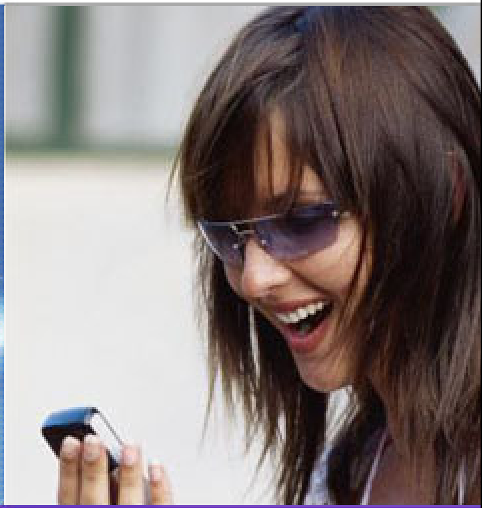
Next Generation Cellular Networks: Novel Features and Algorithms



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Outline

Overview

Why OFDM?

MIMO, Pre-coded CDMA, Supercast

Interference mitigation through dynamic fractional frequency reuse

Femto Cells - Architecture and Algorithms

Standards Evolution (3GPP2)

3rd Generation Partnership Project 2 "3GPP2"

CDMA IS-95-A (2G)
- Voice
- 14.4 kbps
- CSD & PD

IS-95-B
- Voice
- 64 kbps Packet
- RF Backward Comp.

cdma2000 1X (3G)
- Hi-Capacity Voice
- 153 kbps Packet
- RF Backward Comp.

cdma2000 1xEV-DO Rev 0 (2000)
- Web browsing
- 2.4 Mbps FL
- 153 kbps RL
- RF Backward Comp.

cdma2000 1xEV-DO Rev A (2004)
- Optimized VoIP
- 3.1 Mbps FL
- 1.8 Mbps RL
- RF Backward compatible

cdma2000 1xEV-DO Rev B (2006)
- Initial video telephony
- Nx4.9 Mbps FL
- Nx1.8 Mbps RL
- RF Backward Comp.

Ultra Mobile Broadband (2007)
- Enhanced video telephony
- Video streaming
- 288 Mbps FL*
- 75 Mbps RL
- Enhanced BCMCS

BCMCS → EBCMCS (OFDM Based)
- Broadcast Services
- RF Backward Comp.

* Based on 4 X 4 MIMO using 20 Mhz

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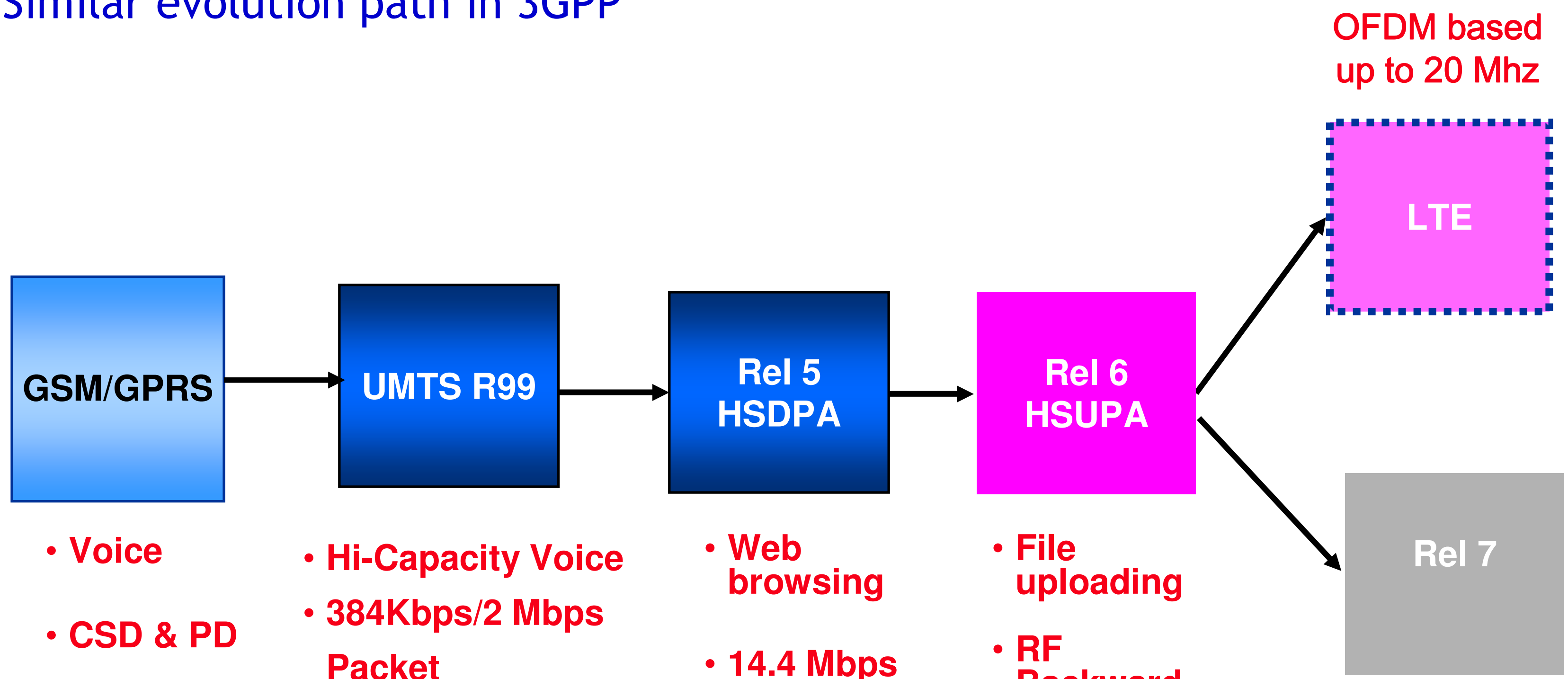
Standards Evolution (3GPP)

Similar evolution path in 3GPP



GSM/GPRS
- Voice
- CSD & PD

UMTS R99
- Hi-Capacity Voice
- 384Kbps/2 Mbps Packet

Rel 5 HSDPA
- Web browsing
- 14.4 Mbps FL
- RF Backward Comp.

Rel 6 HSUPA
- File uploading
- RF Backward Comp.

Rel 7
- VoIP Enhancements
- Push-to-talk
- RF Backward Comp.

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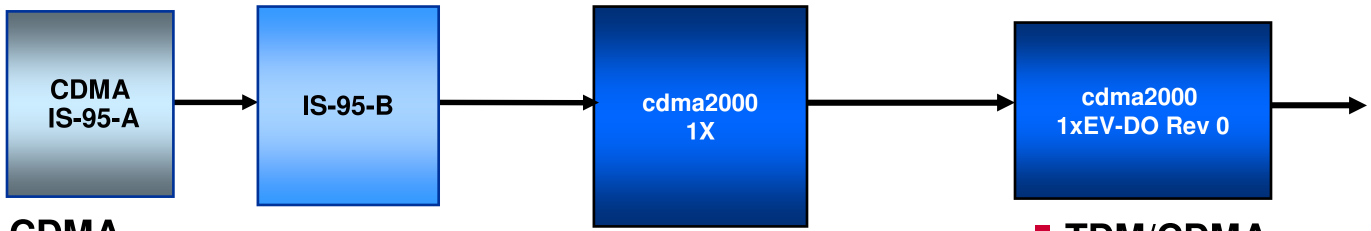
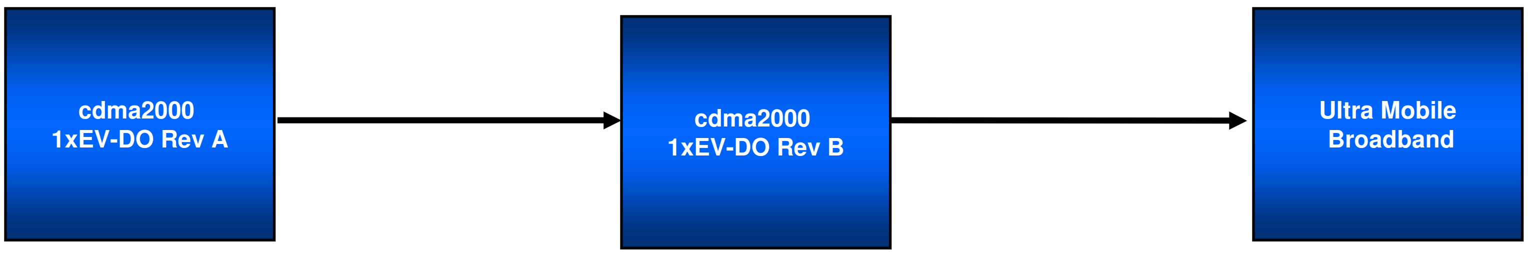
Technology Evolution



- CDMA
- Slow Power Control
- Non-coherent Reverse Link
- Convolutional Codes

- Fast Power Control
- Coherent Reverse Link
- Tx Diversity
- Enhanced coding

- TDM/CDMA
- Turbo Codes
- AMC
- FL-HARQ

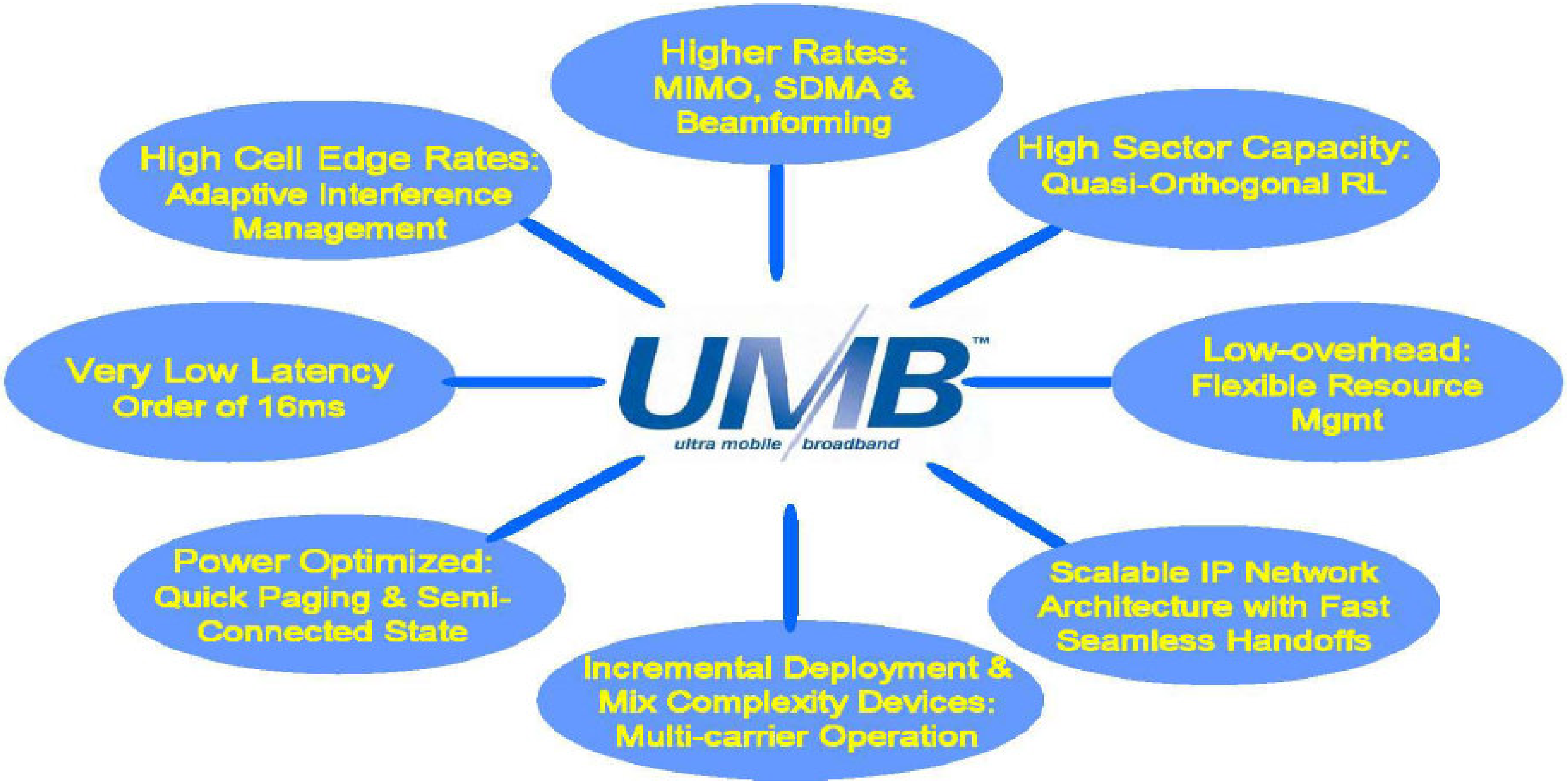


- QoS Support
- Fast RoT control
- RL-HARQ

- Multi-channel CDMA
- Multi-link RLP

- OFDMA
- Pre-coded CDMA
- SDMA/MIMO
- Superposition coding
- Interference mitigation
- Optimized handoffs, architecture

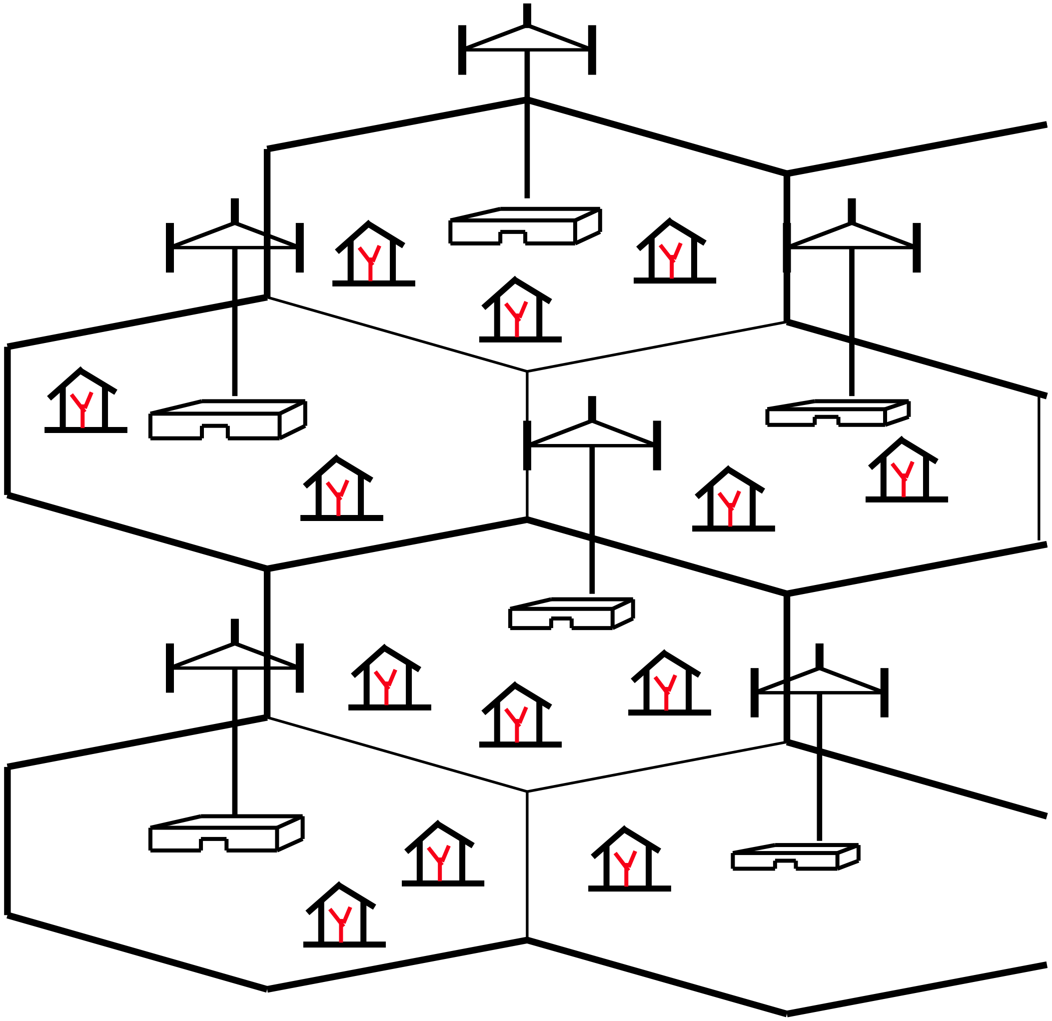
UMB Features



Ultra Mobile Broadband™ and (UMB™) are trade and service marks owned by the CDMA Development Group (CDG).

