Cooperative Wireless Communications - Towards Gigabit Wireless Technologies and Standardization

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Course outline

- Capacity of wireless channels: overview of basic information theory (AWGN channel)
- Diversity technique: time, frequency, space
- Multi-input, multi-output (MIMO) systems: Channel models for MIMO, space-time coding, spatial multiplexing, tradeoff between multiplexing and diversity, degrees of freedom
- Multi-user MIMO: uplink/downlink MIMO, multi-user diversity, precoding
- High-throughput MAC utilizing MIMO technique: IEEE 802.16 (WiMAX), 3GPP LTE, and IEEE 802.11 (WiFi)
- Cooperative communications and relaying: simple cooperation protocols and its applications, cooperative MIMO
- Cooperative MAC protocols for wireless LANs and Cellular systems

Multiple-input Multiple-output (MIMO)

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SISO capacity in AWGN channel

- System model for Single-Input Single-Output (SISO) based transceivers

$$y = hx + w$$

- Channel capacity with additive white Gaussian noise (Shannon bound)

$$C = W \log_2(1 + \frac{E_s}{N_0})$$

  - The higher the bandwidth or SNR, the higher the capacity
  - Performance of modern coding and modulation schemes are very close to the Shannon bound

Channel fading

- Fading is the deviation of the attenuation that a carrier-modulated telecommunication signal experiences over certain propagation media
- Fading models
  - Rayleigh: Non-Line-of-Sight propagation
  - Ricean: Line-of-Sight propagation
  - Nakagami: rapid fading in high frequency, long distance propagation
- Rate of fading changes in time domain
  - Slow fading: static fading level for each packet
  - Fast fading: multiple fading levels for each packet
- Rate of fading changes in frequency domain
  - Flat fading: same fading level within the signal bandwidth
  - Frequency selective fading: multiple fading levels within signal bandwidth

Single antenna system in fading channels

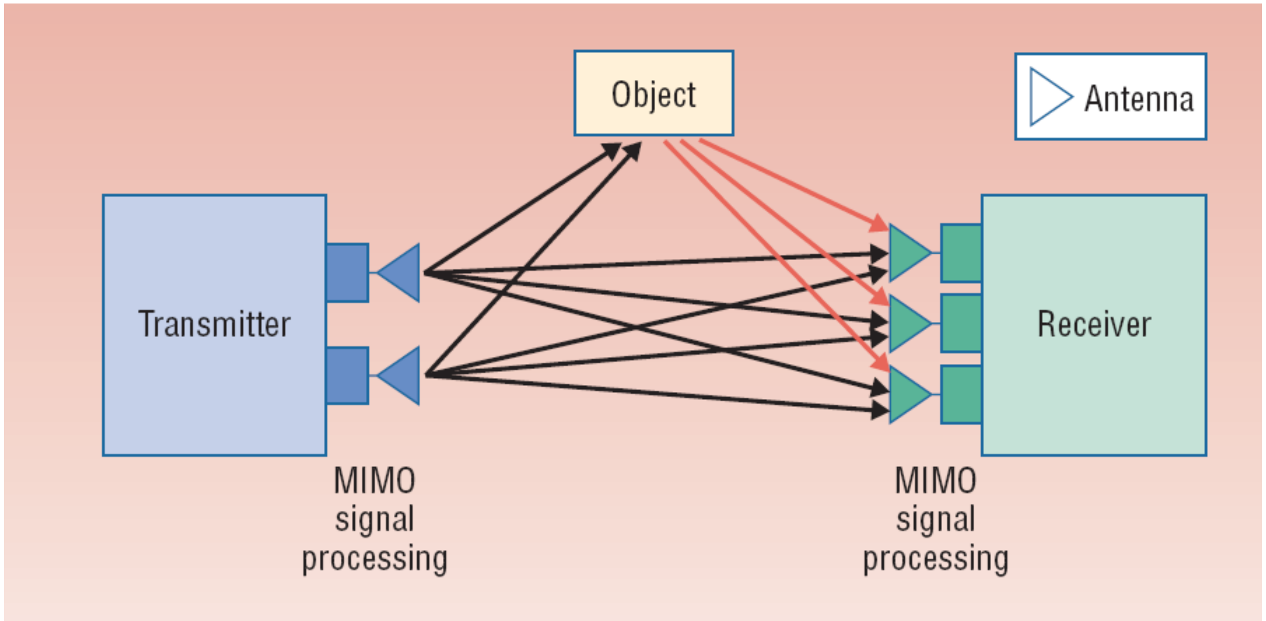
- When the fading level changes, the channel gain changes
- The information theory capacity, which depends on the signal strength is a random variable
- When the instantaneous channel capacity is below our desired transmission rate, an outage happens (leading to a burst of errors)
- In a practical communications, when the fading is deep, signal quality deteriorates and packet loss probability increases

Is Gigabit wireless possible?

