

# **OFDMA for Mobile Broadband Wireless Communications - A System View**

**Junyi Li**

**Vice President of Technology**

**QUALCOMM FLARION TECHNOLOGIES**

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# Outline

- Introduction
- OFDMA
  - Basic idea and operation
  - Resource orthogonality and granularity
  - Power dynamic range
- Interference issues
  - Concept of self noise
  - Intra-sector design
  - Inter-sector design
  - Inter-cell design
- Statistical Multiplexing
  - Orthogonal versus non-orthogonal multiplexing
  - Segment scheduling
  - MAC states and state scheduling
- Flat end-to-end IP network
  - Simultaneous multiple connections
  - Handoff
  - Macro-diversity

# ***Evolution of Wireless Communications***

We have witnessed dramatic changes in wireless communications

- Air interface: FDMA/TDMA to CDMA to OFDMA
- Network: circuit-switched to packet-switched
- Traffic: voice centric to data centric multi-media

What trends have triggered those changes?

- Increasingly powerful and sophisticated devices
  - Digital processing power
  - Variety of applications
  - Higher peak rate, higher throughput, lower latency, ...
- Increasingly popular IP networks
  - Proprietary wireless networks have high cost to develop, maintain and evolve
- Increasingly demanding user experience
  - Wireline broadband rate plus mobility

## ***How does OFDMA fit into the picture?***

We need to understand OFDMA from *a system view*, i.e., do not simply treat OFDMA as just another form of physical layer waveforms

# ***Challenges in Wireless Communications***

## Channel

- Channel fading
  - Doppler spread causes channel variations over time
  - Delay spread causes variations over frequency
- Large power dynamic range
  - Path loss, shadowing, short and long term fading

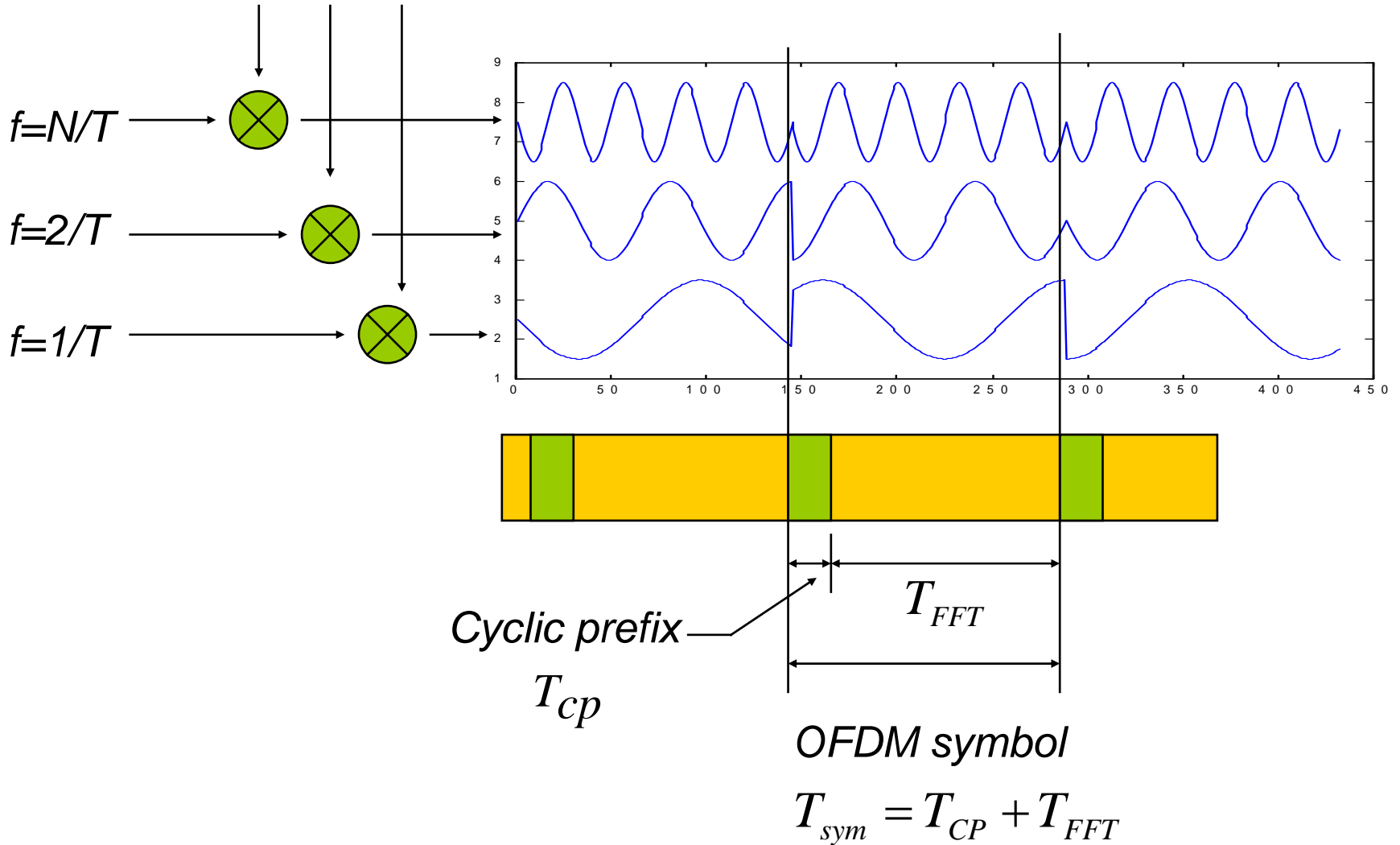
## Interference

- Sharing of bandwidth
  - Self interference
  - Interference within a sector
  - Interference between sectors within a cell
  - Interference between cells