3GPP LTE has similar features

Femto Cells – Fixed-Mobile Convergence



- Femto cells are low power cellular base stations deployed in homes
- Cell phones can be used inside homes with the home broadband connection as backhaul

Benefits

- Operator
  - Reduce backhaul capacity requirements
  - Reduce CapEx and OpEx
  - Reduce customer churn through bundling and new converged services
- Consumer
  - Superior in-building coverage and quality without change in phones
  - One number and one phone and location specific pricing

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New algorithms for Next Generation Networks

Physical Layer

- Synchronization, frequency offset estimation, power control, peak limiting…. need to be reworked for OFDM
- Soft handoff is replaced by separate forward and reverse links; network directed and mobile requested handoffs

Resource Management

- Frequency and time domain scheduling for persistent and bursty unicast data and multicast streaming
  - Out-of-cell interference reduction through scheduling (fractional frequency reuse)
  - MIMO
- Dynamic load balancing schemes

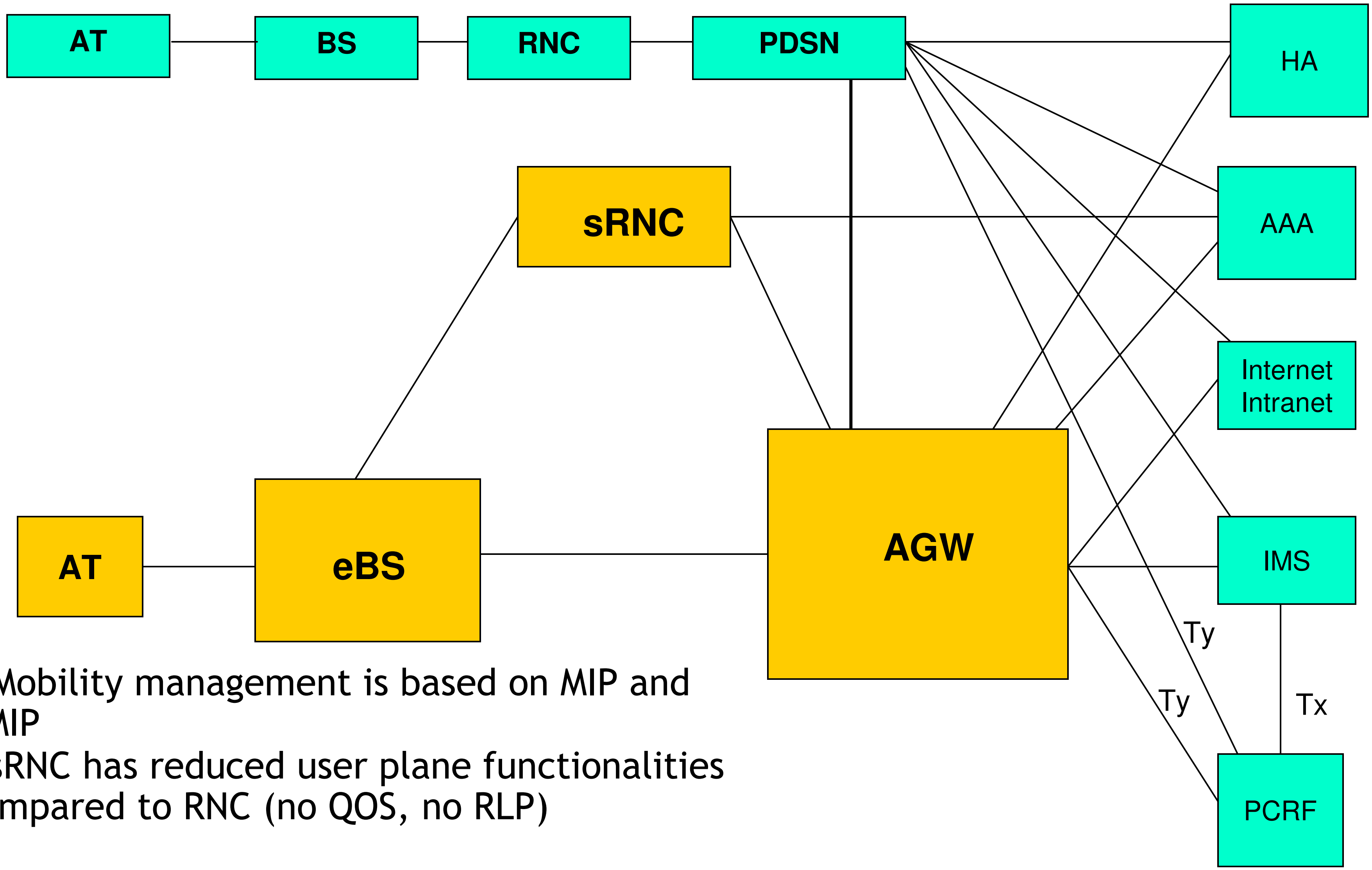
Self Configuration

- Neighbor discovery, Frequency planning, Preamble sequence planning

Femto cells

- Co-existence of macro and femto cells - Femto cell transmit power adjustment

Network Architecture (UMB)



- Mobility management is based on MIP and PMIP
- sRNC has reduced user plane functionalities compared to RNC (no QOS, no RLP)

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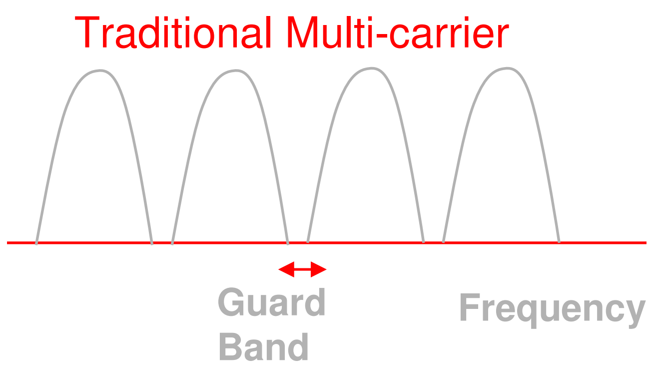
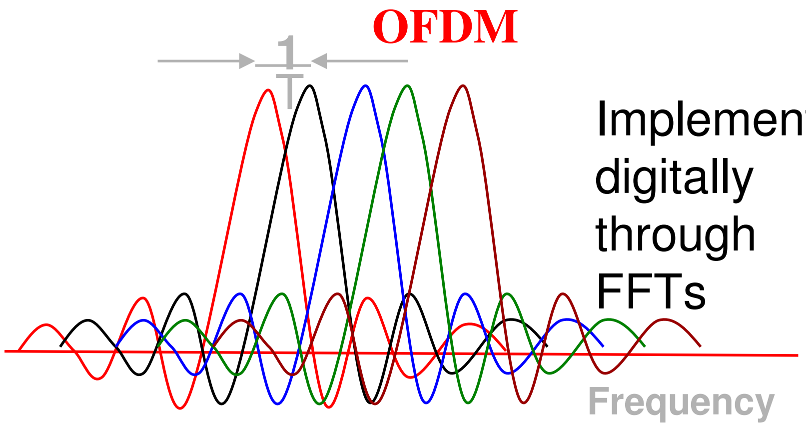
Femto Cells - Architecture and Algorithms

What is OFDM ?

Orthogonal Frequency Division Multiplexing is block transmission of N symbols in parallel on N *orthogonal* sub-carriers



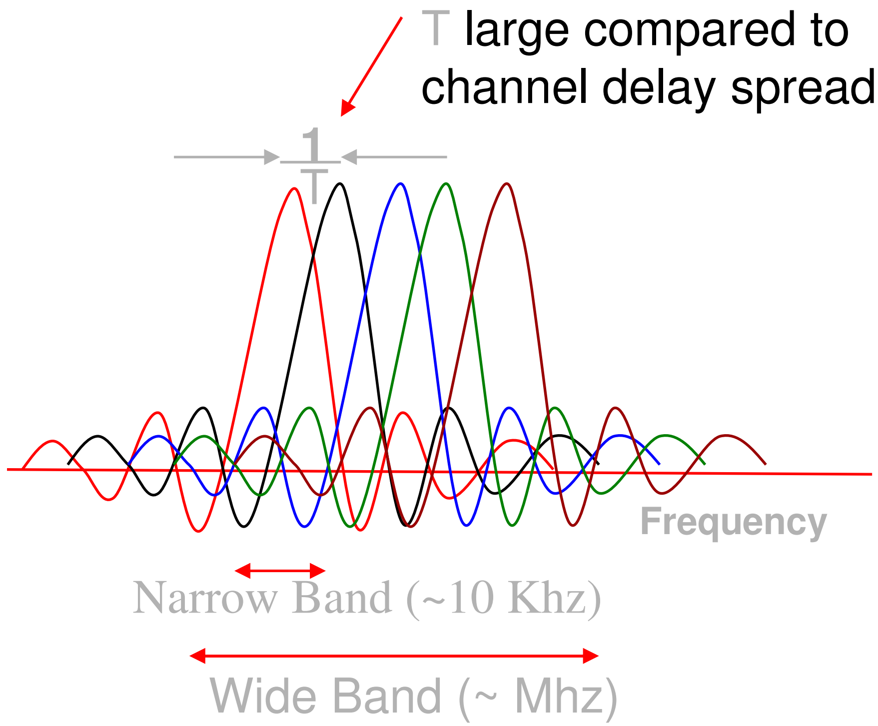


Implemented digitally through FFTs

OFDM invented in Bell Labs by R.W. Chang in ~1964 and patent awarded in 1970

Widely used: Digital audio and Video broadcasting, ADSL, HDSL, Wireless LANs

High Spectral Efficiency in Wideband Signaling



Sub-carriers remain orthogonal under multipath propagation

- Closely spaced sub-carriers without guard band
- Each sub-carrier undergoes (narrow band) flat fading
    - Simplified receiver processing
- Frequency or multi-user diversity through coding or scheduling across sub-carriers
- Dynamic power allocation across sub-carriers allows for interference mitigation across cells
- Orthogonal multiple access

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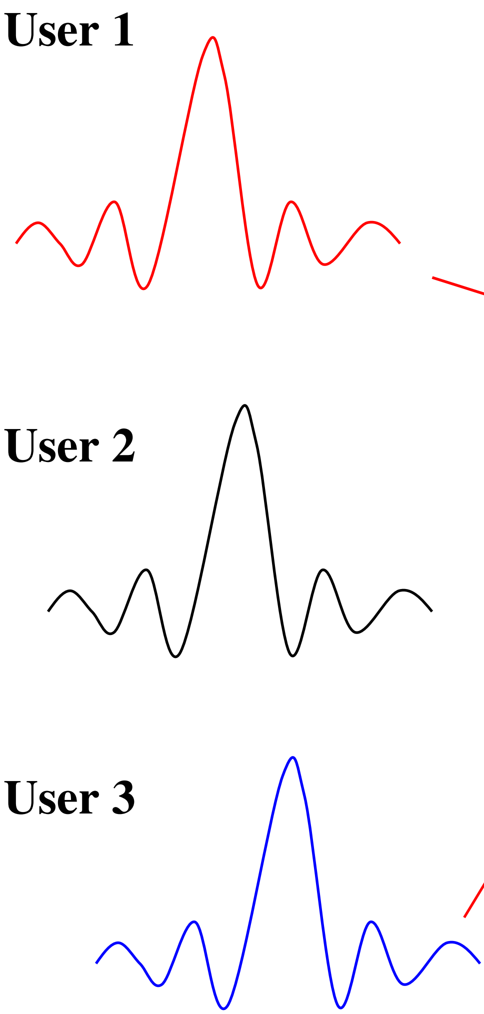
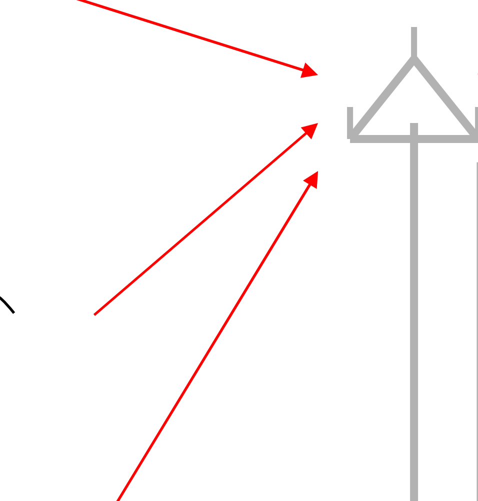
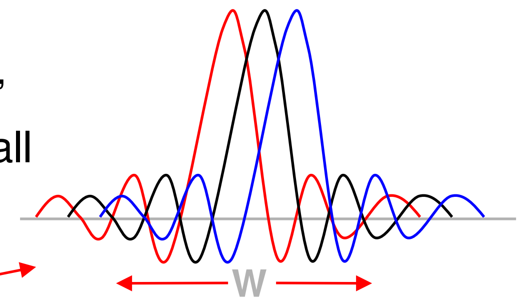
Reverse link Orthogonal Frequency Division Multiple Access



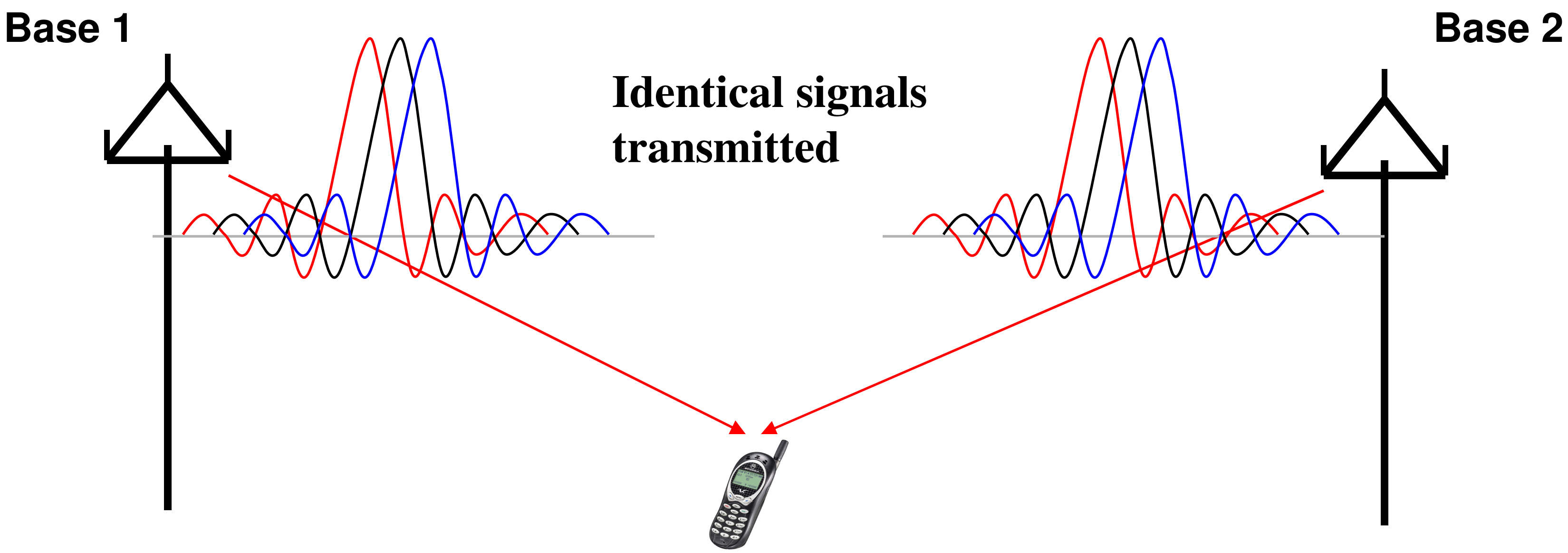
- Users are carrier synchronized to the base
- Differential delay between users' signals at the base need to be small compared to T