- Bandwidth and transmission power for IEEE 802.11 are regulated by the FCC
- Capacity of single antenna systems are bounded by Shannon capacity
- Highest spectral efficiency (measured in bit/s/Hz) of single antenna systems is around 6 bit/s/Hz
  - Transmission power is limited
  - Current circuit design supports only up to 64 QAM wireless transmissions
- 150+ MHz bandwidth required for gigabyte wireless
- Frequency resources are too precious
- For example, only 2.4-2.483Ghz for 802.11 systems

MIMO is the key to gigabit wireless

- MIMO stands for Multiple-in, multiple out (MIMO), i.e., multiple antenna systems
- More than one antenna at both transmitter and receiver



- Multiple data streams can be transmitted using advanced signal processing technique
- The spectrum efficiency could be multiple times of its SISO counterpart

MIMO capacity

- System model

$$\mathbf{Y} = \mathbf{H}\mathbf{x} + \mathbf{W}$$

- Channel capacity for MIMO system (AWGN)

$$C = W \log_2[\det(\mathbf{I} + \frac{E_s}{N_0}\mathbf{H}\mathbf{H}^{\mathbf{H}})]$$

- In higher SNR region, capacity for MIMO systems increase linearly with the number of antennas
- Thus much higher data rate can be supported at the PHY layer
- Spectrum efficiency could be much higher than 10 bit/s/Hz

Diversity

- Diversity scheme refers to a method for improving the reliability of a message signal by utilizing two or more communication channels with different characteristics
  - Time diversity: Multiple versions of the same signal are transmitted at different time instants, such as interleaving
  - Frequency diversity: The signal is transferred using several frequency channels or spread over a wide spectrum that is affected by frequency selective fading.
  - Space diversity: The signal is transmitted over several different propagation paths.
  - Polarization diversity: Multiple versions of a signal are transmitted and received via antennas with different polarization.
  - Multiuser diversity: Multiuser diversity is obtained by opportunistic user scheduling at either the transmitter or the receiver.
  - Antenna diversity: use multiple antennas to achieve reliable transmissions.
  - Cooperative diversity: Achieves antenna diversity gain by utilizing the cooperation of distributed antennas belonging to a group of nodes.

Diversity gain

- For a SISO system, when the instantaneous channel capacity is less than the transmission rate R, reliable communication is not possible. Outage probability is defined by

$$P_{out} = P\{R > W log_2(1 + h^2 \frac{P}{N})\}$$

In high SNR region, p_{out} decreases linearly with SNR.

- If the signal is transmitted over two independently faded channels, p_{out} is

$$P_{out} = P\{R > W log_2(1 + (h_1^2 + h_2^2)\frac{P}{N})\}$$

In high SNR region, p_{out} decreases linearly with SNR square.

- Diversity order is defined by the order that P_{out} decreases with SNR. When there are two independently faded channels, diversity order is 2.

Antenna diversity

- Use multiple independently fading signal paths to reduce the error probability
  - Low probability that independent fading signal paths simultaneously experience deep fades
  - Need multiple antennas spaced sufficiently apart (~ $\lambda/2$)
- Maximum diversity gain (D) for M x N system = MN
- Transmitter diversity: when there are multiple antennas on the transmitters, space-time coding (STC) is one scheme to achieve higher diversity order
- Receiver diversity: Signal received by multiple receiving antennas can be combined together to improve reliability, such as maximal-ratio combining (MRC)

Transmitter diversity: Space-time codes

- Redundant copies of a data stream to the receiver in the hope that at least some of them may survive the physical path between transmission and reception in a good enough state to allow reliable decoding.
- Encoding
  - Usually represented by a matrix. Each row represents a time slot and each column represents one antenna's transmissions over time.

$$\text{time-slots}\downarrow \overset{\text{transmit antennas}\;\longrightarrow}{\begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n_T} \\ s_{21} & s_{22} & \cdots & s_{2n_T} \\ \vdots & \vdots & & \vdots \\ s_{T1} & s_{T2} & \cdots & s_{Tn_T} \end{bmatrix}}$$

  - Alamouti code: designed for a two-transmit antenna system and has the coding matrix:

$$C_2 = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix},$$

    Each symbol is transmitted on both antennas, thus diversity is achieved.
- Decoding
  - If any pair of columns taken from the coding matrix is orthogonal, only linear processing is required at the receiver, thus greatly reducing decoding complexity;
  - Otherwise, decoding is much more complex.

Spatial multiplexing

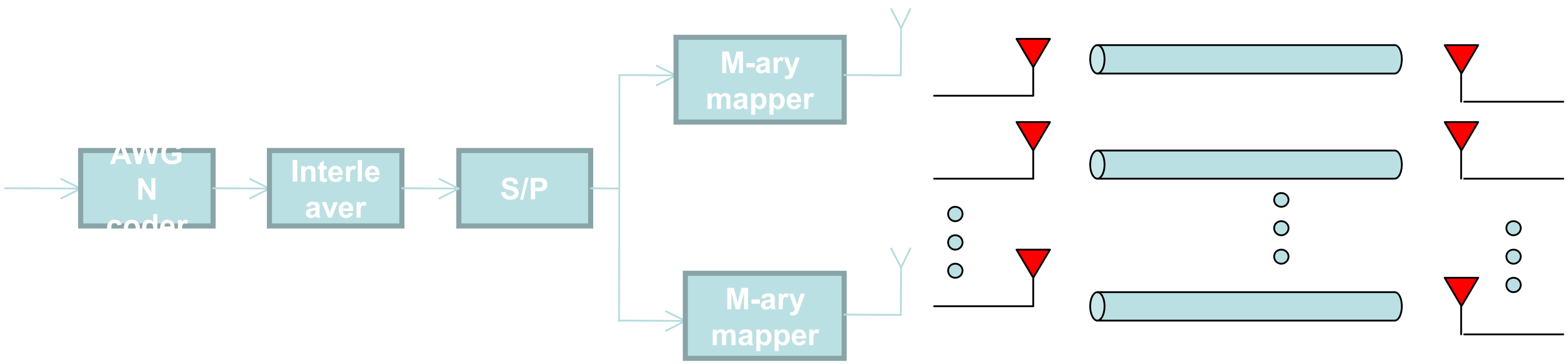
- Transmit independent and separately encoded data signals, so called streams, from each of the multiple transmit antennas.
- Degree-of-freedom If the transmitter is equipped with N_t antennas and the receiver has N_r antennas, the maximum spatial multiplexing order (the number of streams) is

