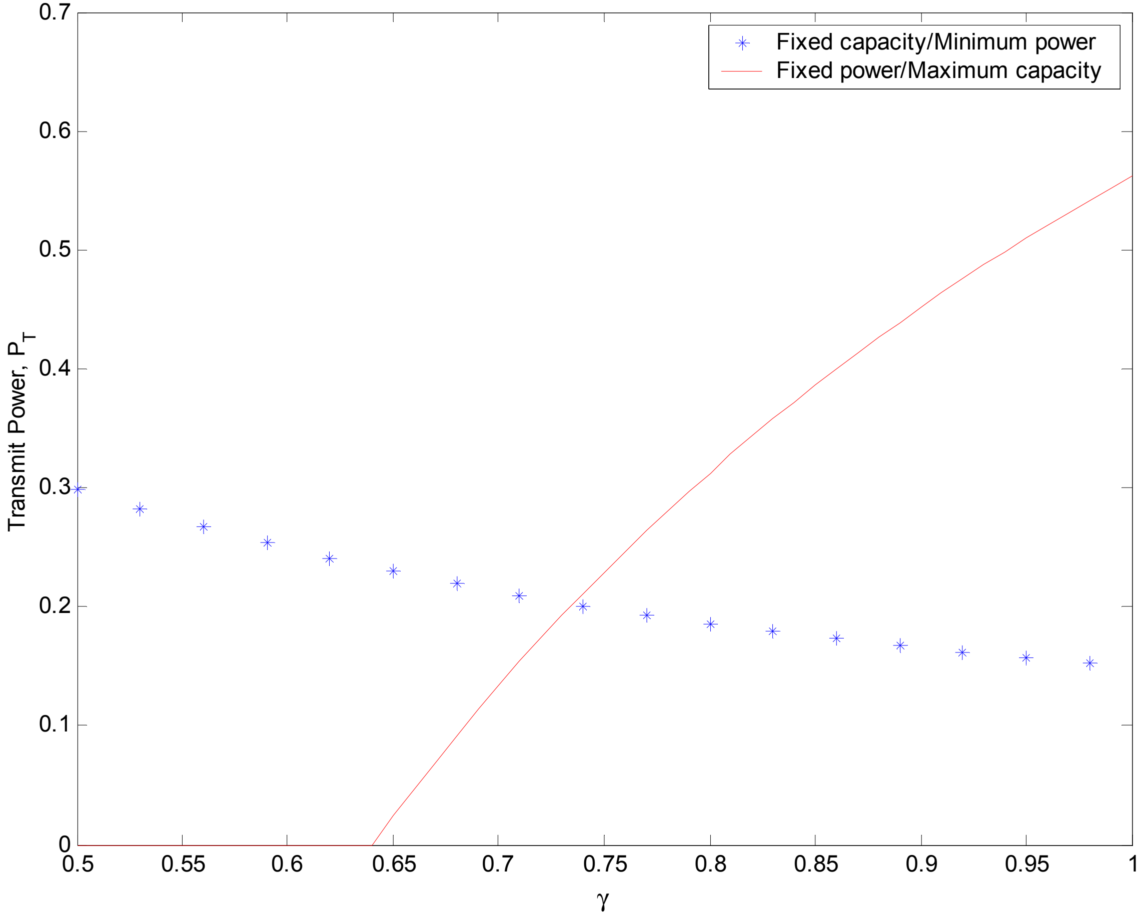
And for the case of input traffic with probability density function $p_\Lambda(\lambda)$, independent from slot to slot

$$J_n(b_n,\gamma_n) = \min_{P_T(b_n,\gamma_n)}\left\{\begin{aligned}&P_T(b_n,\gamma_n) + \\ &\int_0^\infty\int_0^\infty J_{n+1}\left(\max\left(\lambda, b_n + \lambda - \frac{1}{2}\log_2\left(1+P_T(b_n,\gamma_n)\gamma_n\right)\right),\alpha\right) f(\alpha)p_\Lambda(\lambda)d\alpha d\lambda\end{aligned}\right\}$$