- Efficient use of spectrum by multiple users
- Sub-carriers transmitted by different users are orthogonal at the receiver
  - No intra-cell interference
- CDMA uplink is non-orthogonal since synchronization requirement is ~ 1/W and so difficult to achieve

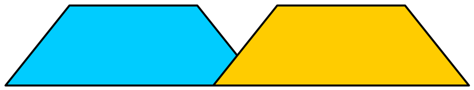
Efficient Broadcasting



- Sub-carriers remain orthogonal in the combined received signal
- Transmissions from neighboring base stations do not interfere with each other
  - Individual average signal-to-interference-and-noise ratios (SINR) are higher
  - Combining results in additional average SINR improvement
- Significant gain over CDMA with Rake in interference limited scenarios

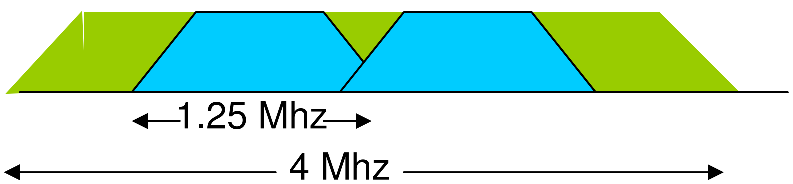
Flexibility and Scalability

EV-DO Rev A



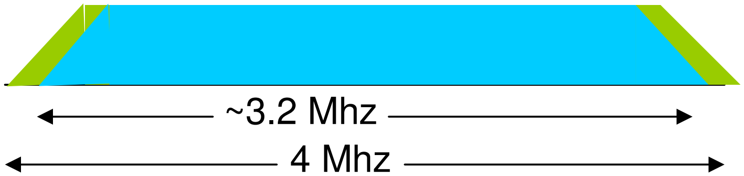
• Single mobile can communicate only in 1.25 Mhz of spectrum

EV-DO Rev B



• Single Mobile can communicate in N X 1.25 Mhz of spectrum

UMB



• Flexibility to better utilize available spectrum

  • 5 Mhz specifications allows <= 5 Mhz deployment

  • Made possible by proper design of control signaling

• Specifications designed for scalablity up to 20 Mhz

OFDMA makes it simpler to achieve flexible and scalable deployments

Deployment Flexibility - UMB OFDM Numerology

	FFT Size					
Parameter	**128**	**256**	**512**	**1024**	**2048**	**Units**
Chip Rate	1.2288	2.4576	4.9152	9.8304	19.6608	Mcps
Subcarrier Spacing	9.6	9.6	9.6	9.6	9.6	kHz
Bandwidth of Operation	≤ 1.25	1.25–2.5	2.5–5	5–10	10–20	MHz
Cyclic Prefix Duration	6.51, 13.02, 19.53, 26.04	6.51, 13.02, 19.53, or 26.04	6.51, 13.02, 19.53, 26.04	6.51, 13.02, 19.53, 26.04	6.51, 13.02, 19.53, 26.04	μs
Windowing Guard Interval	3.26	3.26	3.26	3.26	3.26	μs
OFDM Symbol Duration	113.93, 120.44, 126.95, 133.46	113.93, 120.44, 126.95, 133.46	113.93, 120.44, 126.95, 133.46	113.93, 120.44, 126.95, 133.46	113.93, 120.44, 126.95, 133.46	μs

Deployment flexibility achieved through configurable FFT Size and CP length

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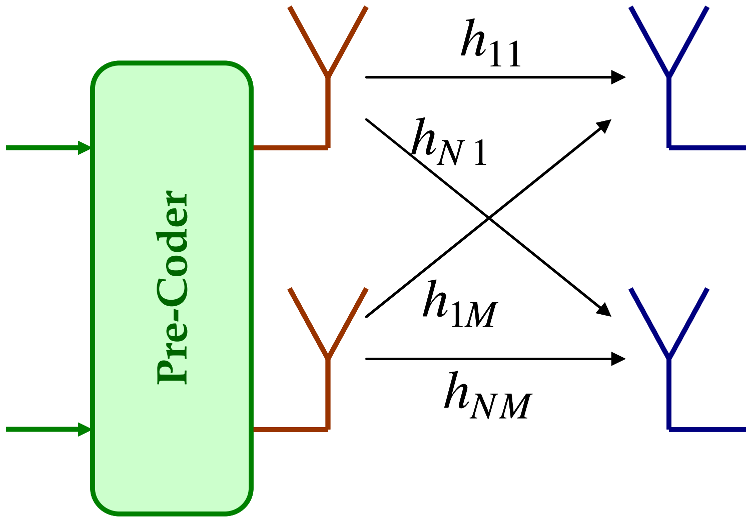
Femto Cells - Architecture and Algorithms

MIMO

MIMO dramatically increases spectral efficiency at high SNRs by exploiting scattering

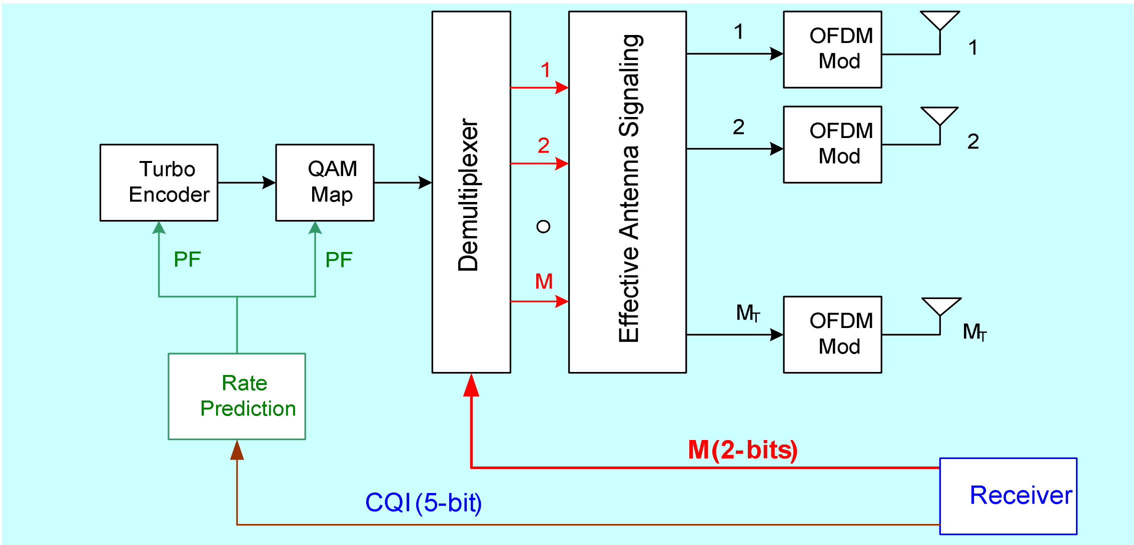


- Open loop and cloded loop MIMO schemes
- Beamforming/SDMA/MIMO achieved through appropriate selection of pre-coder
- Dedicated pilots for channel estimation
- Optimized feedback through precoder selection
- Flexible number of streams per user
- Each scheduled sub-band can use its own pre-coder

Unitary precoders can be used for equalizing power across the real antennas

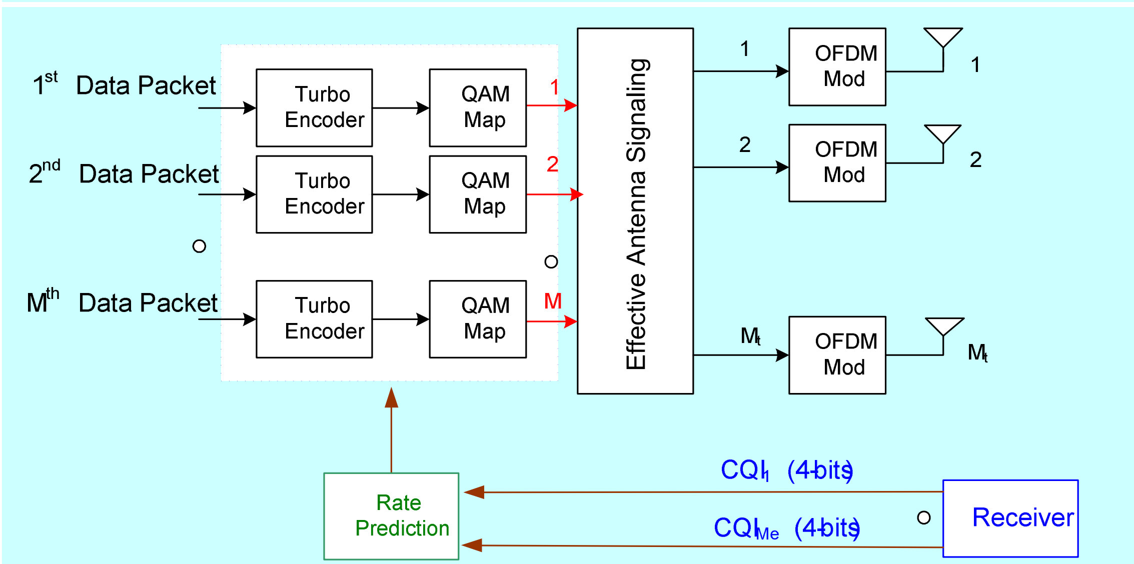
Non-unitary precoders can be used with feedback

MIMO in UMB (Single Code Word MIMO or Multi-codeword MIMO)



AT feeds back CQI and number of streams

Maximizes Diversity



AT feeds back per stream CQI for desired number of streams

Enables successive cancellation receiver

Source: Qualcomm

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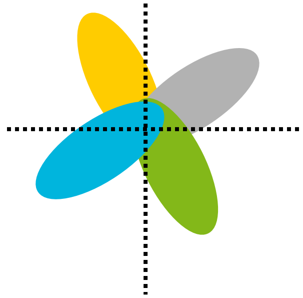
Multi-user MIMO / SDMA

System broadcasts a set of precoders

- Precoders are matrices of weighting vectors
  - Example: beam forming vectors corresponding to specific directions in the case of low angle spread environments

FFT Precoder for Omni-sector

$$e^{-j\theta}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -j & -1 & j \\ 1 & -1 & 1 & -1 \\ 1 & j & -1 & -j \end{bmatrix}$$



Mobile estimates the channel and feeds back the precoder matrix and vector(s) that is matched to the channel

Transmission scheduler picks the precoder matrix and the set of users scheduled for each slot by optimizing a scheduler metric

- Users that have nearly orthogonal channels are scheduled together in the same time-frequency resource

Feedback for closed loop MIMO

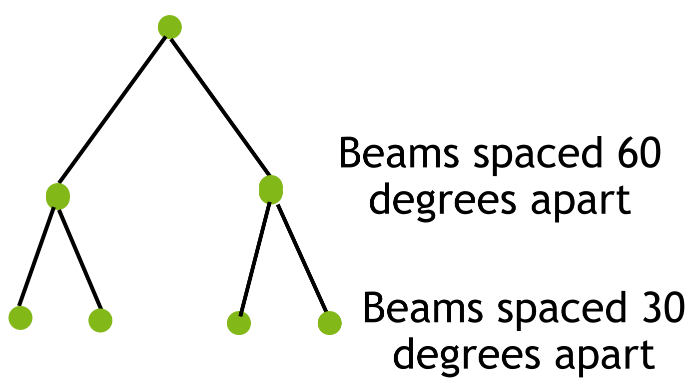
Highly flexible indication of precoder and SINR

- Periodicity, number of streams, sub-band granularity

Hierarchical Code Book Design

- Allows additional bits of feedback to refine information about the channel

Example



Two bits of feedback in each turn

1st bit indicates refinement or not

2nd bit indicates code vector

Quantization algorithms for design of unitary precoders

Reverse Link Control Signaling (Pre-coded CDMA)

Orthogonal access such as OFDMA requires explicit assignment of resources by the base station to guarantee orthogonality

For bursty data/control there is need to allocate and de-allocate resources frequently

Terminals need to make a request for allocation of resources when there is data to send

- Uncoordinated access for control signaling

Uncoordinated access methods

- Reserve OFDMA sub-carriers specifically for access
  - **Collision based access**
- Use **spreading within the reserved sub-carriers (pre-coded CDMA)**

Benefits of pre-coded CDMA

- Statistical multiplexing of bursty control and traffic signals
- Reduced latency for control signaling