$$\mathbf{N_s} = \min(N_t, N_r)$$

- In order to achieve near N_s capacity gain
  - High SNR region
  - Richly scattered environment
- An intuitive explanation
  - When SNR is high, the effect of noise becomes minimum
  - Richly scattered environment ensure channel matrix **H** is not singular
  - Receive can easily recovers the N_s streams by solving the linear equation **Y=Hx.**

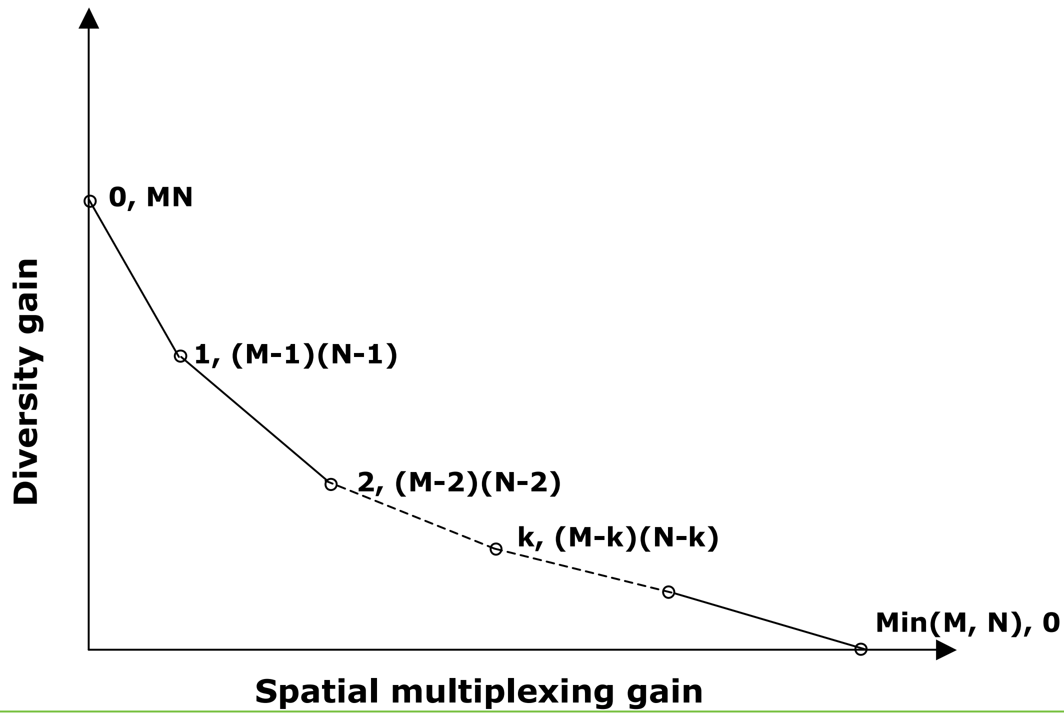
BLAST: Bell Labs Layered Space-Time

- BLAST takes advantage of the spatial dimension by transmitting and detecting a number of independent co-channel data streams using multiple, essentially co-located, antennas.
- The central paradigm behind BLAST is the exploitation, rather than the mitigation, of multipath effects in order to achieve very high spectral efficiencies (bits/sec/Hz), significantly higher than are possible when multipath is viewed as an adversary rather than an ally.



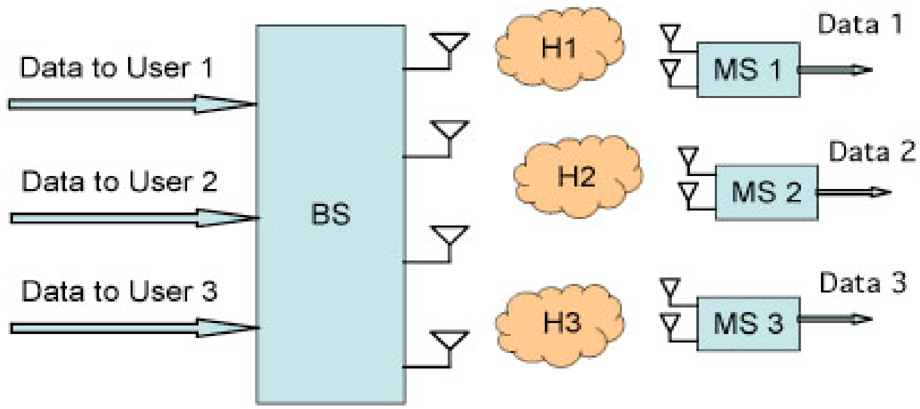
Diversity-Multiplexing tradeoff

- Multiple antennas can be used for
  - Increasing the amount of diversity
  - Increasing the number of degrees of freedom
- Both types of gains can be simultaneously obtained for a given multiple antenna channel
- However, there is a fundamental tradeoff between how much of each any coding scheme can get.