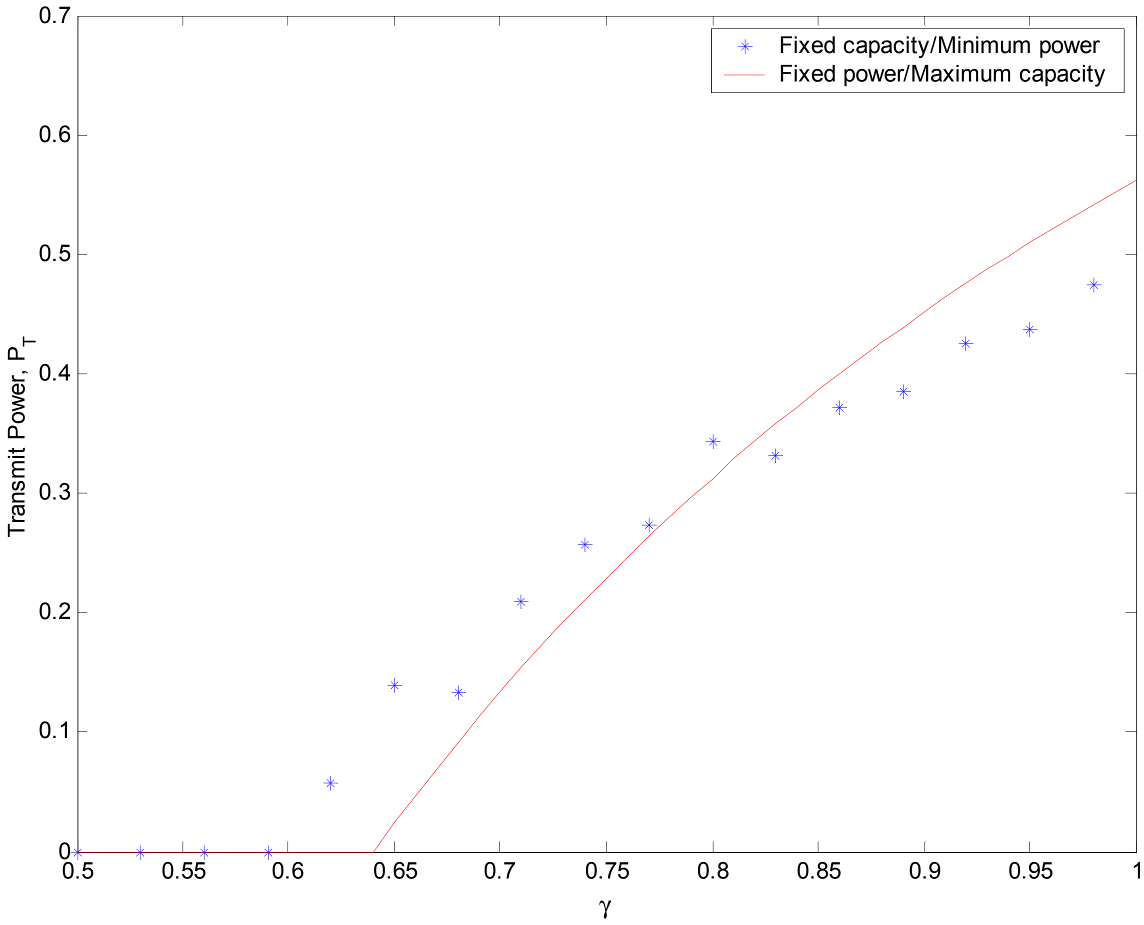
Example for Comparing Methods

- γ: uniform distribution in the range of [0.5,1]
- Capacity C = 0.25 bits/dimension
- Knowing the required capacity γ_0 can easily be obtained, γ_0 = 0.639 1/Watt
- The distribution of γ is independent of transmit power and independent from slot to slot
- Results for dynamic programming have been obtained for different horizons N