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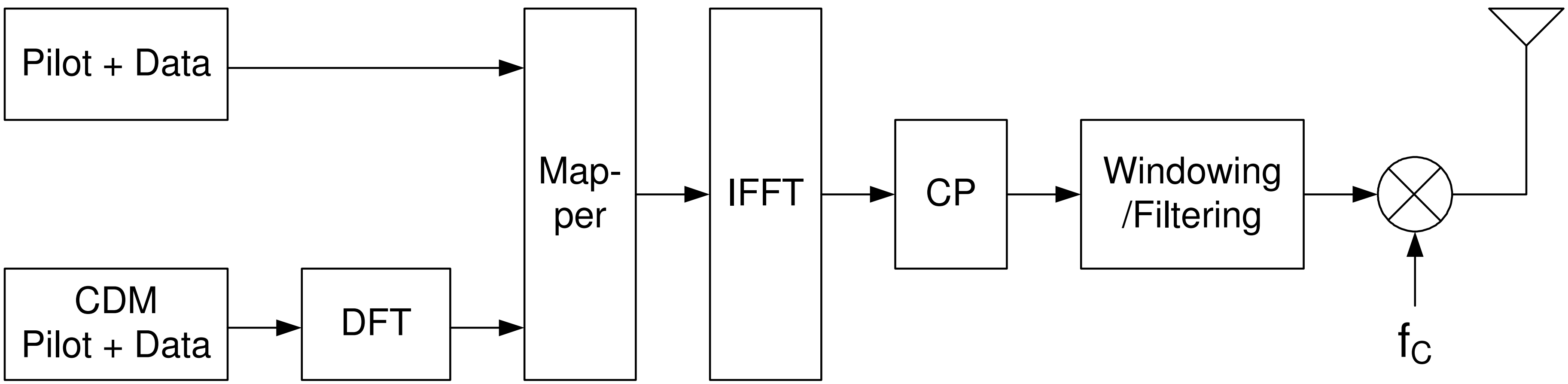
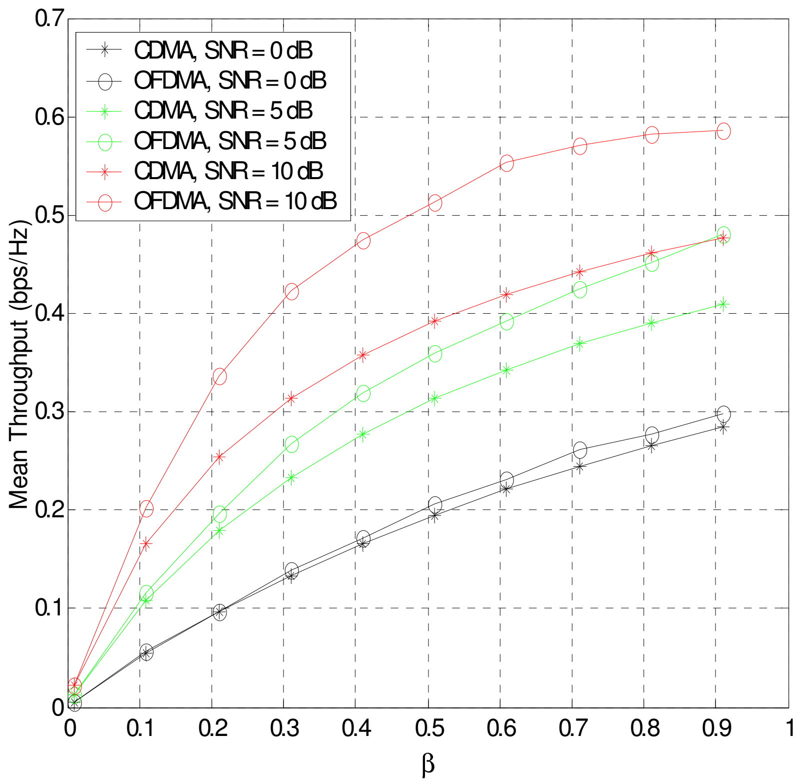
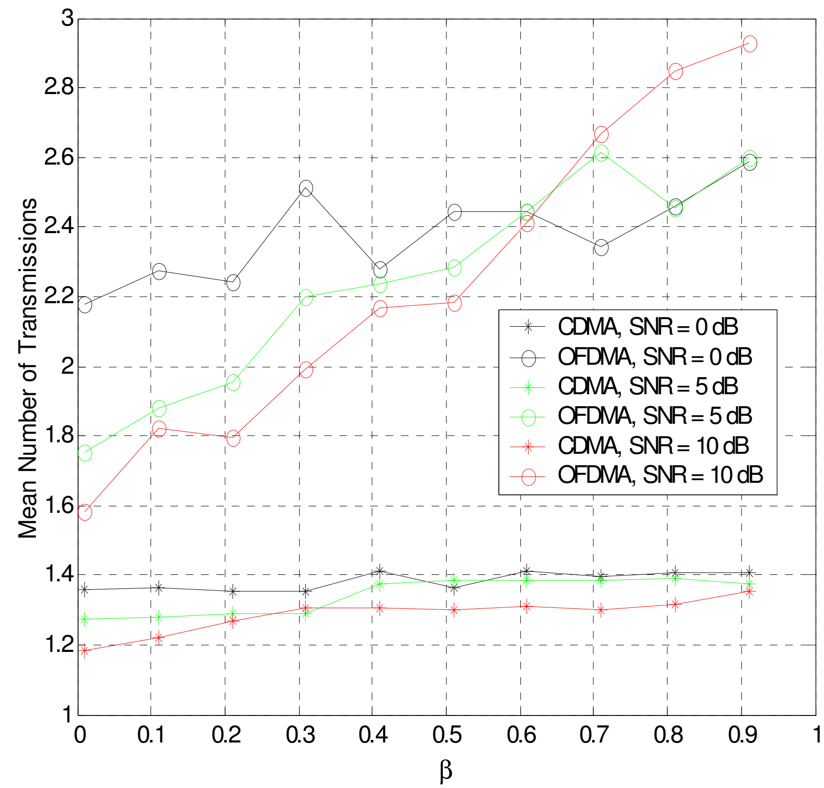
Hybrid OFDMA/CDMA Signal Flow



Performance of Collision-based Vs CDMA uncoordinated access





Throughput performance is comparable at low SNRs and delay performance is better for CDMA access

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Multicast Services

Frequency multiplexing of multicast service and unicast service

- A sub-set of sub-carriers on specific interlaces is reserved for multicast service

Synchronous SFN (single frequency network) Mode

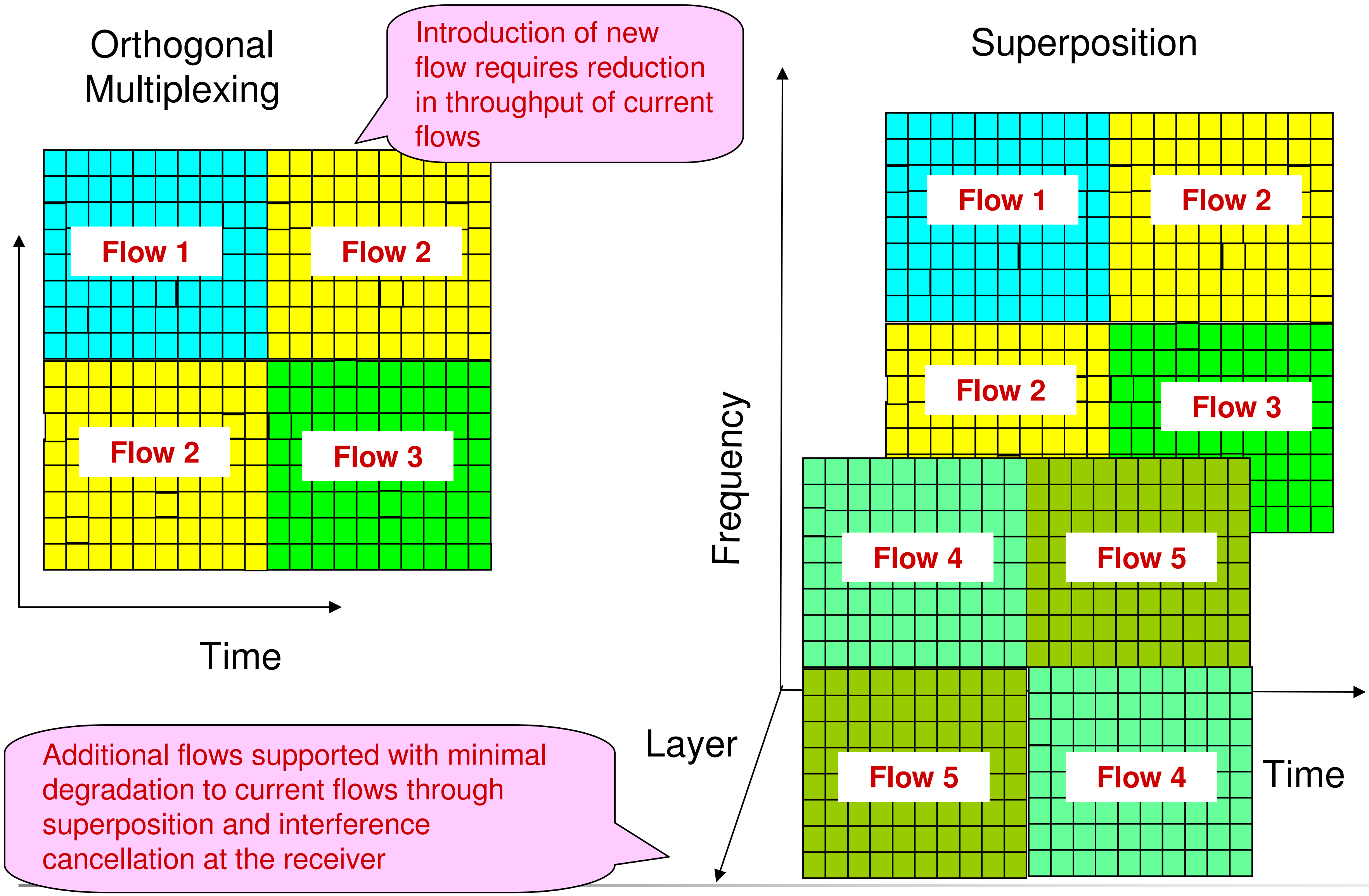
- Cluster of base stations transmit the same multicast message at the same time in the same set of sub-carriers
- OFDM symbols with longer cyclic prefix to tolerate larger delay spread
- Power combining gain

Asynchronous Mode

- Different base stations can independently schedule multicast transmissions
- Multicast transmissions in one cell interfere with unicast transmissions in neighboring cells

Multicast scheduling algorithms

Supercast: superposition of unicast flows over multicast flows



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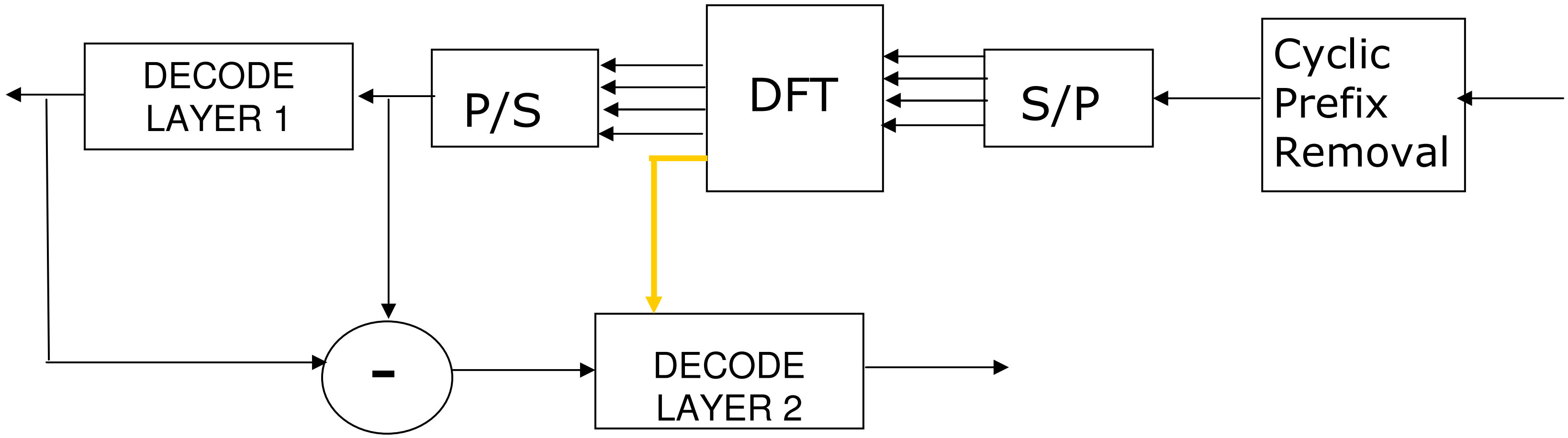
Successive Cancellation Receiver

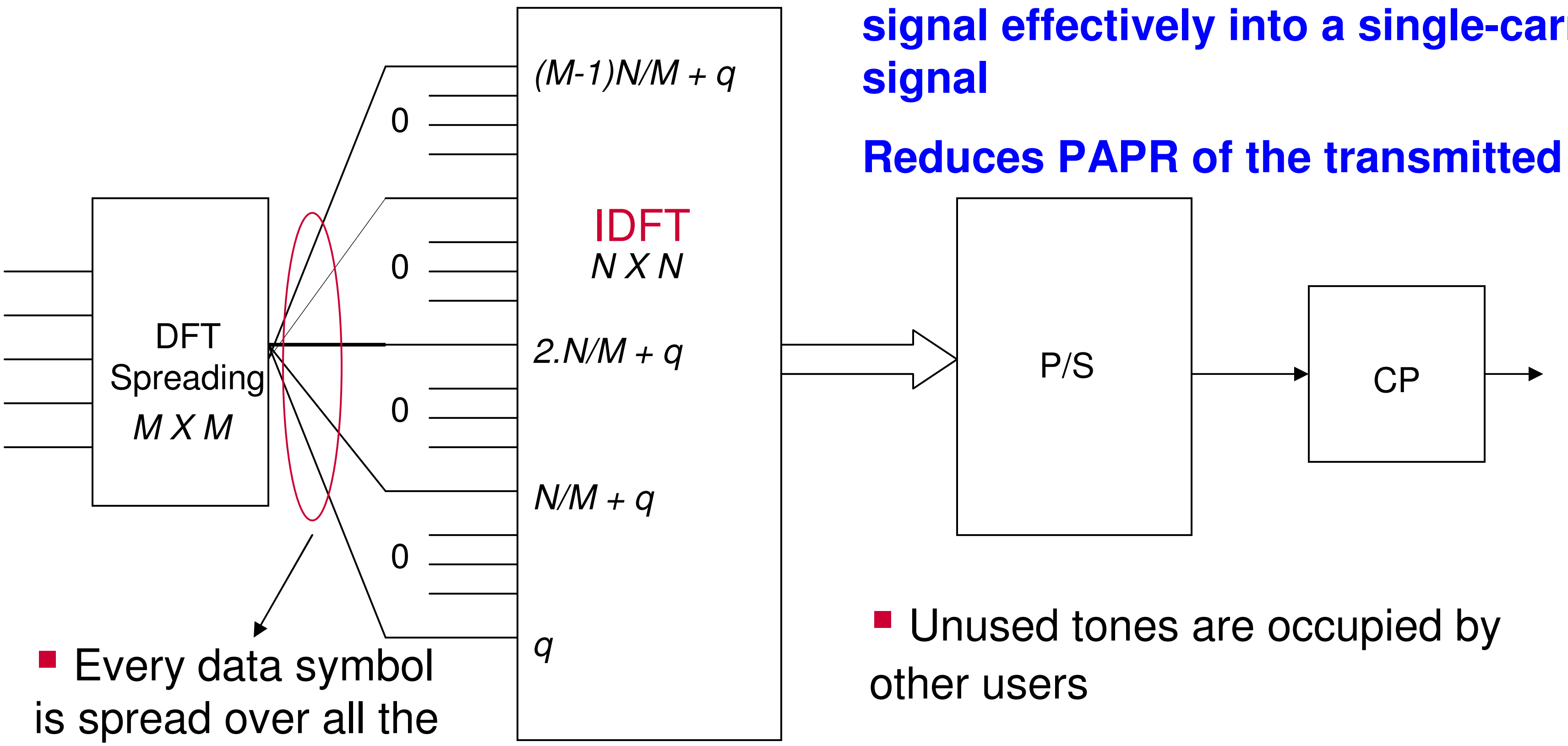


- Overlaid unicast pilot symbols and broadcast pilot symbols with different sequences facilitates unicast rate determination
- Successive interference cancellation receiver at the high SINR terminal
- Significant excess SNR for broadcast stream facilitates successive cancellation
- With Layer 1 as broadcast and Layer 2 as unicast, Layer 2 benefits from out-of-cell interference reduction leading to larger SNR differences between two layers

DFT-Spread-OFDM Transmission

Frequency domain DFT spreading turns signal effectively into a single-carrier signal

Reduces PAPR of the transmitted signal



- Every data symbol is spread over all the tones
- Sinusoids can be viewed as the spreading sequences

- Unused tones are occupied by other users
- Orthogonality across users is retained even after signal propagation through multipath channel

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Femto Cells - Architecture and Algorithms

Fractional Frequency Reuse

Edge users of neighboring sectors are placed in different frequency sub-bands to avoid mutual interference

Various reuse factors and interference mitigation levels can be achieved by

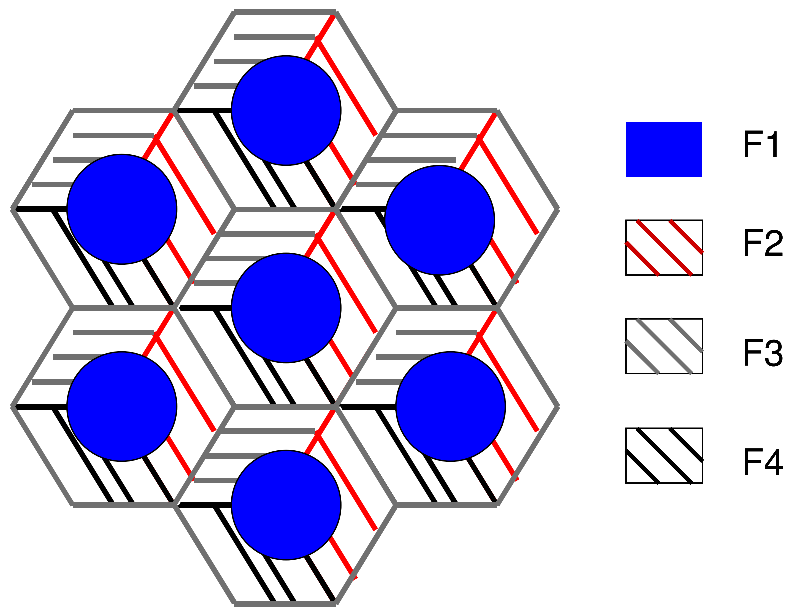
- Adjusting the proportion of bandwidth assigned to each category
- Adjusting power transmitted in each band

Adaptive reuse can be achieved

Objectives

- Improve cell edge throughput at the expense of average sector throughput
- Improve overall average sector throughput while maintaining same fairness

Example of fractional reuse



Why should we expect a gain in sector throughput?