Multi-user MIMO

- Allow a BS with N antennas send to/receive from multiple MS, each with M antennas (M<N) simultaneously, using the same frequency, time and code.
- Multi-user MIMO can leverage multiple users as spatially distributed transmission resources, at the cost of somewhat more expensive signal processing.



- A single base station transmits to multiple mobile stations simultaneously over the same frequency band.
- Substantially increasing the sum data-rate to/from all users.
- The capacity is bounded by the degrees of freedom of the channel matrix H, where H is the channel between antennas on the BS and antennas on all MS.

Uplink/Downlink

- Uplink: receiver has more antennas than each transmitter, thus BS can distinguish each stream of information, by doing a joint decision on the received signals

$$\mathbf{Y} = \mathbf{H}\mathbf{x} + \mathbf{W}$$

  - Each transmitter (MS) contributes one or a few streams of **x**
  - Receiver (BS) has all streams of **Y**
  - Thus receiver can solve this equation
- Downlink: each receiver has less antenna than the transmitter, thus they cannot decode any information if the signals are sent together
  - The transmitter (BS) contribute all streams of **x**
  - Each receiver (MS) has only few streams of **Y**
  - Thus receiver cannot solve this equation
- Precoding: in order to enable the BS to send multiple streams to several MS, precoding is needed for downlink
  - If H is known at the transmitter (BS), instead of transmitting x, it transmits $\mathbf{H}^{-1}\mathbf{x}$

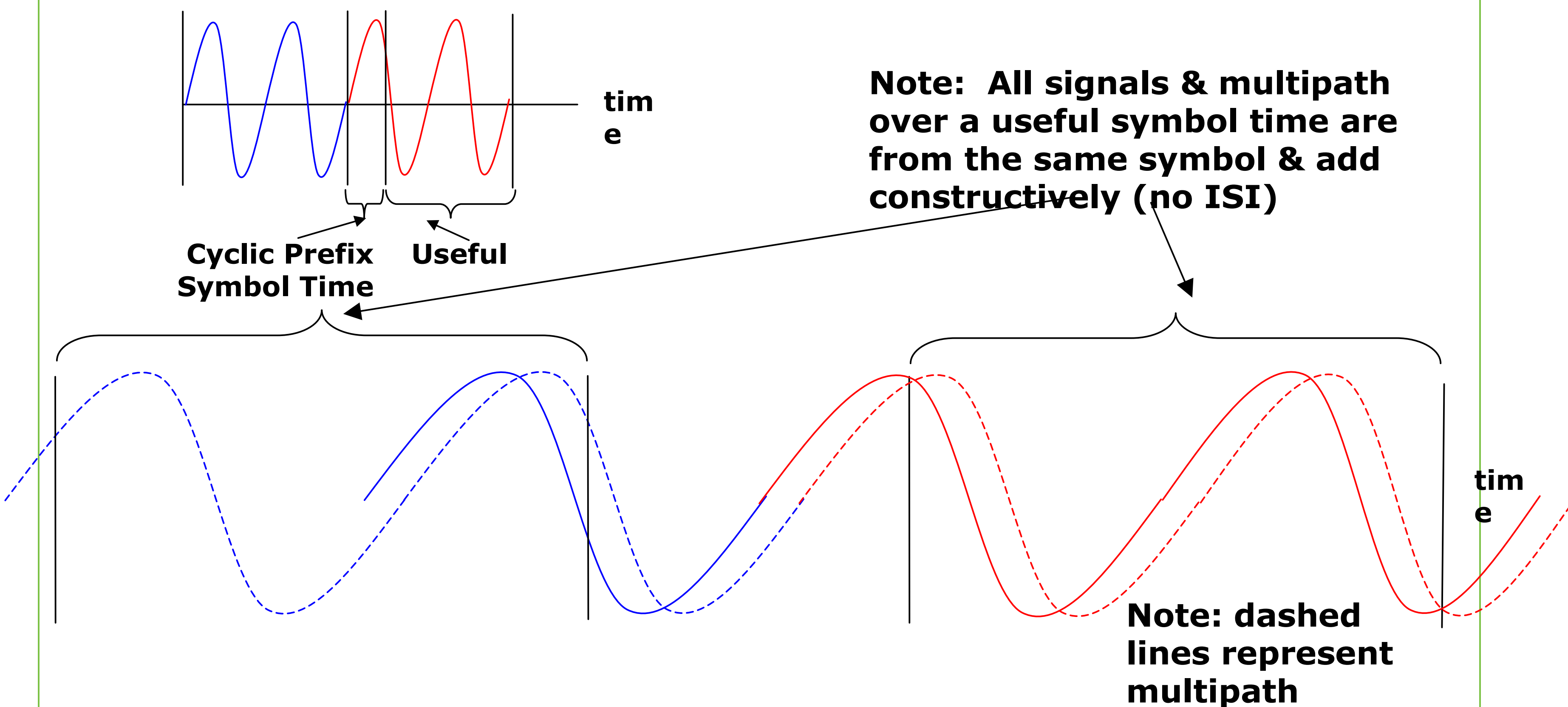
$$\mathbf{Y} = \mathbf{H}(\mathbf{H}^{-1}\mathbf{x}) + \mathbf{W} = \mathbf{x} + \mathbf{W}$$