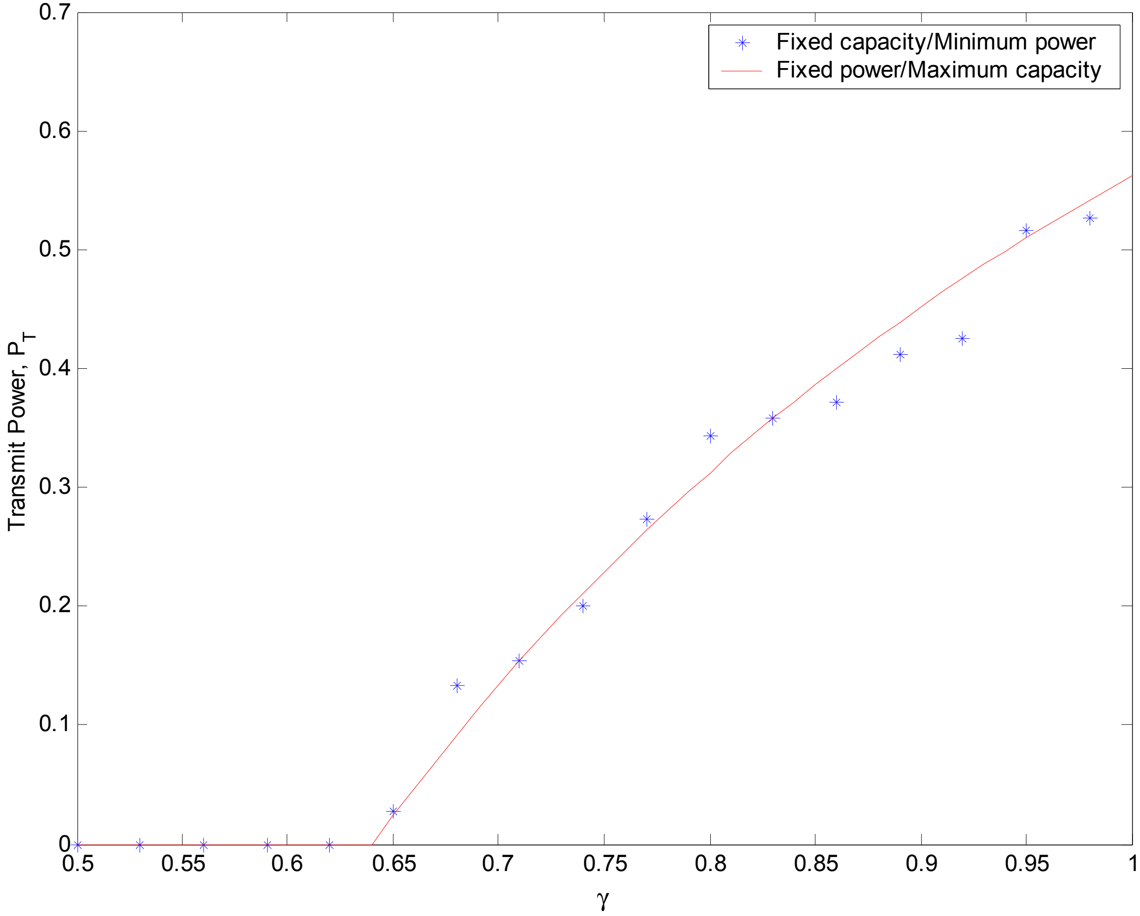
Transmission Strategy for N=1



Transmission Strategy for N=5

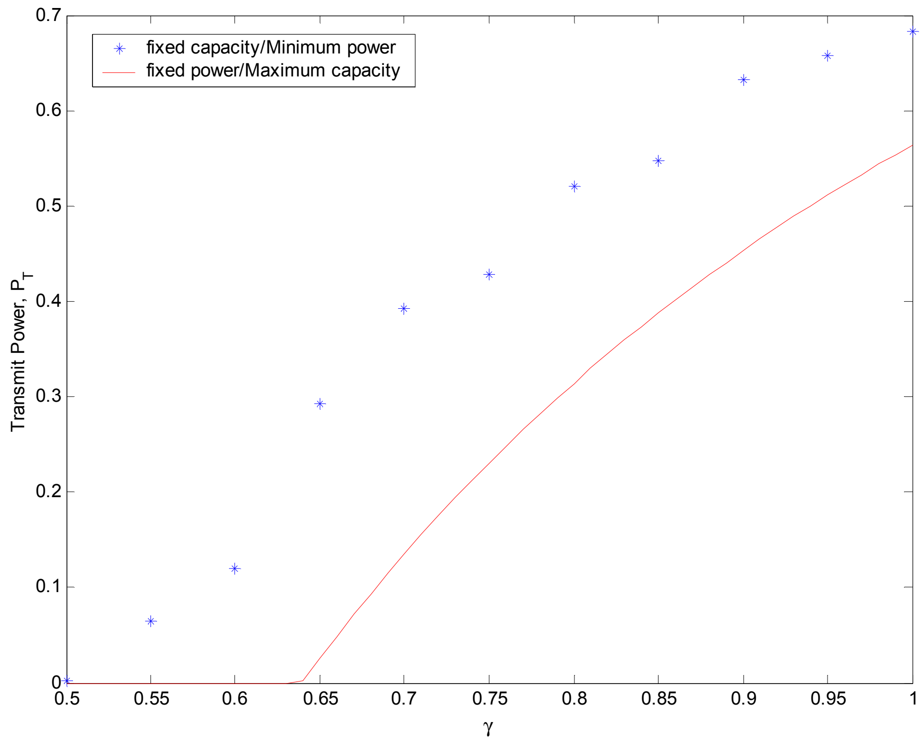


Transmission Strategy for N=15



Transmission Strategy with Bernoulli Traffic

- Probability of packet arrival = 1/8
- Information bits in one packet = 1



B. Jabbari

Multi-hop Formulation

$$J_n^{(j)}(b_n, \gamma_n^{(j)}) =$$

$$\min_{P_T(b_n,\gamma_n)} \left\{ \begin{array}{l} J^{(j)} + P_T(b_n, \gamma_n^{(j)}) + \\ \int_0^\infty J_{n+1}^{(j)} \left(\max\left(0, b_n - \frac{1}{2}\log_2\left(1 + P_T(b_n, \gamma_n^{(j)})\gamma_n^{(j)}\right)\right), \alpha^{(j)} \right) f(\alpha^{(j)}) d\alpha^{(j)} \end{array} \right\}$$