Users at the cell edge experience low SINRs

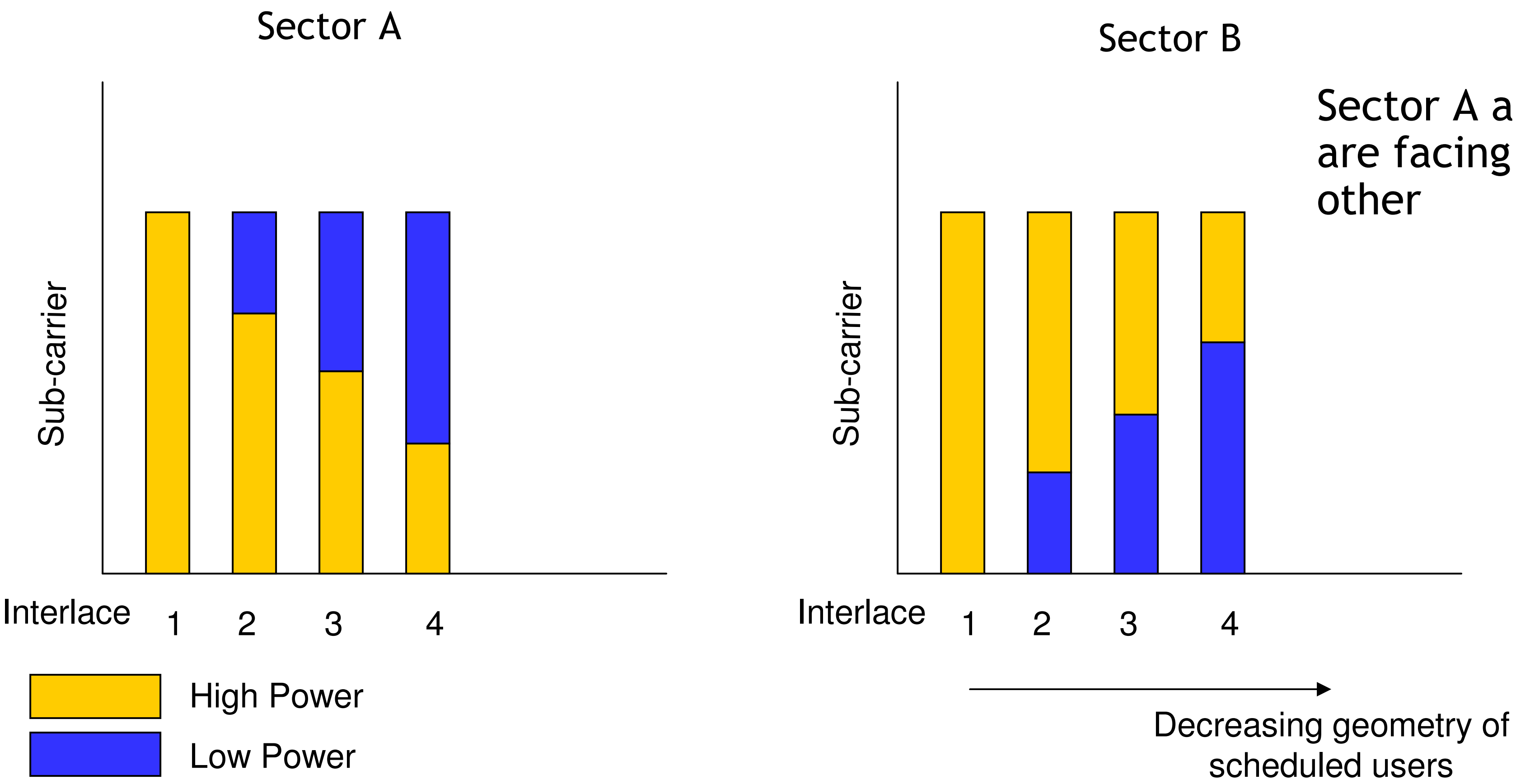
- Large ratio of bandwidth to bit rate
- Low spectral efficiency is achieved through low coding rates
- Small practical coding gain beyond a certain coding rate hence use repetition or sub-channelization

Sub-channelization implies significant fraction of the power is used on only a portion of the bandwidth used to serve the weak user even though universal reuse

- Exploit for interference avoidance
- Neighboring sectors should assign orthogonal sub-carriers to cell edge users
- Need an adaptive distributed implementation
  - Example: Use priorities in time and frequency to achieve distributed coordination
  - Take interference into account when assigning sub-carriers to users

"Fractional Reuse" while still using all of the sub-carriers

Transmit with low transmit power when occupying low priority sub-carriers



Sector A and B are facing each other

Resource Partitioning for FFR Scheduling in UMB

Sub-carriers are partitioned into

- Distributed resources zone (sub-carriers span the whole band for diversity)
- Contiguous resources zone (sub-carriers are grouped together)

The DRCH / BRCH zone is further partitioned into one or multiple sub-zones

• DRCHs / BRCHs hopping is defined within each DRCH / BRCH sub-zone in a sector specific way

One or more sub-zones over multiple interlaces constitute a “Resource Set”

FFR is performed based on the resource sets

• Different PSD can be defined in different resource sets

Multiple physical sub-bands can be represented in each resource set through sub-band hopping; on the other hand, multiple sub-zones can be defined within each physical sub-band

– enables both sub-band scheduling and FFR

Channel Quality Indication (CQI) for FFR

Goal is for the scheduler to obtain sub-zone specific instantaneous CQI based on regular CQI reports and additional information from relatively infrequent interference measurement reports

Reporting Approach

– regular CQI reports for rate adjustment/power control

– a message containing CQI adjustment for each resource set that AN should apply to corresponding CQI reports to derive CQI for each sub-zone

UMB specifications has the necessary messages for deriving required information

Algorithm for CBR Flows – General Approach

CBR Traffic

- Constant packet arrival rate with an activity factor

Scheduling Goal

- Maximize number of CBR flows in each cell with given amount of bandwidth and power

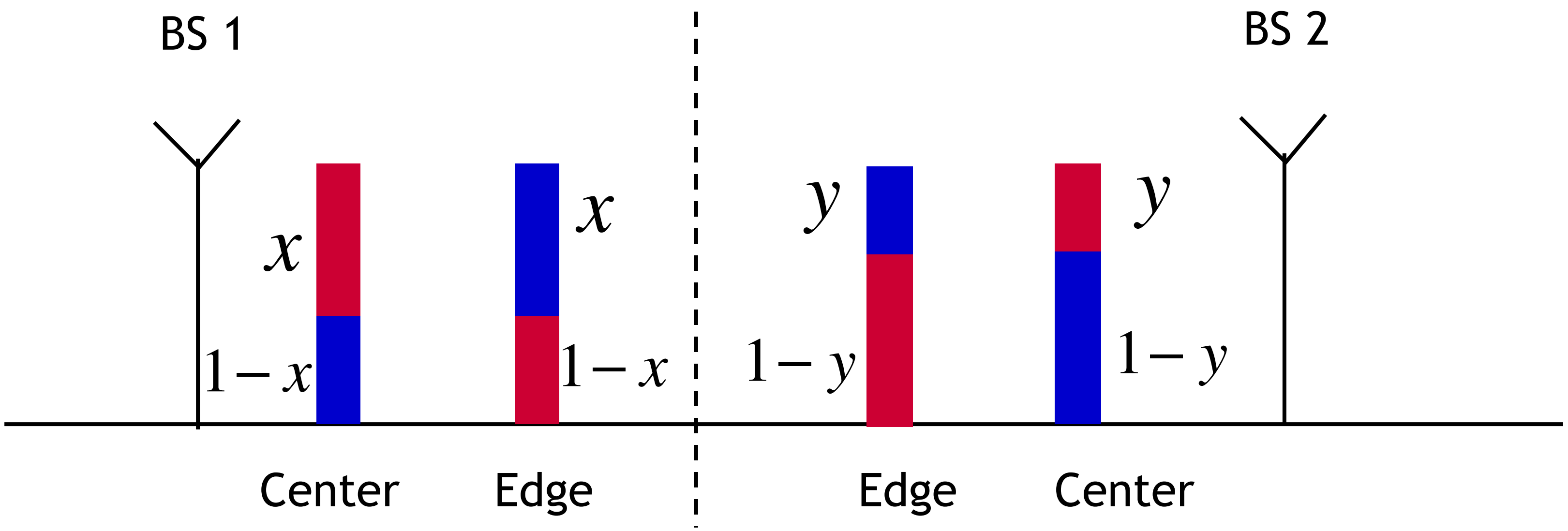
Algorithm approach

Each sector allocates users to resource sets/sub-bands, based on a local "selfish" objective, e.g. minimize total power allocation (possibly, weighted by resource set) to serve a fixed number of users

As a result, neighboring sectors "automatically" try to avoid each other's interference -- WITHOUT explicit inter-cell coordination

An efficient FFR pattern is created "automatically" -- WITHOUT explicit frequency planning

Symmetric 2 cells, 2 sub-bands, 2 user classes case - I

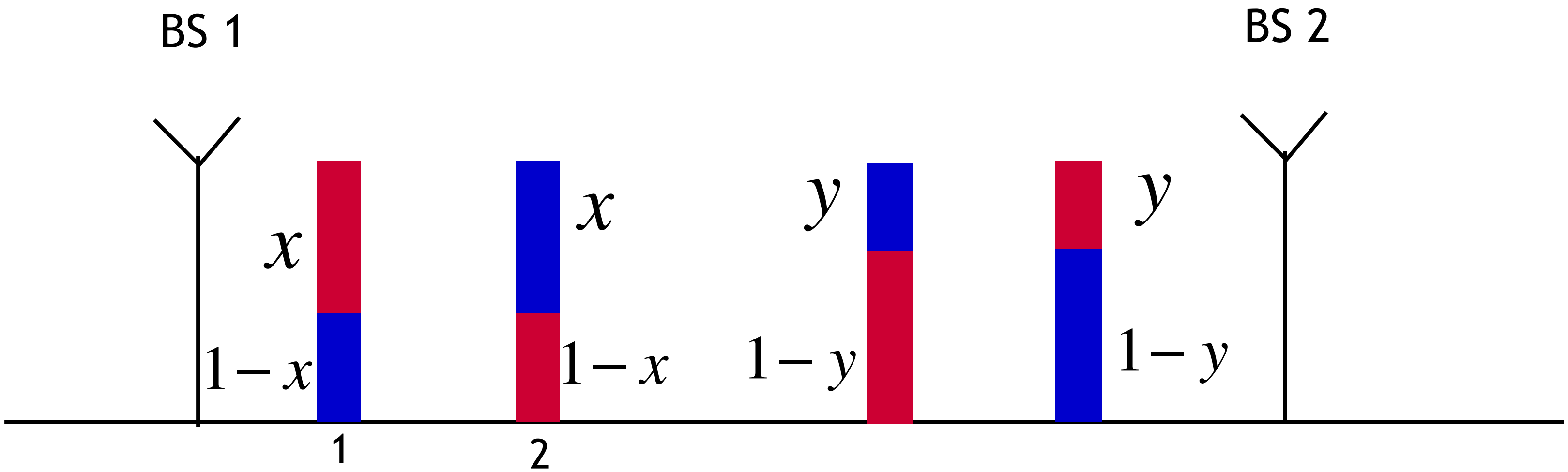


Red and blue are the two sub-bands with same number of sub-carriers each

x, y are the fractions of Edge users assigned to the blue sub-band

Same number of users at Center and Edge locations

Symmetric 2 cells, 2 sub-bands, 2 user classes case - II



Power Allocation Equations

$$P_B^1 = x\frac{\Gamma}{G_2^1}\left(N_0 + P_B^2 G_2^2\right) + (1-x)\frac{\Gamma}{G_1^1}\left(N_0 + P_B^2 G_1^2\right)$$

$$P_B^2 = y\frac{\Gamma}{G_2^1}\left(N_0 + P_B^1 G_2^2\right) + (1-y)\frac{\Gamma}{G_1^1}\left(N_0 + P_B^1 G_1^2\right)$$

Similar equations for red sub-band powers

Lemma

Unique solution to power allocation exists and power iterations converge to this solution

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Symmetric 2 cells, 2 sub-bands, 2 user classes case - III

Dynamical System

"Move users away from interference"

$$x = x - \delta * sign\left(\frac{dP^1}{dx}\right)$$

$$y = y - \delta * sign\left(\frac{dP^2}{dy}\right)$$

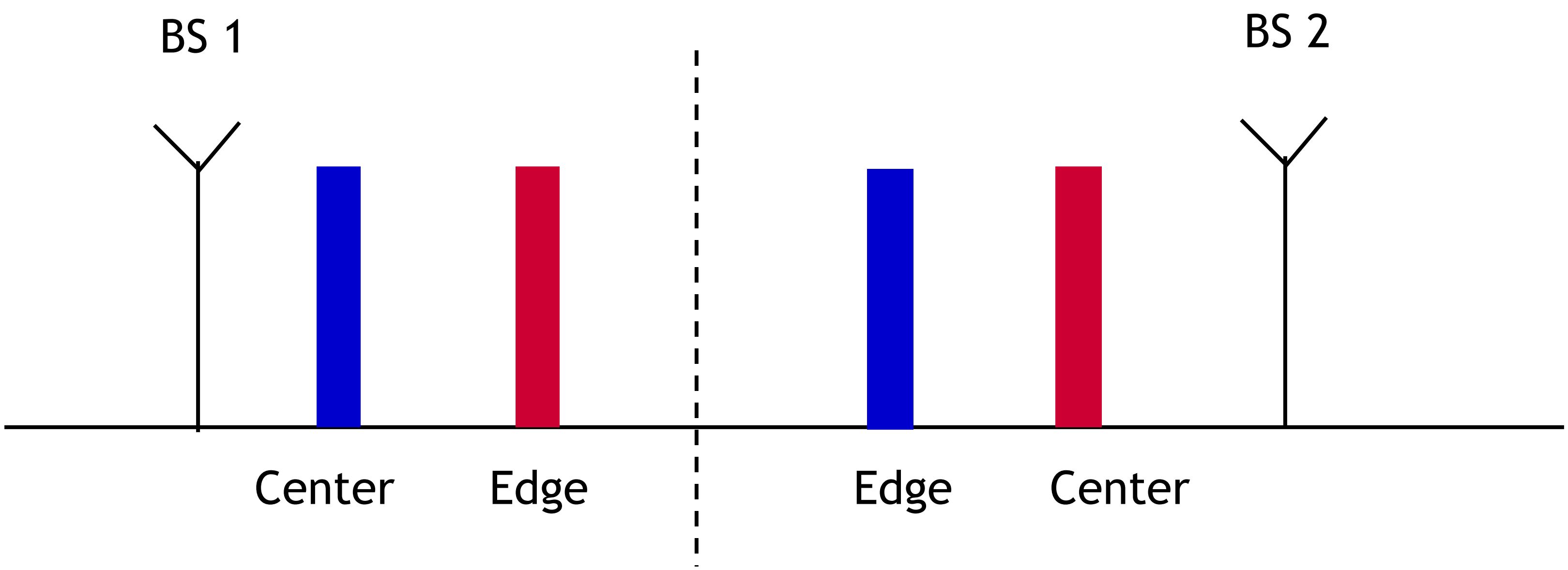
After reassignment of users power is allowed to converge before next reassignment of users