  - Each receiver is than able to decode its own streams, since there is no interference from other streams
  - Channel state info (CSI) has to be available at the transmitter for precoding
  - Requires feedback from the receiver to the transmitter

Orthogonal Frequency Division Multiplexing (OFDM) for Broadband Wireless

Why OFDM in broadband?

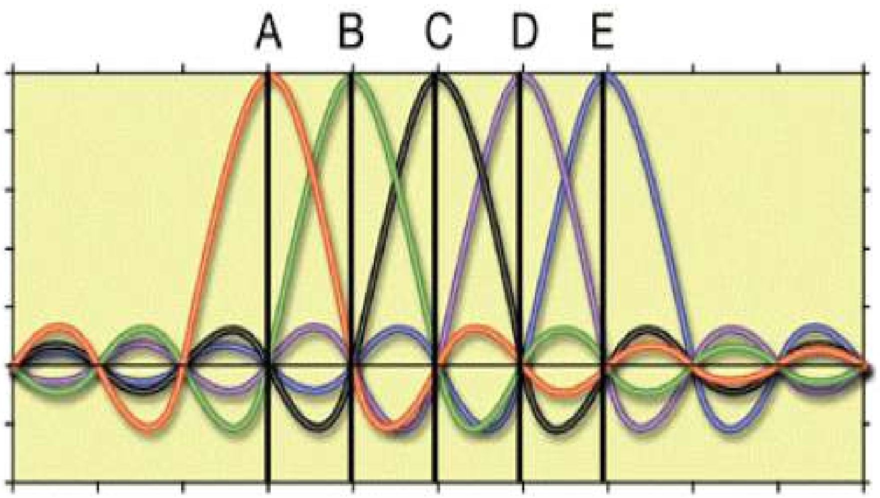
- **Narrow bandwidth → long symbol times → all significant multipaths arrive within a symbol time minimizing ISI → no equalization → low complexity**



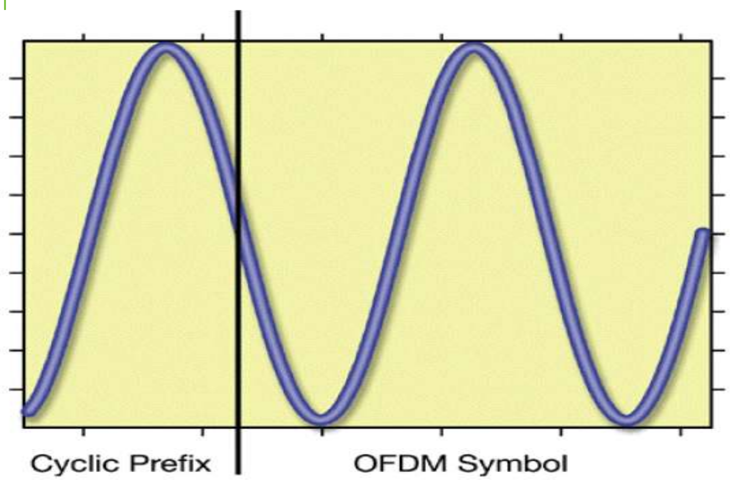
Why OFDM in broadband?

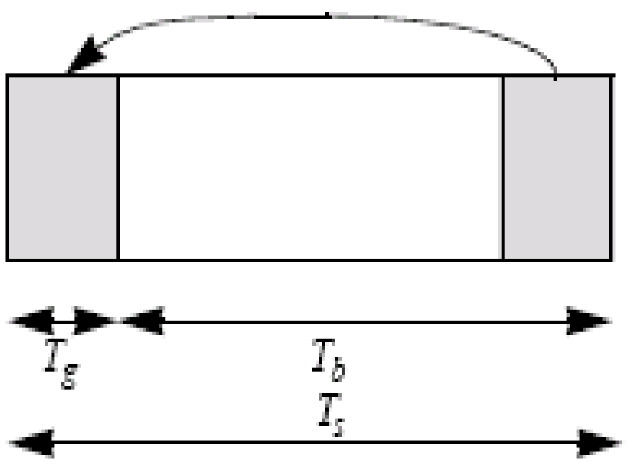
- In broadband communications systems, bandwidth is significantly larger than coherent bandwidth
- Each frequency component of the signal sees different channel response
- It is almost impossible to build a low cost time domain equalizer to remove the ISI
- Frequency Domain Equalization: If the signal is transmitted in frequency domain X(f), and the channel response H(f) is know. Equalization can be easily done by dividing the received signal by H(f).
- Advantages of OFDM
  - Can easily adapt to severe channel conditions without complex equalization
  - Robust against narrow-band co-channel interference
  - Robust against Inter-symbol interference (ISI) and fading caused by multipath propagation
  - High spectral efficiency
  - Efficient implementation using FFT
  - Low sensitivity to time synchronization errors
  - Tuned sub-channel receiver filters are not required (unlike conventional FDM)
  - Facilitates Single Frequency Networks, i.e. transmitter macrodiversity.
- Disadvantages of OFDM
  - Sensitive to Doppler shift.
  - Sensitive to frequency synchronization problems.
  - High peak-to-average-power ratio (PAPR), requiring linear transmitter circuitry, which suffers from poor power efficiency.