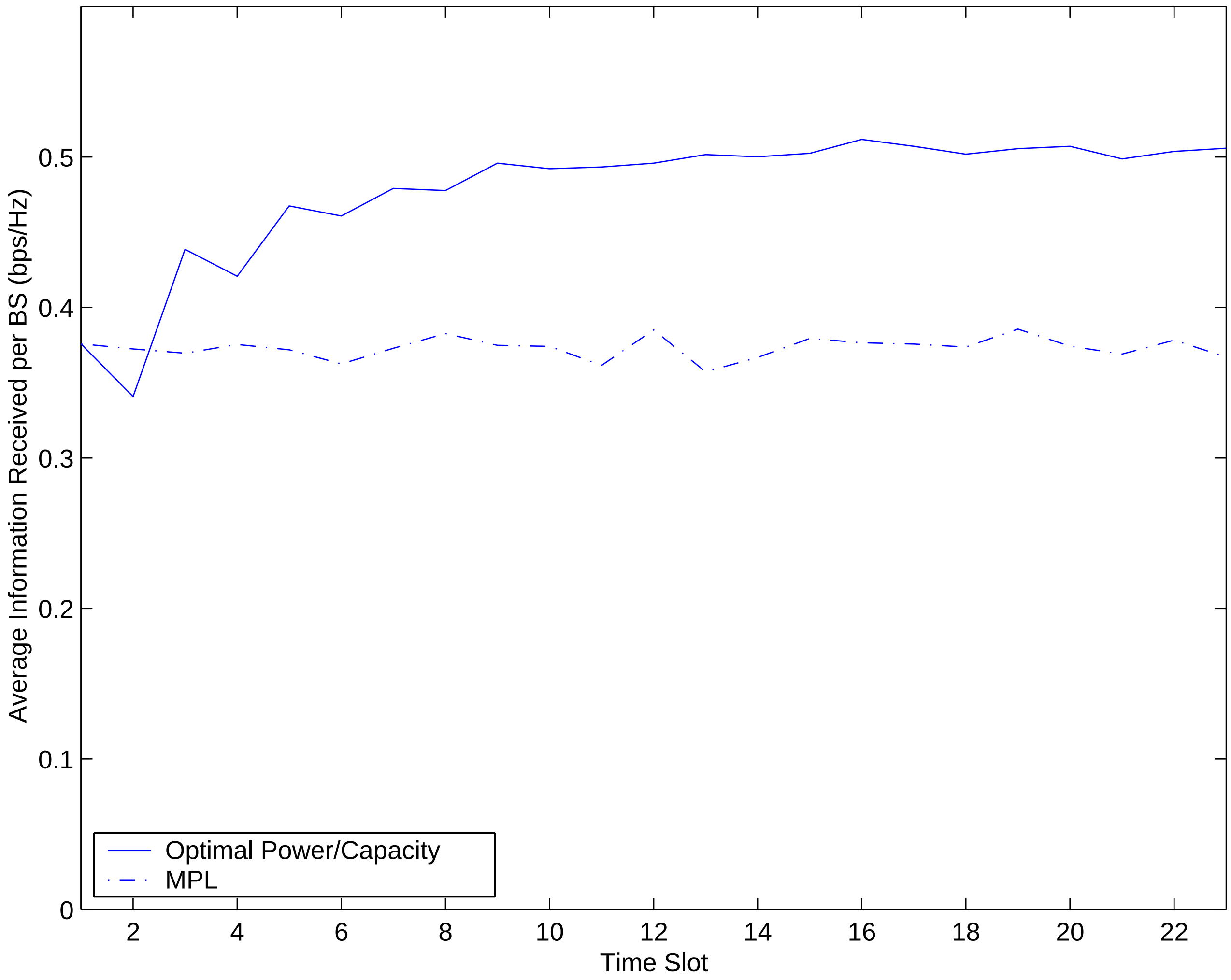
neighbor nodes : superscript j

$J^{(j)}$: reported cost of neighbor node j

$$NexthopIndex = \arg\min_j J_n^{(j)}(b_n, \gamma_n^{(j)})$$

$J_N(b,\gamma) = \frac{2^{2b}-1}{\gamma}$ to empty the buffer in one slot based on Shannon's formula