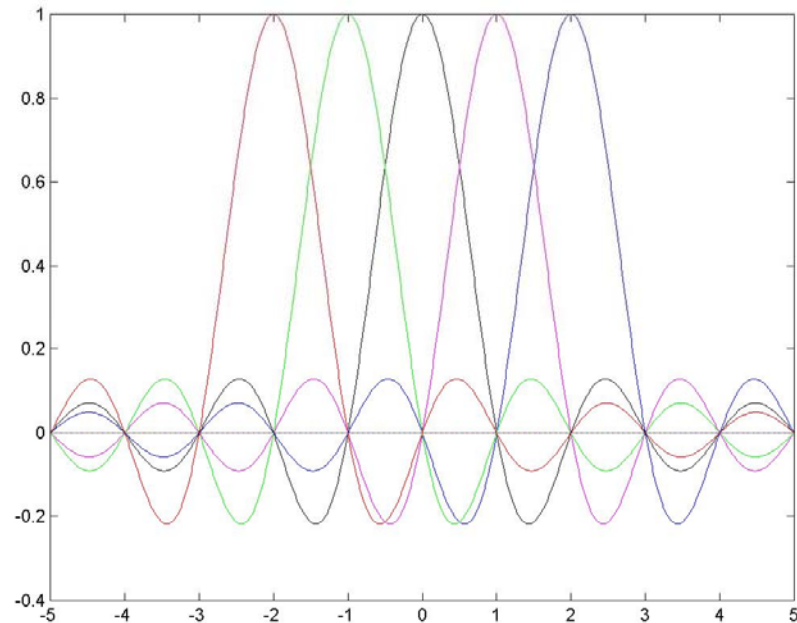
**Challenges => opportunities ?**

# OFDM Modulation

Modulation symbols



# Tone Orthogonality



- Cyclic prefix is introduced to cover channel response, thereby eliminating ISI and ICI
- With appropriate choice of parameters, tones can be made *orthogonal* after multipath delay spread
- **Sinusoid waveforms are *only* eigen-function of a linear time-invariant channel and preserve orthogonality property**

# ***Exemplary Choices of OFDM Parameters***

Cyclic prefix	10 $\mu$ s
Tone spacing	10 kHz
Symbol duration	110 $\mu$ s

- Cyclic prefix length captures expected channel delay spreads
- OFDM Symbol duration
  - Large ratio between useful and cyclic prefix durations
  - Small compared to expected coherence time
- Tone spacing
  - Much greater than expected Doppler frequencies
  - Small compared to expected coherence bandwidth

# ***How much orthogonality is achieved?***

In reality, no signals are perfectly orthogonal due to various impairments

- FDMA signals: using sharp front-end filtering, narrowband channels can be isolated from each other by at least 50 dB
  - Adjacent narrowband channels do not overlap
  - Long filter response requires equalizer to use many taps
- OFDM signals: depending on parameter choice, tone isolation can be as much as 35 dB
  - Spectrum of adjacent tones overlap, thus leading to tighter packing of tones in a given total bandwidth
  - One-tap equalizer suffices
- CDMA signals: orthogonality is generally difficult to achieve
  - Slight time offset, e.g., of a chip, may destroy orthogonality
  - As bandwidth increases, orthogonality is harder to maintain
  - Usually 0 dB isolation is assumed: power of one code completely leaks into another code
    - Protection between CDMA codes comes from processing gain

# ***How much orthogonality is desired?***

Answer depends on system level tradeoff

- 0 dB isolation seems “too little”
  - In CDMA, intra-sector interference dominates total interference
  - Increase in isolation directly translates into capacity gain
- 35 dB isolation seems “decent”
  - Overhead of cyclic prefix is not excessive
  - Benefit of tone isolation seems to outweigh cost
- 50 dB isolation seems “excessive”
  - Return diminishes once isolation exceeds certain level
  - Cost of achieving very large isolation increases significantly

***OFDM seems to strike a good engineering balance***

# ***Basic Idea of OFDMA***

- **Orthogonal multiple access within a sector**
  - Different channels use different tones at a given time
  - Zero intra-sector interference
- **Fast tone hopping**
  - Use of tones changes rapidly, e.g., between successive symbols, and pseudo-randomly between sectors or cells
  - Averaged inter-sector or inter-cell interference

# High-level Comparison

	TDMA/FDMA	CDMA	OFDMA
In-cell interference	Terminals are orthogonal	Terminals are not orthogonal	Terminals are orthogonal
Out-of-cell interference	Must design for worst-case. Frequency reuse factor $> 1$	Terminals see averaged interference. Universal reuse	Terminals see averaged interference. Universal reuse