OFMA basic



Orthogonal Subcarriers





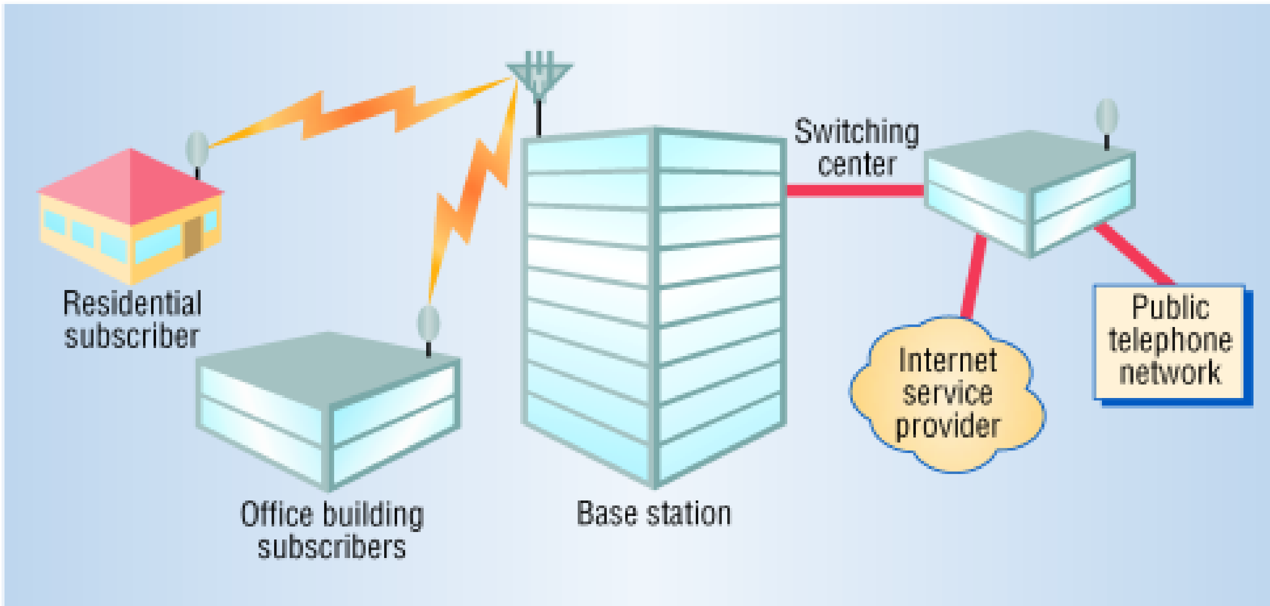
Cyclic Prefix in Time Domain

IEEE 802.16 Wireless Metropolitan Area Network

IEEE 802.16 (WiMAX): the basics

- IEEE Working Group 802.16 on Broadband Wireless Access (BWA)
- First IEEE 802.16 standard published in April 2002 defines WirelessMAN Air Interface
- Standard-compliant product is here.
  - Intel was sampling the 802.16 chip "*Rosdale*".
  - Both Intel and Fujitsu shipped the chip in 2005.
- Application
  - Phase 1 – Fixed location private line service or hotspot back-haul.
  - Phase 2 – Broadband wireless access/wireless DSL
  - Phase 3 – Mobile/nomadic users (802.16e)
  - Phase 4 – Multihop relaying (802.16j)
  - Phase 4 – High capacity system using MIMO(802.16m)
- Features
  - Low cost
  - High speed/data rate
  - Theoretically, it can support up to 75Mbps (802.16e) per channel for both up and down link.
  - If using multiple channels, the rate can be boosted to 350Mbps.
  - Long range (up to 31 miles)
  - Regulations allow 802.16 to transmit at high power
  - Use of directional antenna produces focused signal
  - Mobility
  - To guarantee bandwidth, each base station should serve no more than 500 customers, and cover an area within a 10-mile radius.

Bottom line: the applications



- At the initial stage, WiMax would be used in a point-to-multiple-point (PMP) fashion for internet access. Carrier would set up rooftop transceivers as base stations connected to the internet. Each WiMax base station communicates with fixed, externally mounted service subscribers.
- Technology will be upgraded so that service subscriber can use interior antenna as well in the future.