Optimum Routing vs. Minimum Path Loss



CNL Communications & Networking Laboratory

Concluding Remarks

- Increasing the link efficiency between routers and base stations has a direct effect on network capacity
  - Increasing the density of routers from 0 to 10 times the density of base stations, for efficiency factor of 10 results in a three-fold capacity increase
- MUD can remove the saturation region of capacity versus SNR and therefore take advantage of the conserved power to increase capacity
  - Multifold increase in capacity is possible

References

A Limited List of References

CNL Communications & Networking Laboratory

References

1 M.B. Pursley and H.B. Russell, "Routing in Frequency Hop Packet Radio Networks with Partial Band Jamming," *IEEE Trans. Commun.*, vol. 41, pp. 1117-1124, July 1984.

2 A. Stevens, "Least Interference Routing," in *Proc. Tactical Commun. Conf.*, pp. 42-51, May 1988.

3 Tsudaka, M. Kawahara, A. Matsumoto, and H. Okada, "Power control routing for multi hop wireless ad-hoc network," *Proceedings of the 2001 IEEE Global Telecommunications Conference*, vol. 5 , pp. 2819 -2824, November 2001.

4 R. Dube et al., "Signal Stability based Adaptive Routing (SSA) for Ad-Hoc Mobile Networks," *IEEE Pers. Commun.*, Feb. 1997, pp.36-45.

5 S. Singh and C.S. Raghavendra, "PAMAS-Power Aware Multi-Access protocol with Signaling for Ad Hoc Networks," *ACM Commun. Rev.*, July 1998.

6 A. Michail and A. Ephremides, "Energy Efficient Routing for Connection-Oriented Traffic in Ad-Hoc Wireless Networks," in *The 11th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol.2 , pp. 762 -766.

7 C.-K. Toh, "Maximum Battery Life Routing to Support Ubiquitous Mobile Communications," *IEEE Communications*, vol. 39, June 2001, pp. 138-147.

8 I. Stojmenovic and X. Lin, "Power-Aware Localized Routing in Wireless Networks," *IEEE Trans. on Parallel and Distributed Systems*, vol. 12, Nov. 2001, pp. 1122-1133.

9 Woo, C. Yu, D. Lee, H. Youn, and B. Lee " Non-Blocking, Localized Routing Algorithm for Balanced Energy Consumption in Mobile Ad Hoc Networks," *Proceedings of the Ninth International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems,* Aug. 2001, pp. 117-124.

10 C.A. St. Jean, A.N. Zadeh, and B. Jabbari, "Combined Routing, Channel Scheduling and Power Control in Packet Radio Ad Hoc Networks with Cellular Overlay," to appear in *Proceedings of VTC Spring 2002*, May 2002.

References (Cont'd)

11 E. Biglieri, J. Proakis, S. Shamai, "Fading channels: information-theoretic and communications aspects," IEEE Trans. Inform. Theory, vol. 44, no. 6, Oct. 1998, pp. 2619-2692.
12 A.G. Burr, "Space-time coding in the third generation and beyond," IEE colloquium capacity and range enhancement techniques for the third generation mobile commun. and beyond, Feb. 2000, pp. 1-7.
13 V. Tarokh, N. Seshadri, A.R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," IEEE Trans. Inform. Theory, vol. 44, no. 2, Mar. 1998, pp. 744-765.
14 S. Verdu, "Wireless bandwidth in the making," IEEE Commun. Mag., vol. 38, no. 7, July 2000, pp. 53-58.
15 G.J Foschini, M.J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," Wireless Personal Comm., 1998, pp. 311-335.
16 J.H. Winters, "Smart antennas for wireless systems," IEEE Personal Commun., Feb. 1998, pp. 23-27.
17 C. Perkins, Editor, Ad Hoc Networking, Addison-Wesley, 2001.
18 A.N. Zadeh, B. Jabbari, "Throughput of a multihop packet CDMA network with power control," Proc. IEEE VTC'2000-Spring, 2000, vol. 1, pp. 31-35.
19 A.N. Zadeh, B. Jabbari, "On the capacity modeling of multihop packet CDMA cellular networks," IEEE MILCOM 2001.
20 A.N. Zadeh, B. Jabbari, "Performance Analysis of Multihop Packet CDMA Cellular Networks," GlobeCom 2001, vol. 5, 2001, pp. 2875-2879.
21 A.N. Zadeh, B. Jabbari, "A high capacity multihop packet CDMA wireless network," to appear in the ACM Journal of Wireless Networks, 2002.