# ***How to make OFDMA work?***

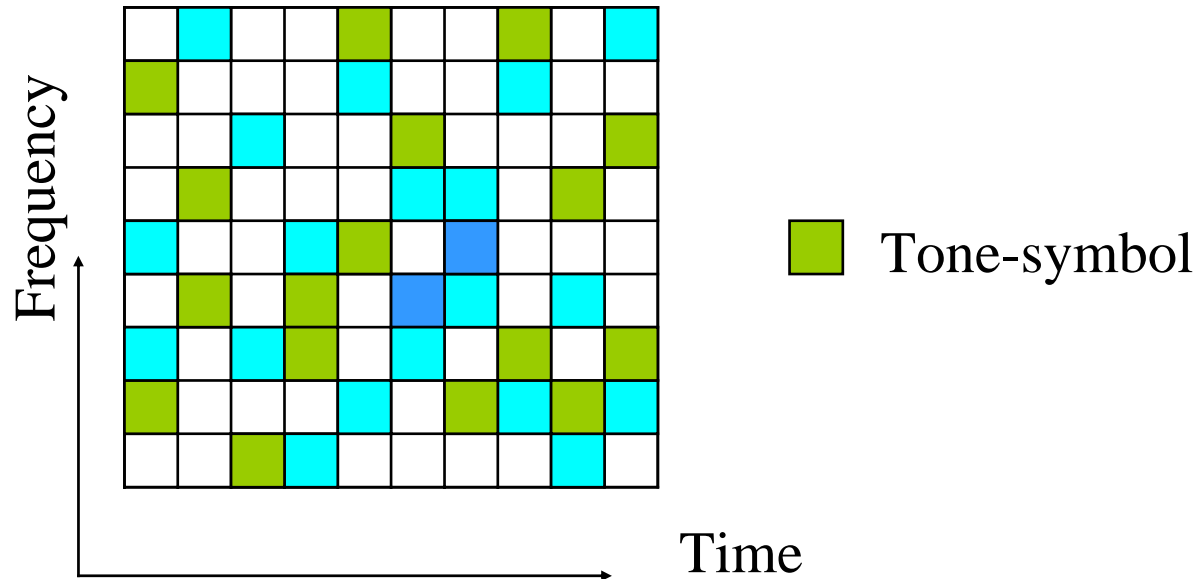
## **Synchronization is the key: time and frequency**

- Downlink
  - Since signals to different terminals comes from a single base station, synchronization is not very different from point-to-point setting
  - Base station fixes transmit symbol time and frequency, and each terminal synchronizes its receiver to downlink signal
- Uplink
  - Since signals comes from different terminals, synchronization is very different from point-to-point setting
  - Base station fixes receive symbol time and frequency for all terminals, and each terminal synchronizes its transmitter so that its signal is synchronized with the base station receiver
- Side notes
  - Unlike FDMA or CDMA in which base station separately processes signals of individual terminals (e.g., narrowband filter or rake receiver), OFDMA allows base station to processes signals of all terminals as one block

# ***Uplink Synchronization***

- Terminal starts with open-loop synchronization, i.e., by slaving DL transmitter to UL receiver
- Residual synchronization errors
  - Symbol time error is round-trip propagation delay
  - Tone frequency error can be twice Doppler
- Closed-loop synchronization is needed to eliminate residual synchronization errors
  - Closed-loop synchronization requires signaling overhead
  - System design has to balance tradeoff between cost of signaling overhead and impact due to synchronization errors
    - Exemplary design choice: closed-loop is only used for correcting UL symbol time but not tone frequency, because tone spacing is sufficiently large to deal with tone frequency error

# Time-frequency Resource



- **Resource orthogonality**
  - Isolation between tone-symbols as high as 35 dB
- **Resource granularity**
  - Basic allocation unit as small as a tone-symbol

# ***OFDMA and Large Power Dynamic Range***

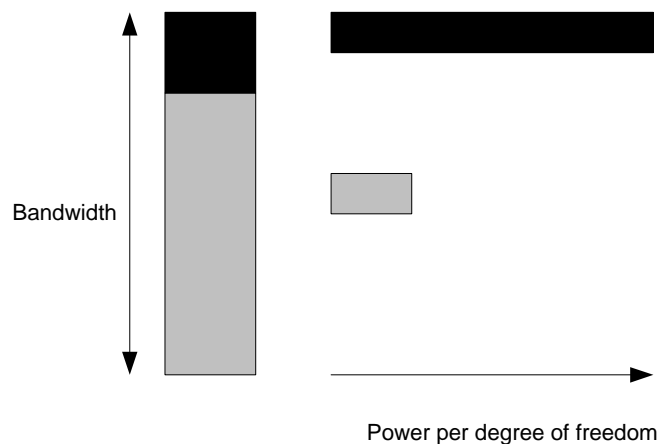
- Nature of wireless channel makes channel gain difference very large across a sector
- Resource orthogonality allows large power dynamic range between users in OFDMA
  - In DL, signal to a close-by user is transmitted at much smaller power than signal to a faraway user
  - In UL, signal from a close-by user is received at much higher power than signal from a faraway user
  - As a comparison, when users are multiplexed in CDMA, the power dynamic range is limited. For example, in UL, users are power controlled to arrive at the base station at equal power

***Large power dynamic range allows OFDMA to achieve high SNR and high data rate by taking advantage of nature characteristics of wireless channel***