Theorem

Dynamical system converges to a Nash equilibrium

Symmetric 2 cells, 2 sub-bands, 2 user classes case - IV

Limiting Allocation



Theorem

The limiting allocation is the minimum power allocation

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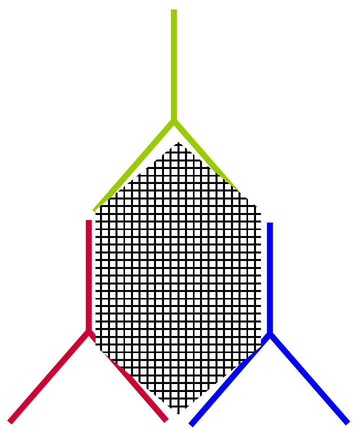
Simulation Setup for CBR traffic simulations

Three Sector Simulation



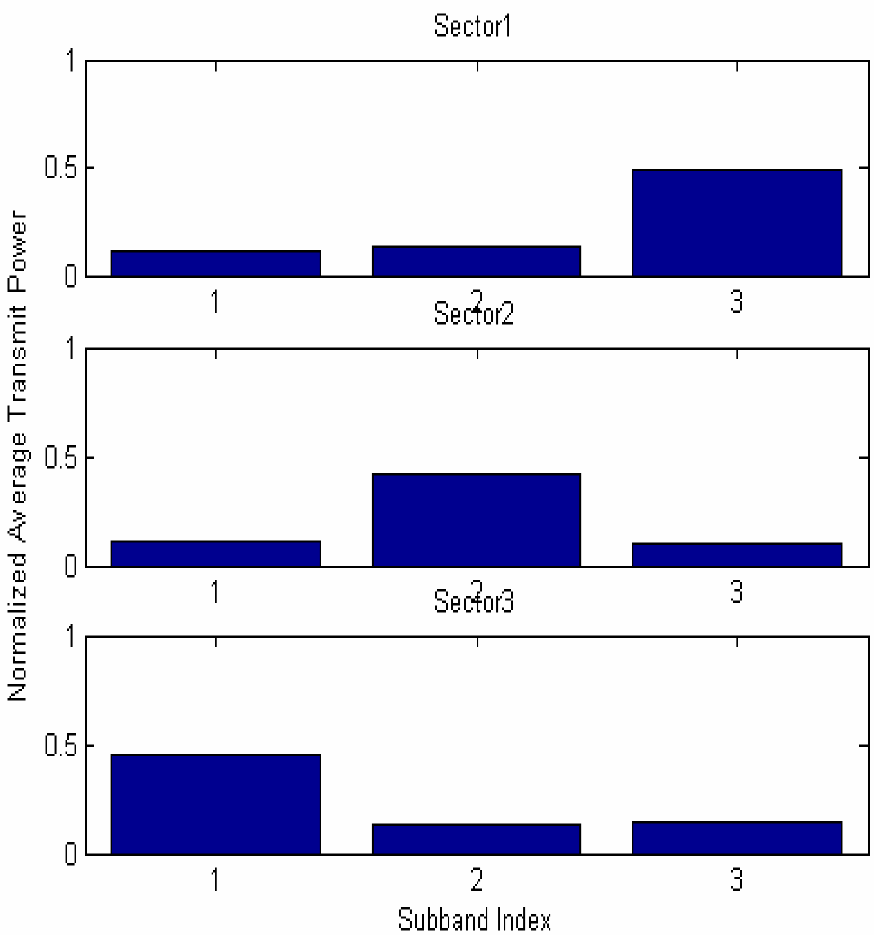
Parameters correspond to cell edge (140 dB path loss) SNR of 10 dB or 20 dB depending on the penetration loss

Parameters Table

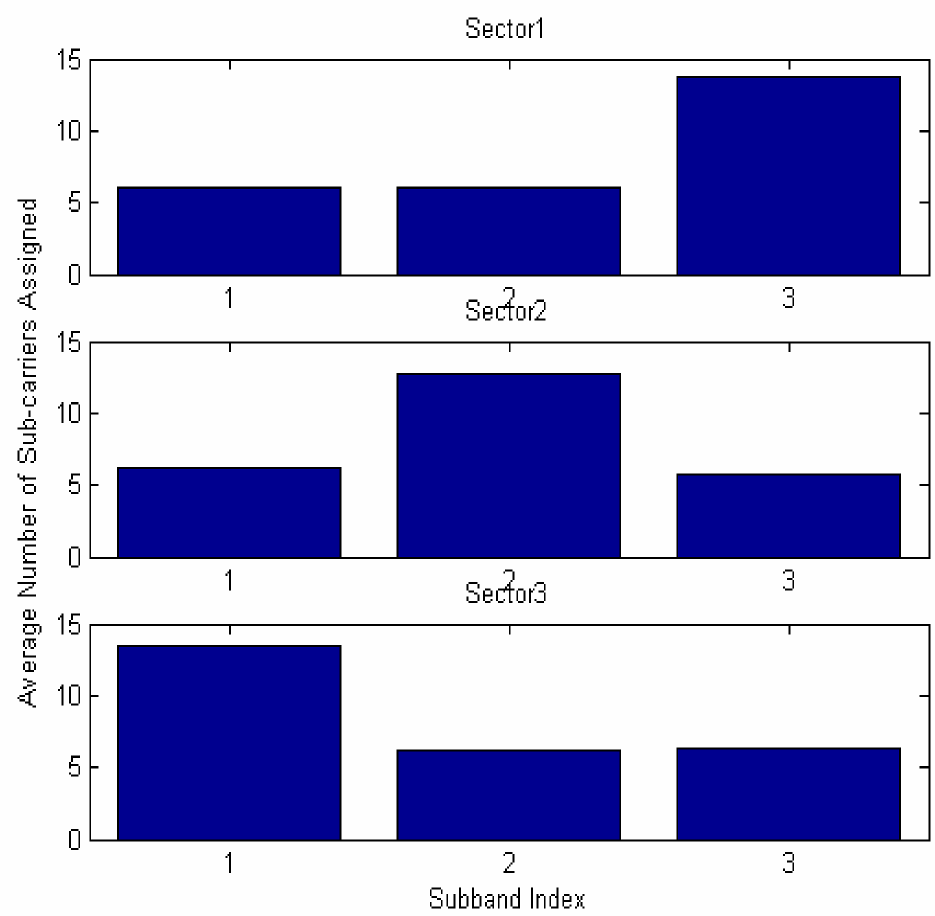
Parameter	Assumptions
Cell Layout	3 sectors
Inter site distance	2.5 km
Path loss model	$L = 133.6+35\log_{10}(R)$
Shadowing	Lognormal 8.9 dB std. dev
Penetration loss	10 dB or 20 dB
Noise Bandwidth	1.25MHz
BS Power	43dBm, 1 antenna
BS antenna gain	15 dB
Rx antenna gain	0 dB
Rx noise figure	10 dB
Channel model	No small scale fading

Uniform Distribution of Users (10 dB cell edge)

Transmit Power Ratio



Number of Sub-carriers



FFR patterns are automatically induced!!

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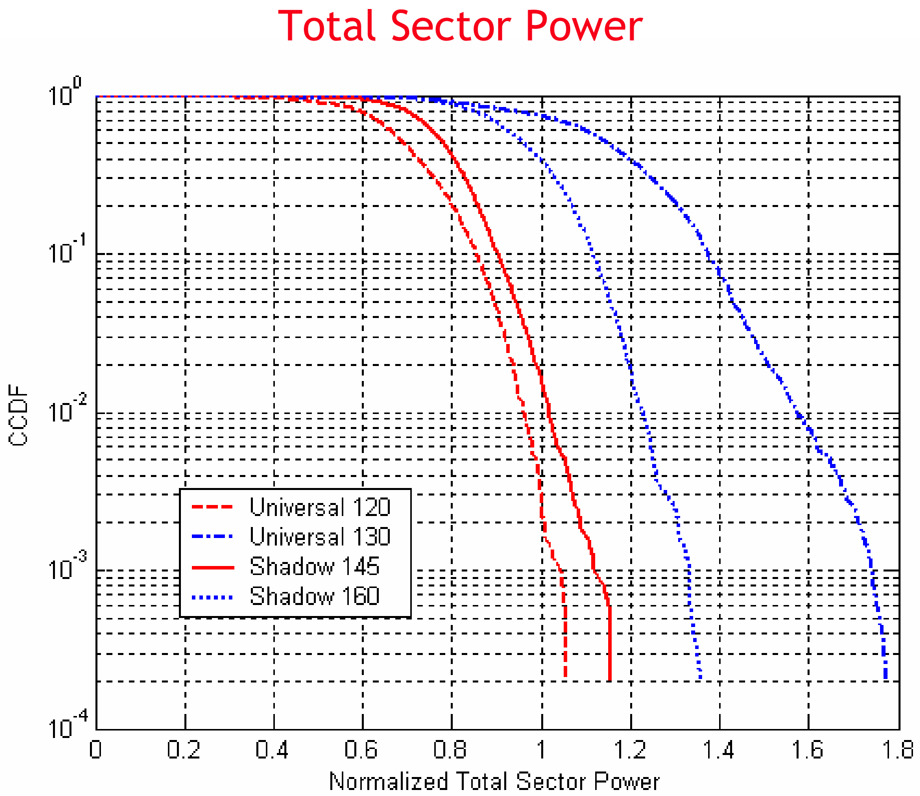
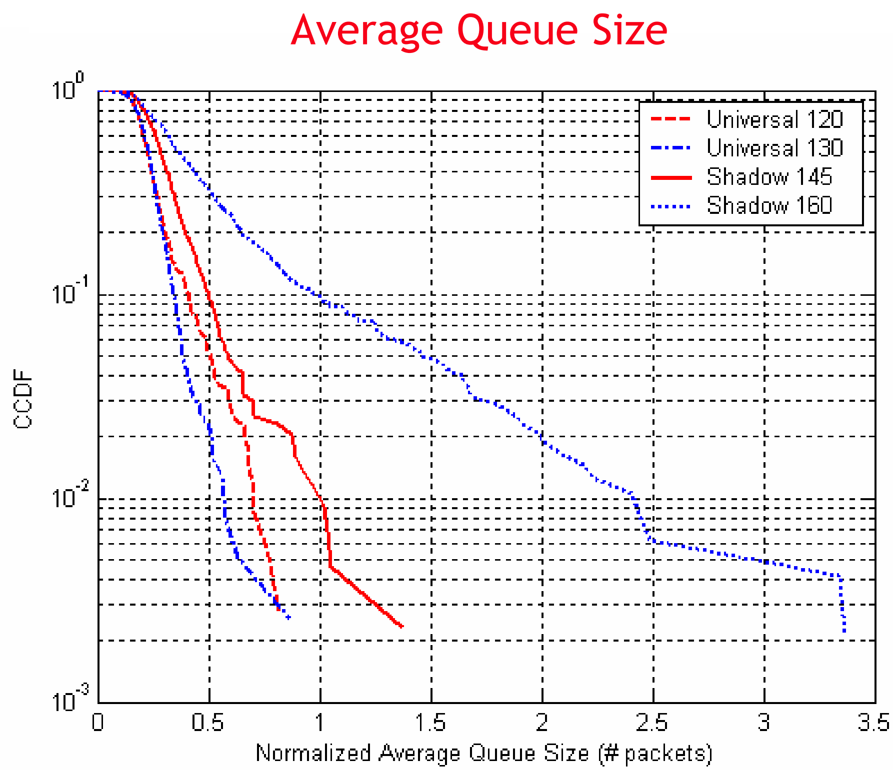
Excess Power and Average Queue Size (10 dB cell edge SNR)



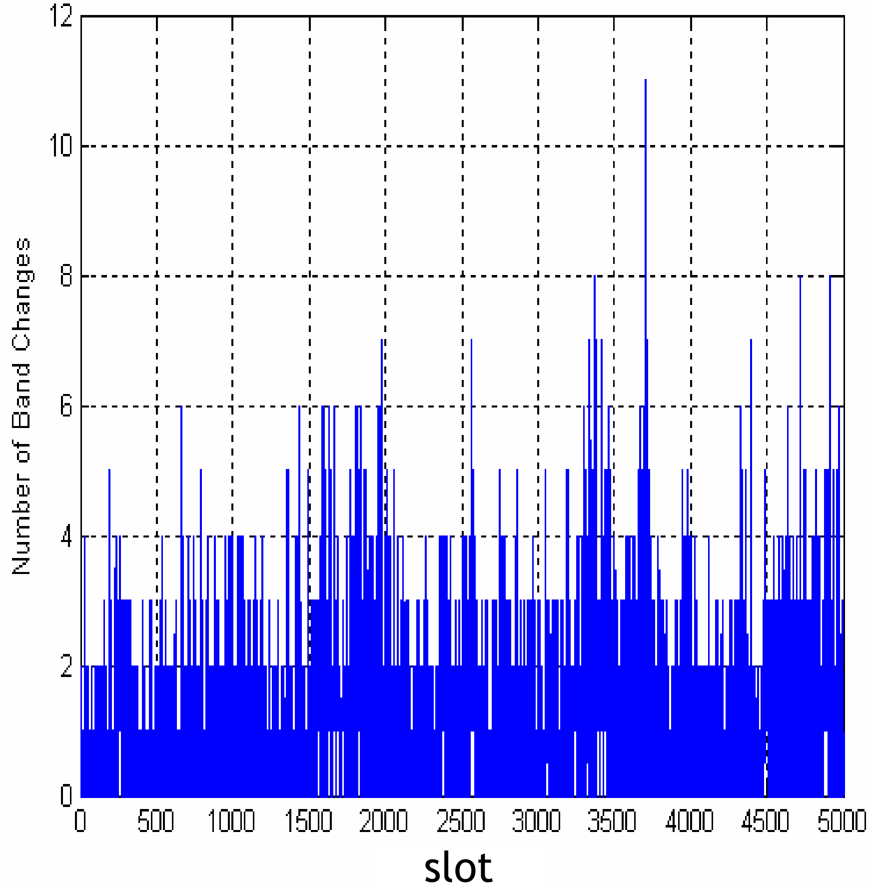


Universal Reuse: ~120 users; Shadow Algorithm: ~145 users

Gain is ~20%

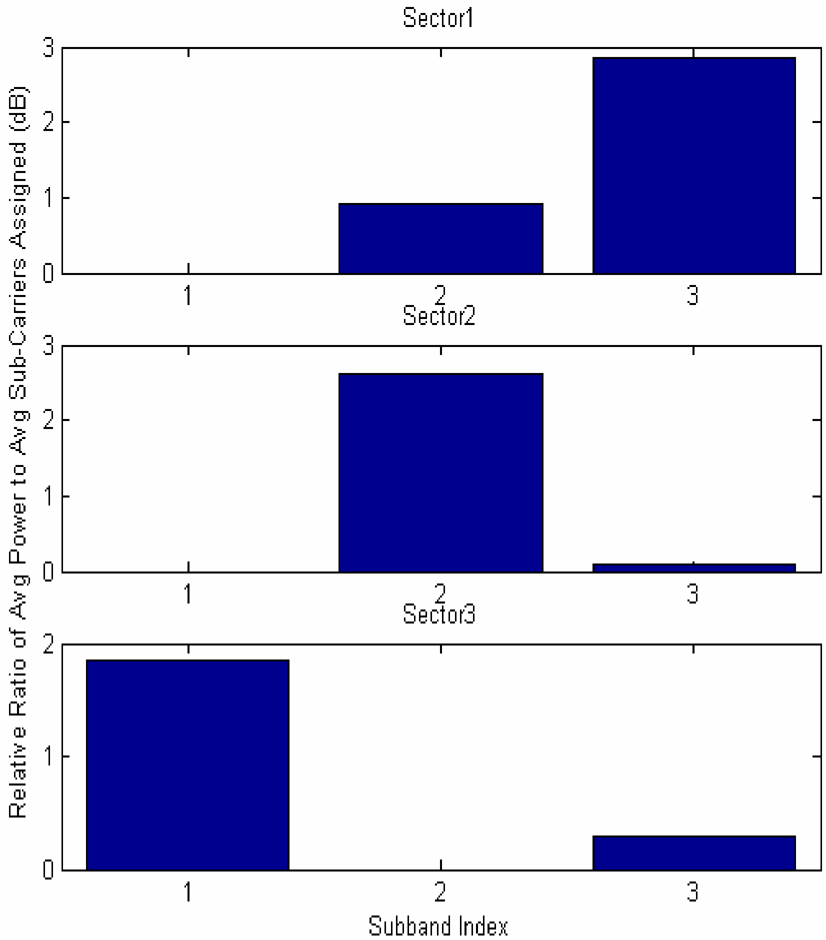
Similar simulation for 20 dB cell edge SNR shows a gain of 30%