Current standard 802.16e

- 802.16e provide enhancements to IEEE std 802.16-2004 to support subscriber stations moving at vehicular speeds (75mph).
- Support higher layer handoff between base stations or sectors
- Operation is limited to licensed bands suitable for mobility between 2 and 6 GHz.
- Fill the gap between very high data rate wireless local area networks and very high mobility cellular systems.
- Supports fixed and mobile services for both enterprise and consumer markets.

Frequency bands

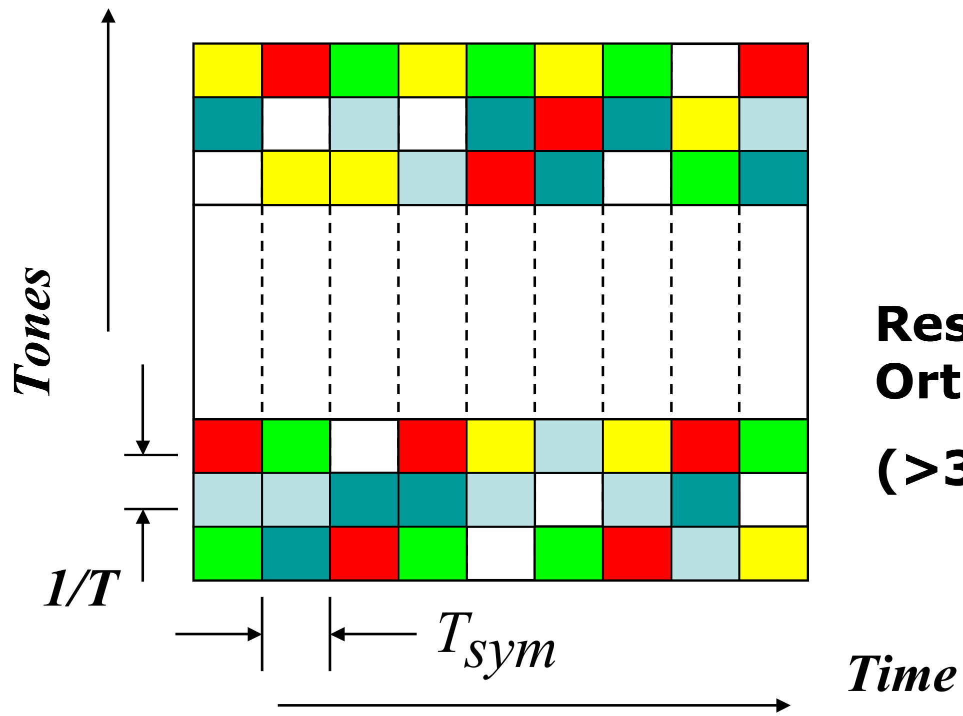
- 10GHz~66GHz licensed band
  - Short wavelength
    - Line-of-sight (LOS) constraint
    - Multipath effect can be ignored
  - Typical channel width is 25MHz (typical U.S. allocation) or 28MHz (typical Europe allocation)
  - Raw data rates can be above 120Mbps
  - Air interface: single-carrier modulation
    - Known as “WirelessMAN-SC” interface.
  - Is suited for point-to-multipoint (PMP) access, serving both small office/home office (SOHO) and medium to large enterprises.

- < 11GHz
  - Longer wavelength
    - No line-of-sight (LOS) problem
    - But multipath becomes an issue.

- License-exempt bands below 11GHz (primarily 5~6GHz)
  - Use dynamic frequency selection (DFS) to detect and avoid interference problem.
  - Note that IEEE 802.11a also operates in the 5GHz band.

OFDMA based air interface

- High-speed downlink and uplink based on OFDMA
  - no in-cell interference
  - no equalization for multipath delay-spread
  - Each subscriber is allocated a frequency-time resource

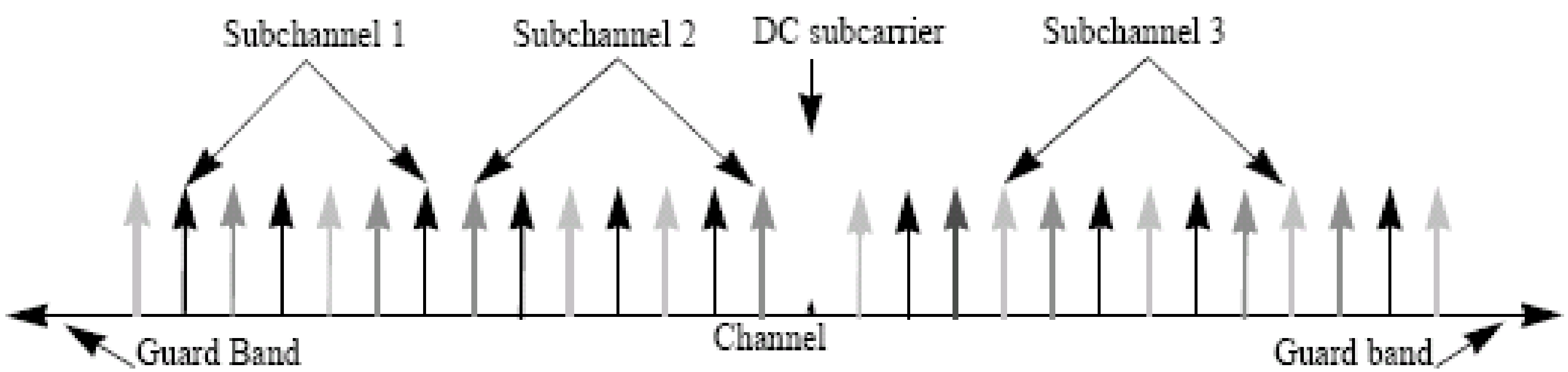


Resource Orthogonality

(>35 dB)