# ***TDM versus FDM***

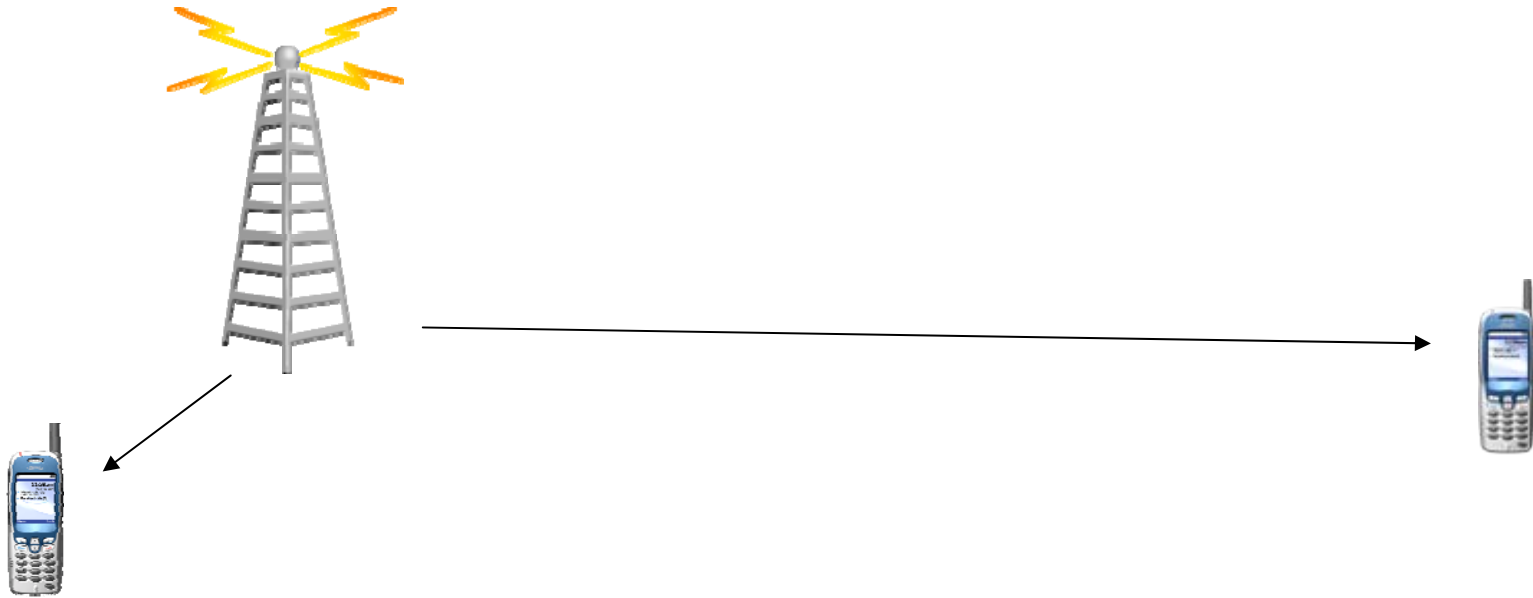
- Dynamic range is not an issue when users are multiplexed in time (TDM). Why bother multiplexing users in frequency (FDM)?
  - TDM: schedule one user at a time
  - FDM: schedule multiple users simultaneously
- In UL, transmitter position varies as different users are scheduled. TDM is clearly undesired because it causes large fluctuation of inter-cell interference and may lead to stability issue
- In DL, transmitter position is fixed (base station). Suppose that the total transmission power is fixed to facilitate inter-cell interference management.
  - In TDM, since both power and bandwidth allocation is fixed, only the rate can be controlled depending on the SNR of the scheduled user
  - In FDM, multiple users can be allocated with different combinations of power and bandwidth
  - Multi-user power/bandwidth allocation can lead to significant DL capacity improvement

# Multi-user Power/Bandwidth Allocation



- In TDM, waste power when transmitting to a close-by user, and waste bandwidth when transmitting to a faraway user
  - Close-by user's rate is saturated due to  $\log(\text{SNR})$  effect and self noise. Reducing power does not significantly affect rate
  - Faraway user's rate is limited by power per degree of freedom. Reducing bandwidth does not significantly affect rate
- This suggests a room for improvement using FDM
  - Schedule close-by and faraway users simultaneously
  - Assign more bandwidth to close-by user but smaller power per degree of freedom
  - Assign larger power per degree of freedom to faraway user but less bandwidth