Number of band assignment changes and PSD



Number of band changes is small relative to the total number of users

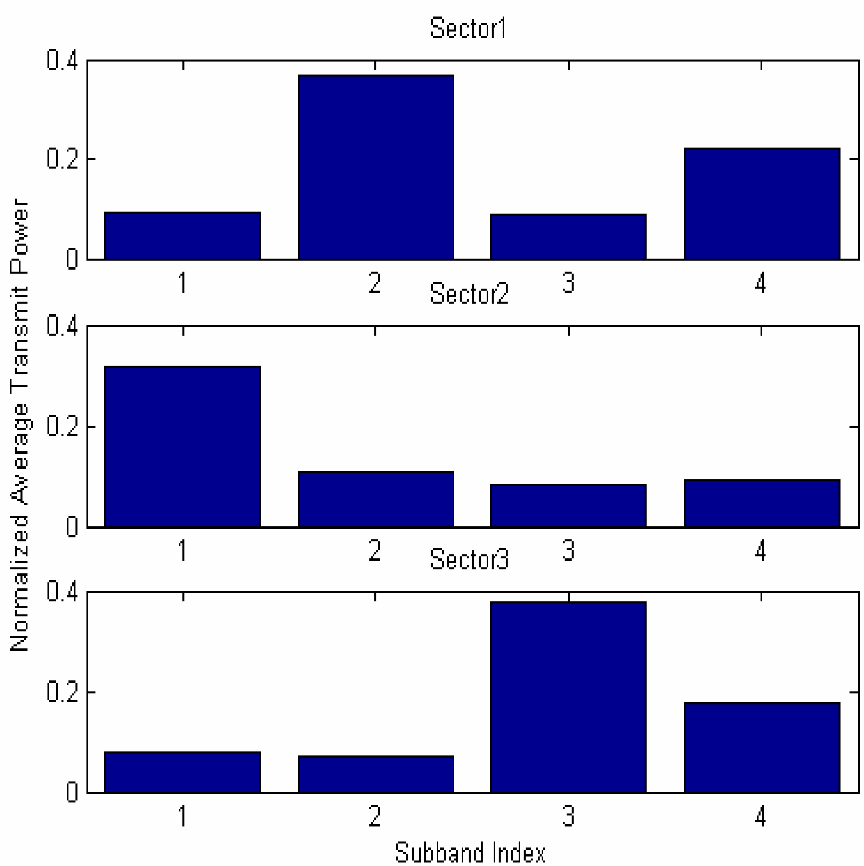
Relative PSD across sub-bands



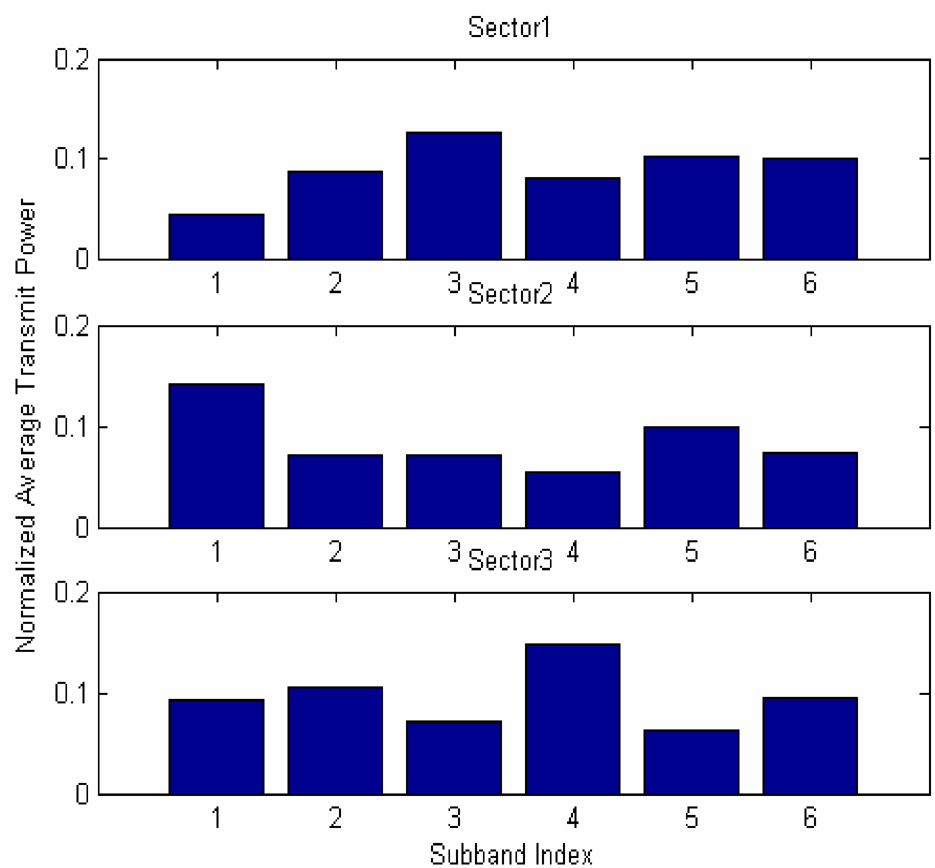
2 to 3 dB more power per sub-carrier in preferred band

Shadow Algorithm with 4 and 6 bands

4 bands



6 bands



Algorithm converges to good solutions giving about the same capacity as 3 bands

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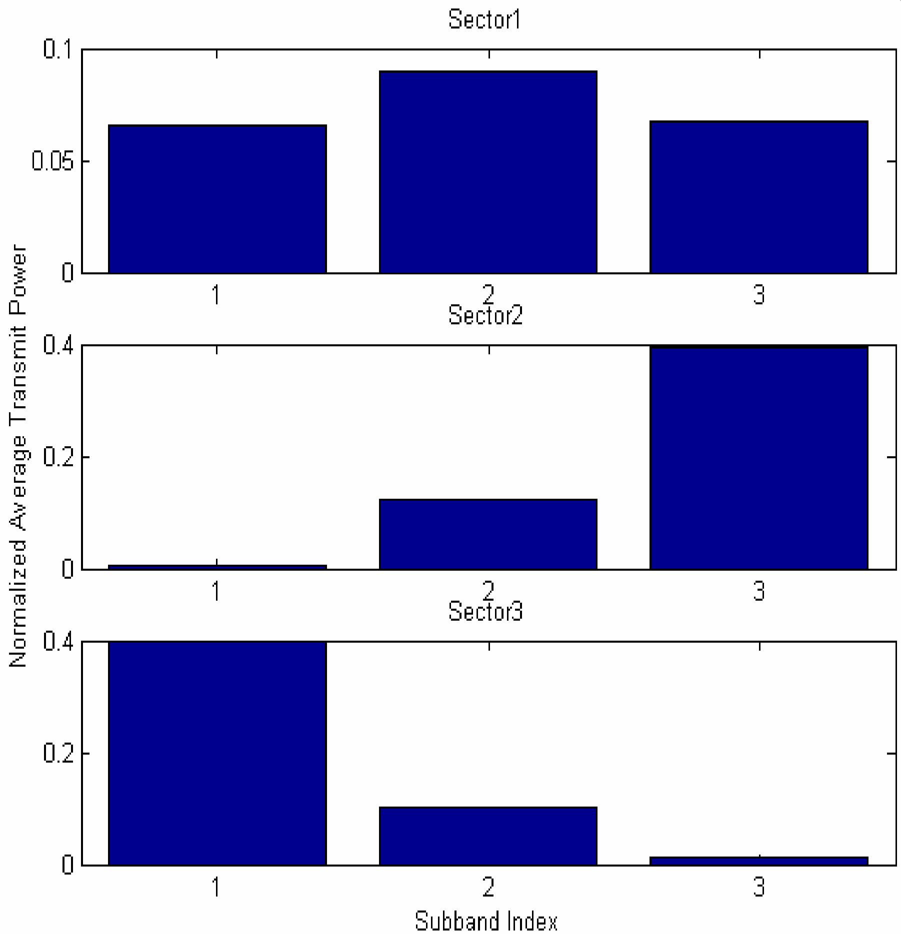
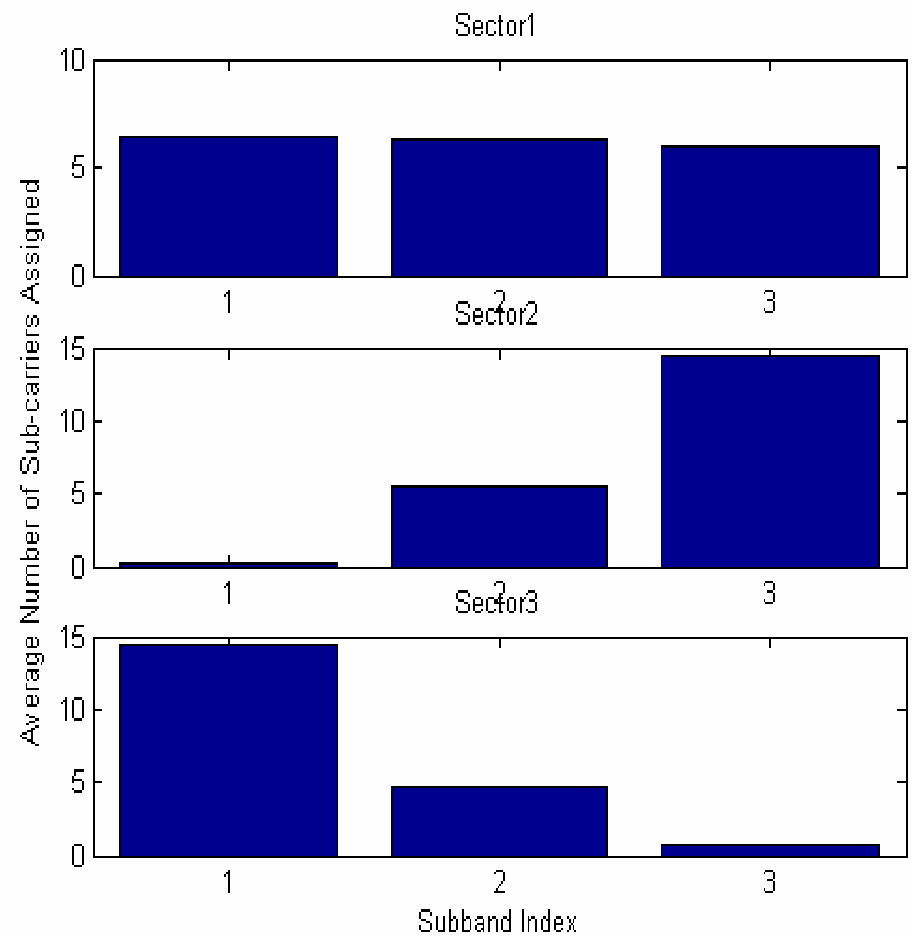
Non-uniform distribution of users - center, edge, edge (20 dB Cell Edge SNR)

Transmit Power Ratio



Number of Sub-carriers



Automatically sectors 2 and 3 avoid each other but overlap with sector 1!
Gain over universal reuse is 45%

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Algorithm for Best Effort Traffic

Objective

- Improve cell edge throughput at the expense of average sector throughput
- Similar to CBR case - each sector allocates users to resource sets, based on a local "selfish" objective

$$\max \sum_i \sum_j \left(\frac{w_i}{\overline{w}} R_{ij}(p_{ij}, m_{ij}) - b_j p_{ij}\right) \quad \text{or} \quad \max \sum_i \sum_j w_i e^{-b_j} R_{ij}(p_{ij}, m_{ij})$$

subject to

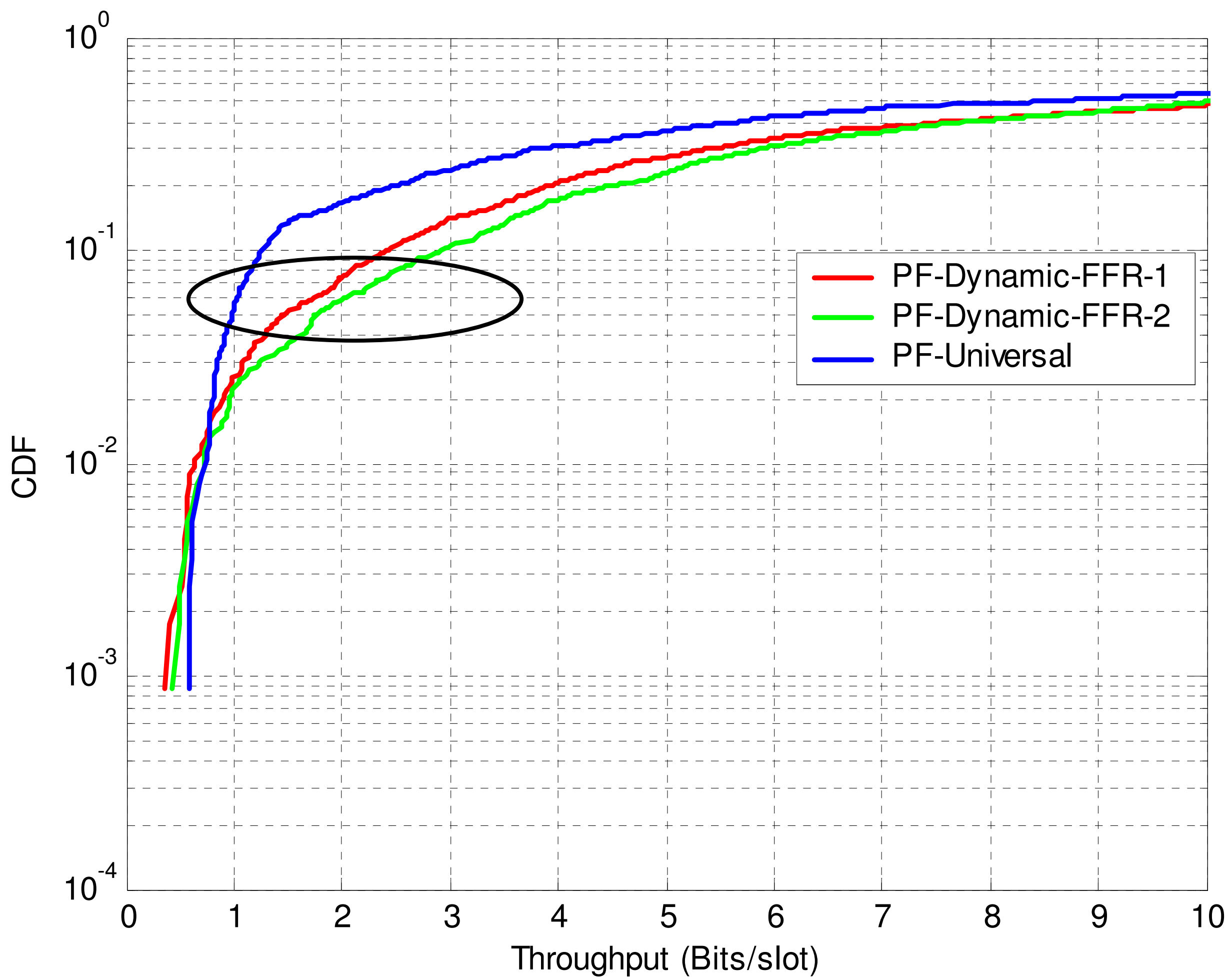
$$\sum_{j,i} m_{ij}(p_{ij}) \le N_j$$

$$\sum_{j,i} p_{ij} \le P_{tot}$$

$\{b_j\}$ is the cost of transmitting power over sub-band *j*

Setting these values appropriately will lead to an efficient fractional frequency reuse automatically and will adapt reuse to changing traffic distributions