# Wireless Channel Model



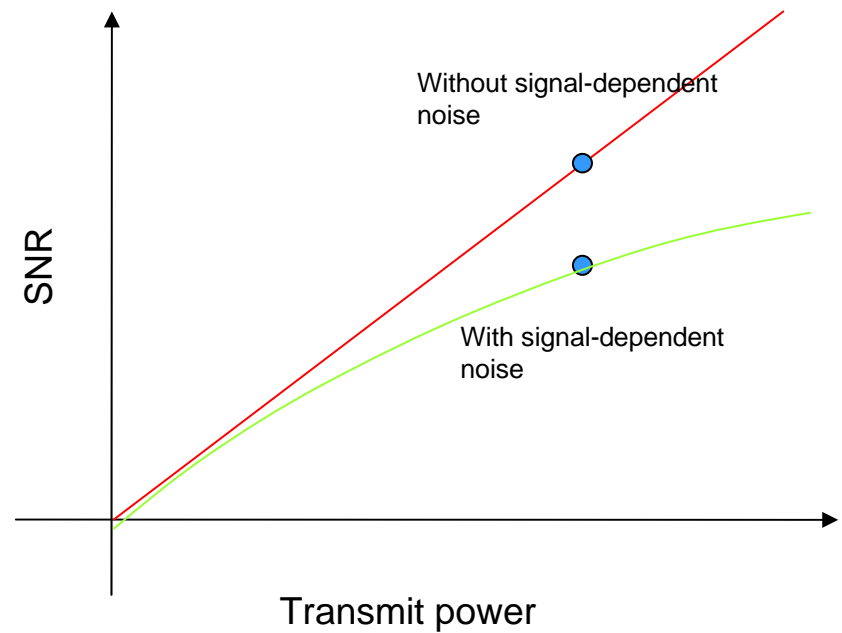
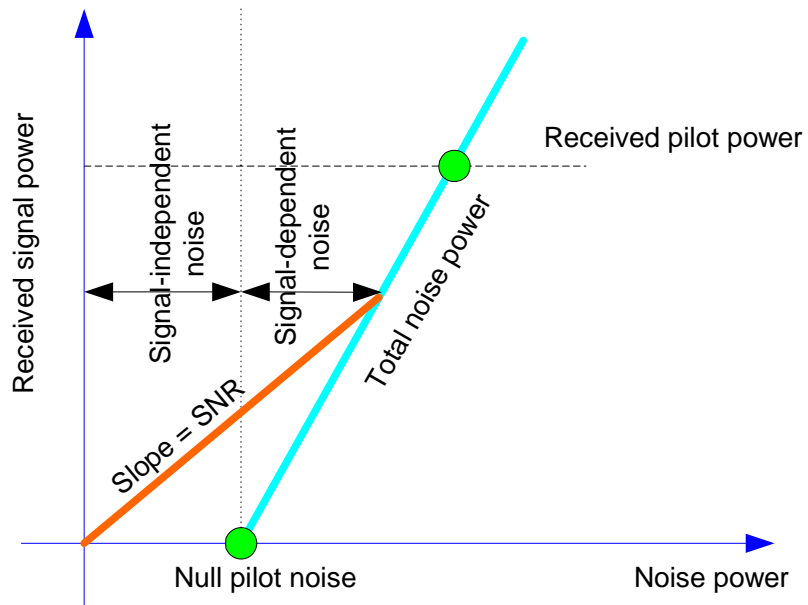
- An interesting observation: while path loss difference between a close-by terminal and a faraway terminal can be as high as 80 dB, SNR difference is much smaller
- Conventional wireless channel model: multipath fading plus noise  $y = hx + n$
- Conventional model cannot explain the real-world observation!

*Is something missing in the conventional model?*

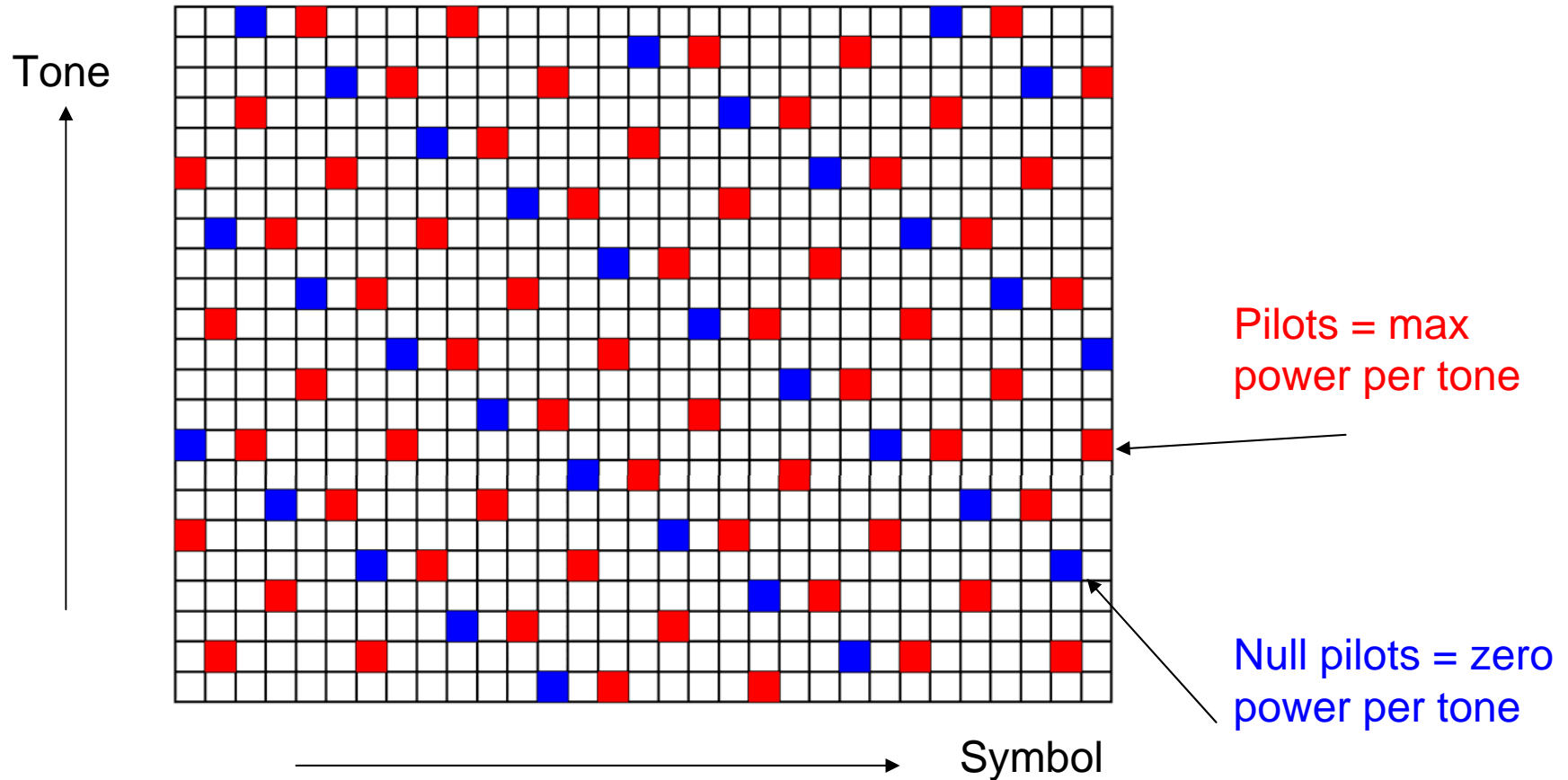
# Self Noise

- Channel ( $h$ ) uncertainty introduces additional noise
  - The power of this noise is proportional to signal power, hence called ‘self noise’
- Revise channel model:  $y = hx + n_1 + n_2 |x|$ 
  - Fading + signal-independent noise + signal-dependent noise
- **Self noise is a fundamental property of mobile wireless systems**
  - In a mobile environment, channel knowledge is intrinsically imperfect because there is only a finite energy available to estimate it
  - Wireless channel has many paths. The higher the SNR intended to achieve, the more paths the receiver has to identify, because unidentified paths contribute to self noise thereby saturating SNR

# Self Noise and SNR



# How to measure self noise?



- Need two parameters to characterize a line
- From both pilot and null pilot, measure two parameters

# ***Why is self noise important in OFDMA?***

- Because of resource orthogonality, self noise may be dominant in high SNR region
  - In CDMA, intra-sector interference usually dominate self noise
- Knowledge of self noise allows sensible multi-user power allocation
  - In TDM scheduling, self noise information is not useful, since transmission power is fixed
  - In FDM scheduling, if a user is already saturated by its own self noise, reduce power allocation to that user and give power to others
- Self noise concept is also important to design *robust* superposition coding
  - Flash signaling
  - Superposition by position

# ***What is rational of reuse 1?***

- Voice has been the dominant application
- Characteristics of voice
  - Voice users do not need more than 8 kbps rate
  - Voice link has to be robust and available all the time at all geographic areas
- Reuse 1 provides what voice needs
  - Voice users have not much use of high SNR
  - Robustness is achieved using soft handoff

# ***What makes data different from voice?***

- Data users can consume much more than 8 kbps and therefore benefit a lot from high SNR
- High burst rate is important for user experience
- Users prefer consistent data rate throughout a cell
- Data connections are more immune to channel fading than voice connections

*For data traffic (where voice is one kind of data applications), we need to revisit the rationale of reuse 1*

# ***Issues of Reuse 1 for Data***

- Reuse 1 limits the data rate at cell edge
  - Data rate is high when close to the base station, but drops significantly at cell edge
  - Service is therefore perceived to be inconsistent
- In downlink, even CDMA (e.g., 1x EV DO) has moved away from soft handoff
  - Soft handoff doubles backhaul loading, potentially a big cost when downlink data rate is high
  - Soft handoff requires scheduling synchronization between base stations, thus limiting scheduling flexibility
- In uplink, soft handoff requires a L2 box (RNC) in an IP network, therefore complicating end-to-end IP architecture and affecting performance
- *Is frequency reuse ( $N > 1$ ) the solution for data?*

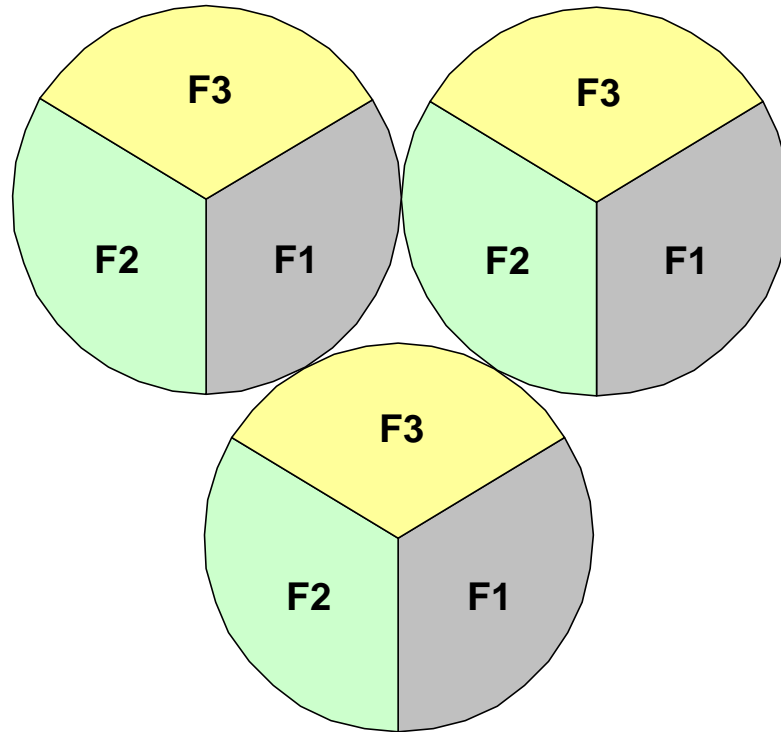
# ***Tradeoff between reuse 1 and frequency reuse***

- Characteristics of reuse 1
  - Larger bandwidth (per cell/sector)
  - Lower C/I
- Characteristics of frequency reuse
  - Smaller bandwidth (per cell/sector)
  - Higher C/I
- *Choice of reuse 1 versus frequency reuse also depends on whether the underlying technology can exploit high C/I and result in high SNR*
  - CDMA is limited by self-noise and intra-cell interference, and thus does not see much benefit from high C/I
  - OFDMA can benefit from high C/I because inter-cell interference dominates