Simulation Results – I (57 sector, Proportional Fair, 20 dB cell edge SNR)



	Sum Throughput	Sum log Throughput
● (red)	1.9558e+004	2.6428e+003
● (green)	1.8540e+004	2.6398e+003
● (blue)	1.9225e+004	2.3984e+003

Factor of 2 improvement in 10-percentile throughput without loss of sector throughput

Objective of cell edge throughput improvement achieved

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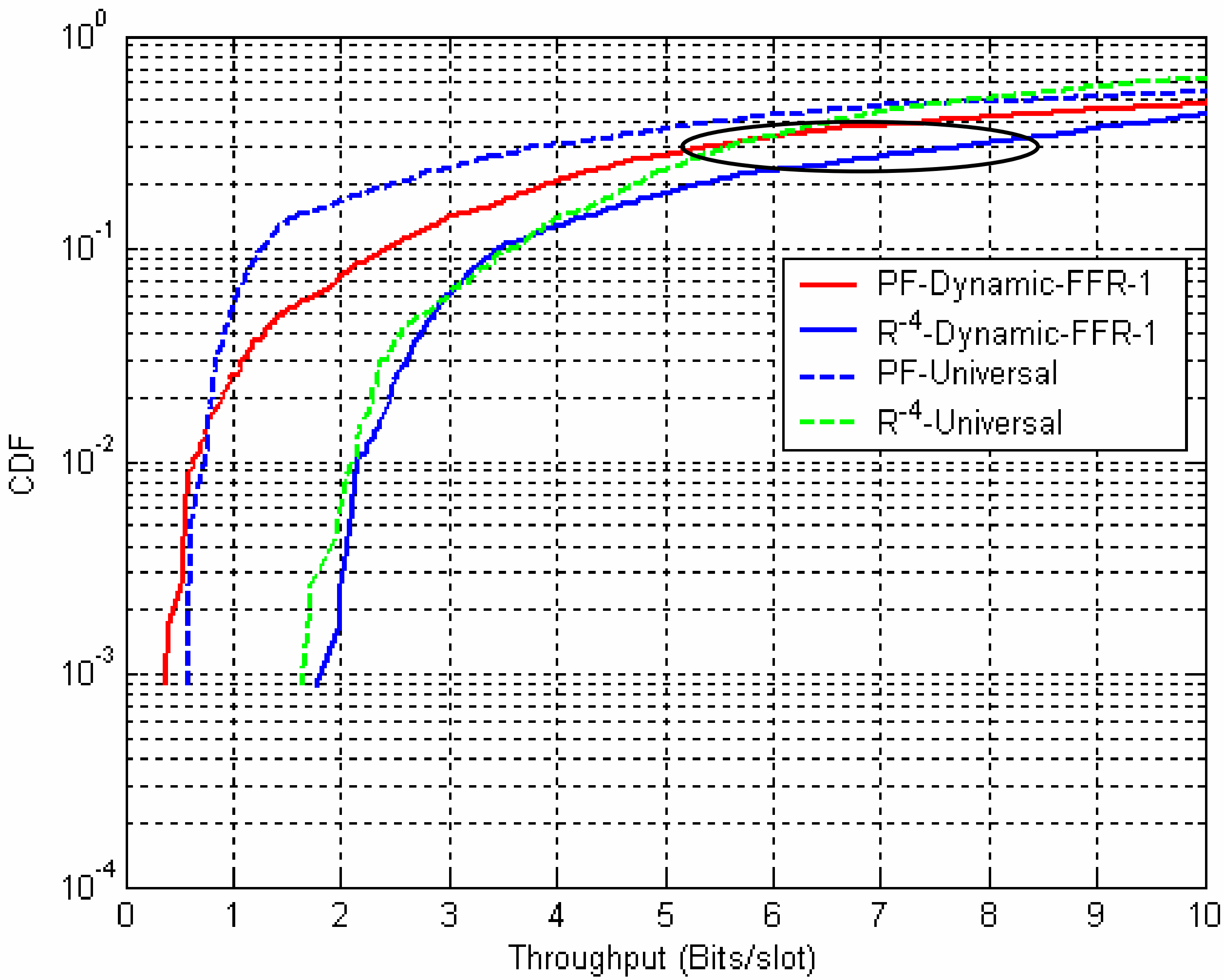
Simulation Results – II (57 sector, Proportional Fair and R^-4, 20 dB cell edge SNR)



	Sum Throughput	Sum log Throughput
PF-Dynamic-FFR-1 (red solid)	1.9558e+004	2.6428e+003
R^{-4}-Dynamic-FFR-1 (blue solid)	1.3483e+004	2.6131e+003
PF-Universal (blue dotted)	1.9225e+004	2.3984e+003
R^{-4}-Universal (green dotted)	1.1836e+004	2.4124e+003

Dynamic FFR still provides gain over universal even when utility function is changed

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Outline

Overview

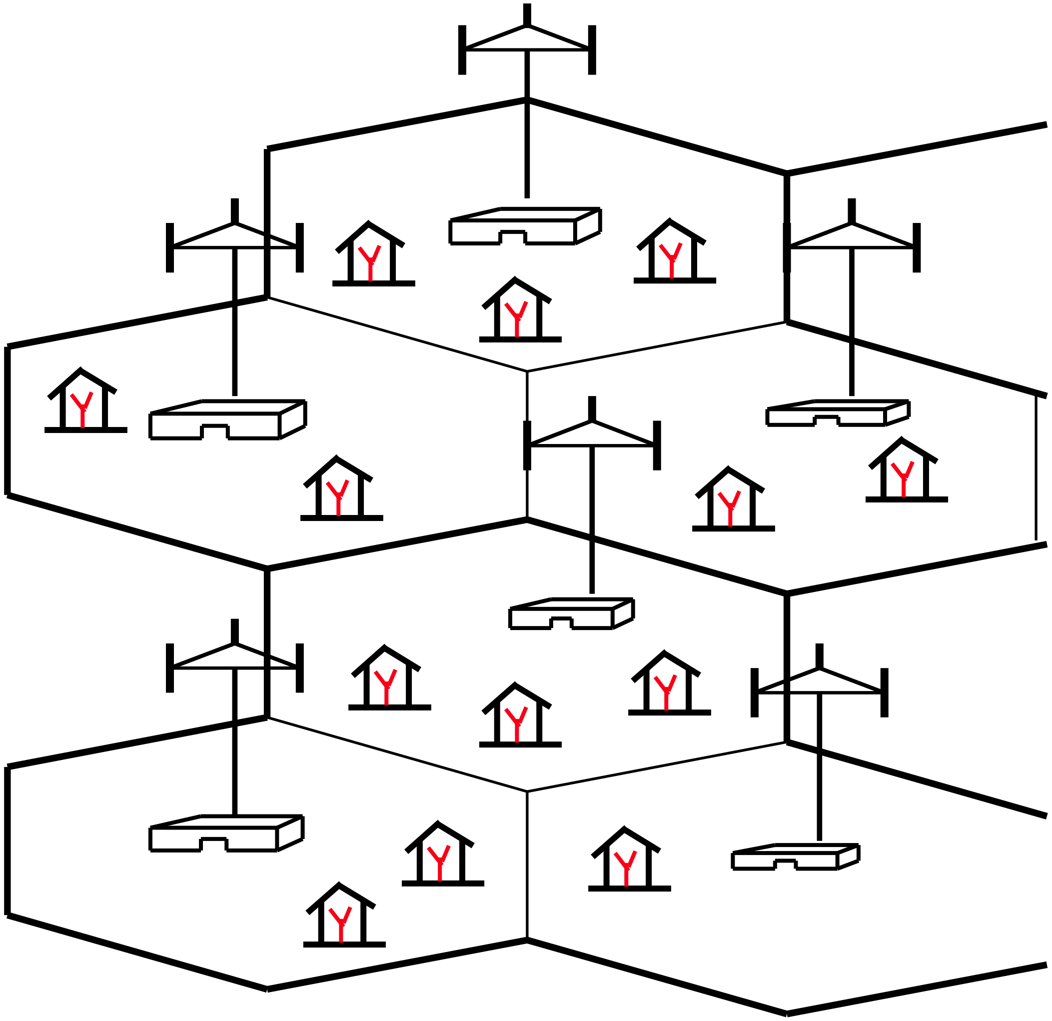
Why OFDM?

MIMO, Pre-coded CDMA, Supercast

Interference mitigation through dynamic fractional frequency reuse

Femto Cells - Architecture and Algorithms

Femto Cells – Recap



▪ Femto cells are low power cellular base stations deployed in homes

▪ Cell phones can be used inside homes with the home broadband connection as backhaul

Benefits

- Operator
  - ➢ Reduce backhaul capacity requirements
  - ➢ Increased wireless capacity
  - ➢ Reduce customer churn through bundling and new converged services
- Consumer
  - ➢ Superior in-building coverage and quality without change in phones
  - ➢ One number and one phone and location specific pricing

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Co-channel Femto Cell Challenges

Coverage of Femto base stations should be limited to within the home

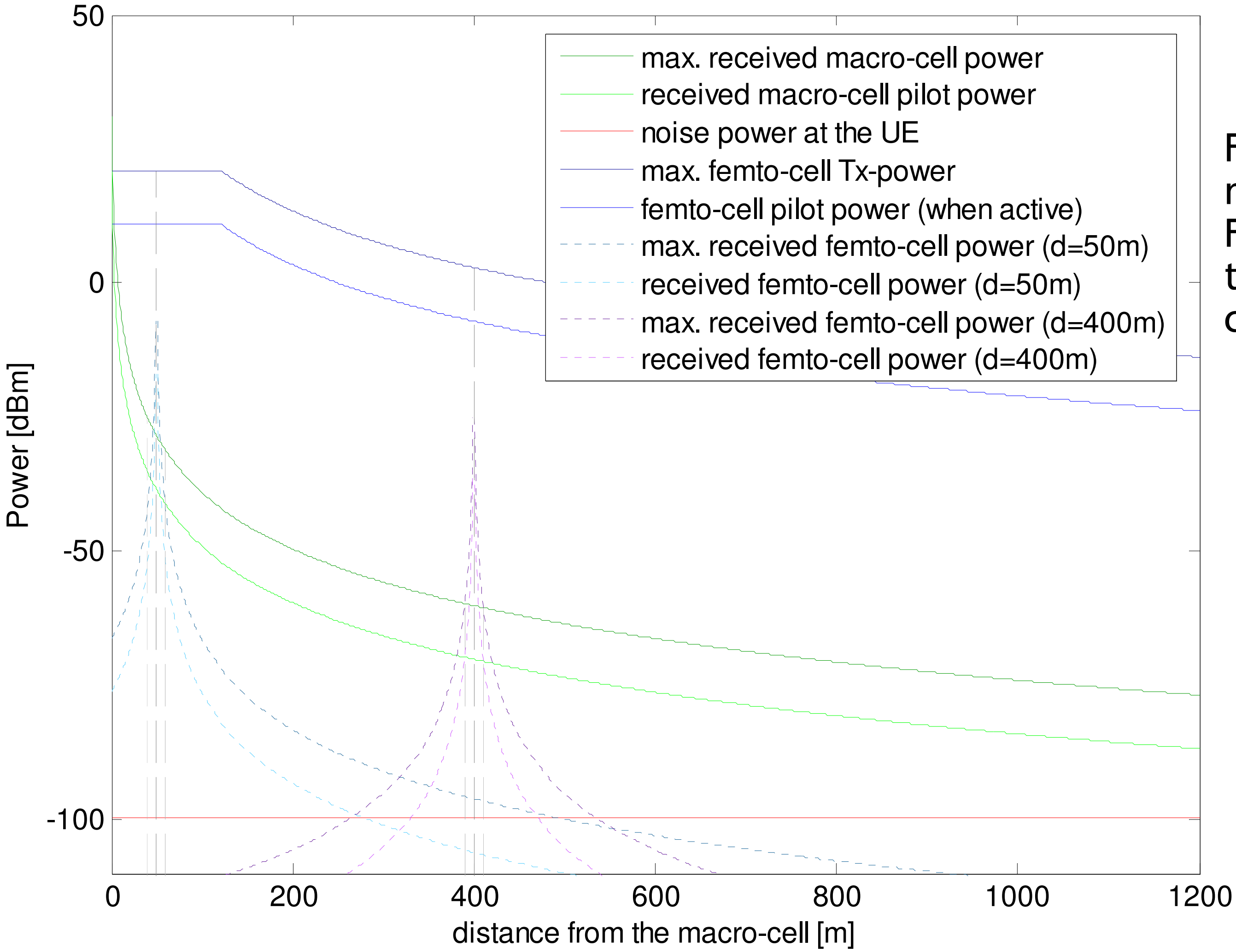
- Leakage outside will result in handoff issues
- Public use of private backhaul

Terminal transmit powers should not cause significant additional interference to macro-cell base stations

Scrambling sequence reuse

- Large number of base stations implies sequence identifying the base station has to be reused
- Poses a neighbor cell identification issue

Coverage Dependence on Location for Co-channel Femto Cells



For the same Femto cell radius transmit power of Femto cell will depend on the location of the Femto cell within the macro-cell

Source: Holger Claussen, Bell Labs

Power Control Algorithm

Base station has to "sense" the required coverage area

- Houses may be of different sizes
- Location of base station within the house

Transmit power setting depends on the distance from macro-cell

Power control based on feedback from mobiles

- Start with low power and as mobile moves around the house increase power to maintain coverage
- Initial value can be based on knowledge of location within the cell

Uplink power control

- Limit mobile transmit powers so that the interference caused at the macro-cell base station does not result in significant capacity loss

Handoff Algorithm

Because of scrambling code reuse the identity of the Femto cell that the mobile wants to handoff to is not known

- Solution: Use mobile location information to identify the Femto cell

Only “home” mobiles should be allowed to handoff to the particular Femto cell

- Interference from passers by can create performance issues for Femto cell especially if it is placed close to a window

Summary

Several novel features incorporated into next generation cellular systems

- Significant performance enhancements will be achieved

New algorithms come into play to exploit the new features

- Distributed coordination strategies can have a significant impact without the burden of additional signaling between base stations
- MIMO research to practice

New deployment scenarios to enhance coverage

Beyond Next Generation

- Dynamic spectrum access / cognitive radio
- Network MIMO

Thank You!