# ***Issues with Traditional Frequency Reuse***

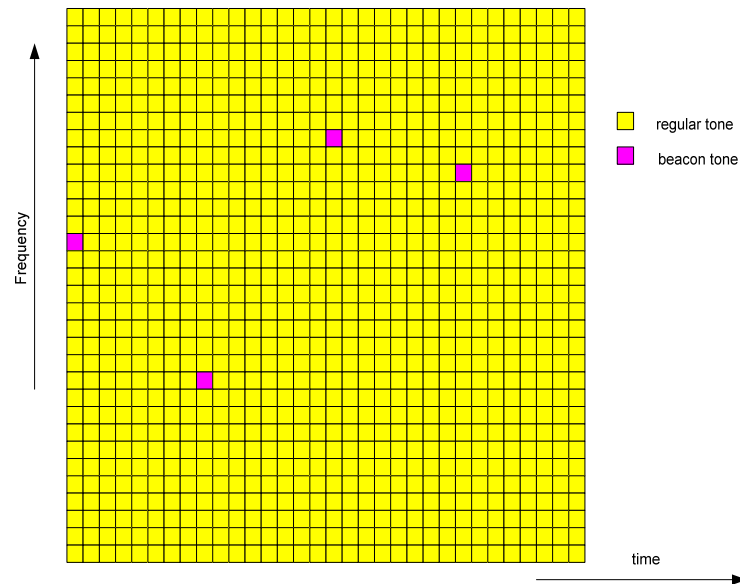
- Frequency planning
- Robustness in handoff: *how do mobiles find out when to trigger handoff and to whom?*
  - Mobiles are in the best position to monitor channel condition and decide when to trigger handoff
  - When a mobile listens to one carrier, it cannot simultaneously monitor other carriers without a second RF chain
  - Mobile can either wait until its current carrier degrades below certain threshold, or periodically scan other carriers at the expense of potential service disruption -> *no clean solution to ensure robust handoff*

# ***Solution to Frequency Planning***



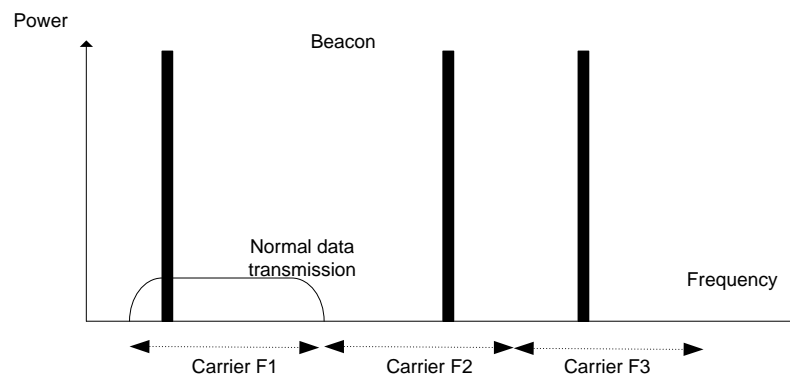
- All three carriers are reused in every cell
- Each sector uses only one carrier;
- Sectors of the same orientation use the same carrier

# Beacon for Robust Handoff



- Beacon is a special OFDM-symbol in downlink in which transmission power of a single tone (beacon tone) is significantly (e.g., 26 dB) higher than average per-tone power
  - Beacon is so strong that it could never be mistaken to be anything produced by Gaussian noise process
- Beacon tone occurs once relatively infrequently (e.g., 100 ms)
  - Negligible overhead and interference impact
- Beacon can be easily detected
  - Does not require timing or frequency synchronization, or channel estimation
  - Exploit unique property of sinusoid tones (impossible for Walsh codes)
  - Almost zero additional computational complexity (no chip-level search required)

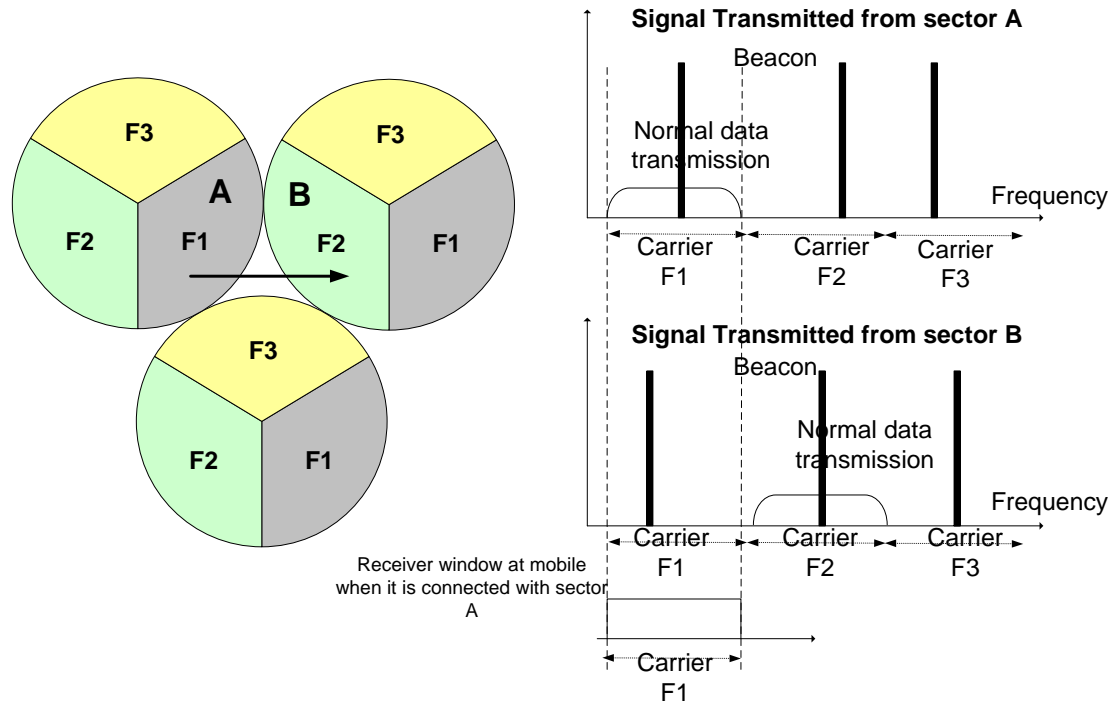
# Inserted Beacon for Handoff in Frequency Reuse



**Sector using carrier F1 for normal data transmission**

- Each sector transmits beacons in every carrier
  - Beacon power fixed and the same for all carriers
  - Fixed symbol timing offset of beacons in different carriers
- Inserted beacons are used to trigger handoff
- Listening to one carrier, a mobile can detect beacons inserted by a sector, which transmits normal data with a different carrier
- Detected beacons provide information about
  - Channel gain from the new sector
  - Carrier in which the new sector carries its normal data transmission

# Illustration of Mobile Operation

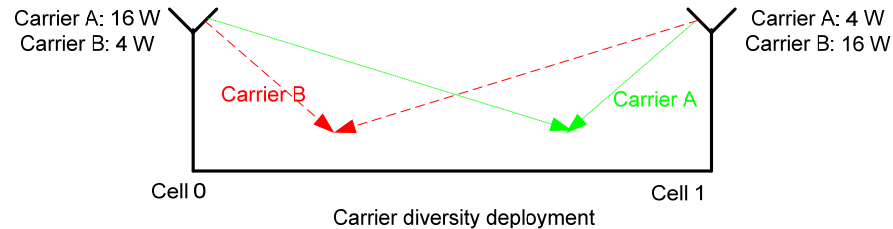
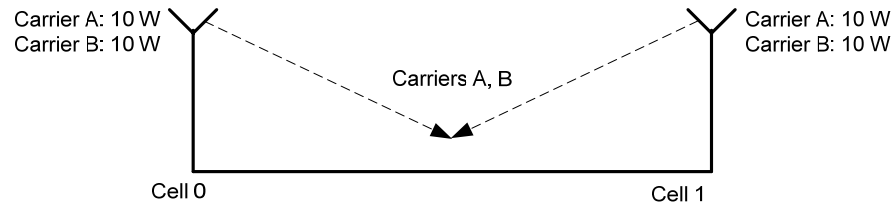


- While being connected with sector A, the mobile carries out beacon detection in the background in carrier F1
- As mobile moves away from sector A to B, it detects a beacon in carrier F1 transmitted by sector B
  - The detected beacon tone indicates that it comes from a different cell, whose normal data transmission is on carrier F2
- Mobile makes handoff decision, tunes to carrier F2 and is connected to sector B

# *Idea of Carrier Diversity*

- Traditional multi-carrier systems
  - Deploy all carriers with identical power patterns
  - Cell boundaries overlap for all carriers
- Carrier diversity systems
  - Offset power pattern for different carrier
  - Cell boundaries non-overlap for all carriers
- Carrier diversity is a new form of diversity available in a multi-carrier system
  - Eliminate low-C/I cell edge
  - Better than many other forms of diversity, carrier diversity is predictable: if a mobile is on the cell edge of one carrier, it can always switch to another carrier for better C/I

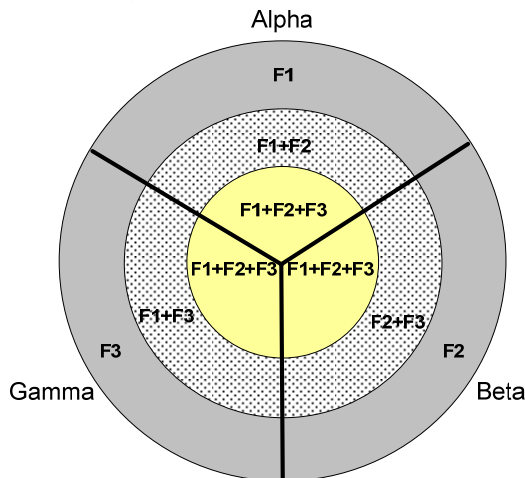
# Illustration of Carrier Diversity



Additional downlink link budget benefit: 16 W versus 10 W

- Carrier diversity also increases downlink link budget
- Key issue to make the idea practical: *how to trigger mobile to handoff from one carrier to another?*
- *Answer: beacon insertion*

# Fractional Frequency Reuse



- Data follows power backoff pattern across carriers in a given sector:
  - A sector has one full-power carrier:
    - Carrier 1 in sector alpha
    - Carrier 2 in sector beta
    - Carrier 3 in sector gamma
  - Other carriers have fixed power backoff from the full-power carrier
  - Example: in sector alpha, 20 W total sector transmit power = 15 W (carrier 1) + 4 W (carrier 2) and 1 W (carrier 3)
  - Power backoff pattern is reused across cells
- Beacon power for all carriers (not just the full-power carrier) is based on the full power, not the reduced power
  - Beacon coverage is the same for all carriers