OFDMA subchannels

- A subset of subcarriers is grouped together to form a subchannel
- A transmitter is assigned one or more subchannels in DL direction
- Subchannels provide interference averaging benefits for aggressive frequency reuse systems



Adaptive modulation & coding

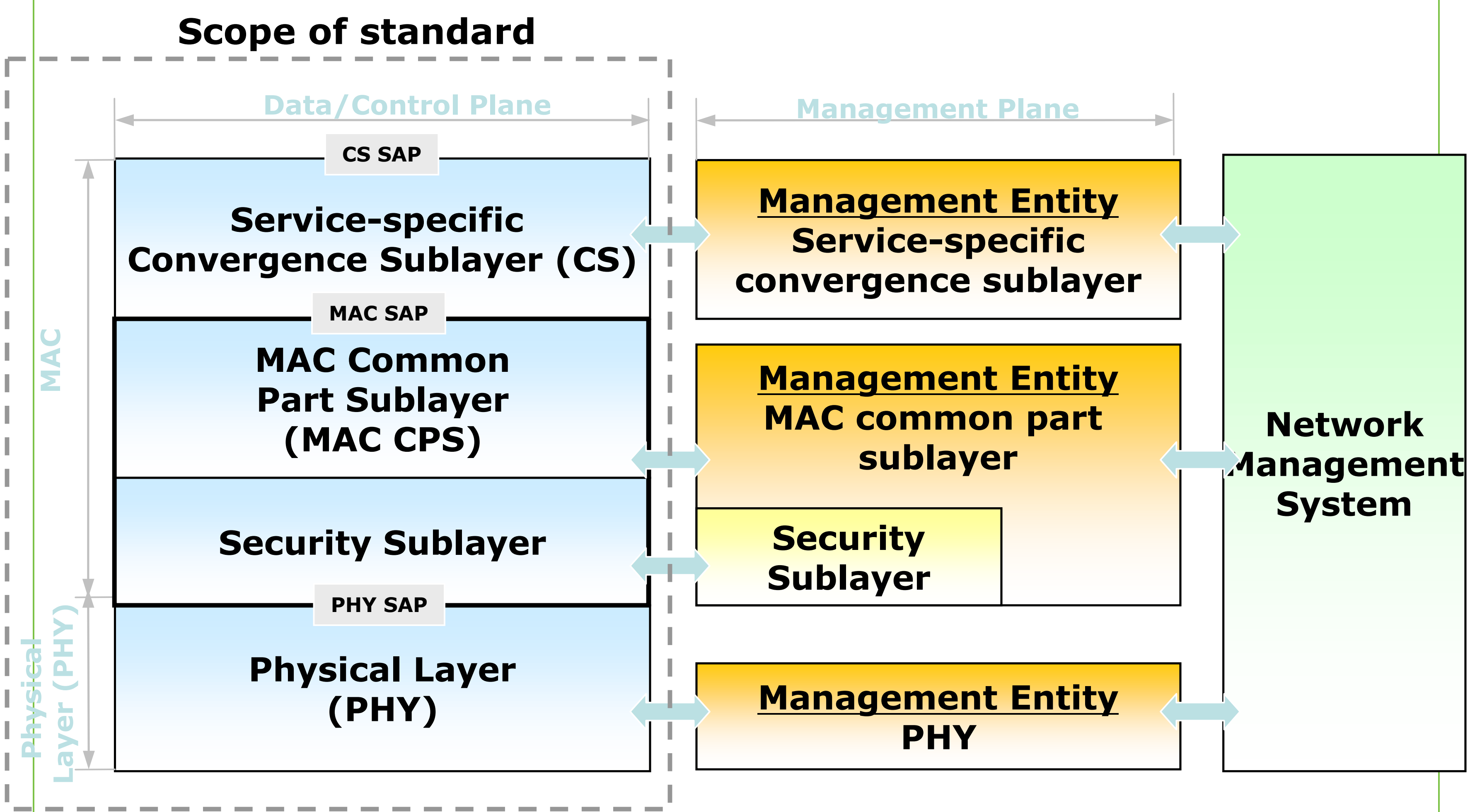
- The 802.16a/d standard defines seven combinations of modulation and coding rate that can be used to achieve various trade-offs of data rate and robustness.

Rate ID	Modulation rate	Coding	Information bits/symbol	Information bits/ OFDM symbol	Peak data rate in 5 MHz (Mb/s)
0	BPSK	1/2	0.5	88	1.89
1	QPSK	1/2	1	184	3.95
2	QPSK	3/4	1.5	280	6.00
3	16QAM	1/2	2	376	8.06
4	16QAM	3/4	3	568	12.18
5	64QAM	2/3	4	760	16.30
6	64QAM	3/4	4.5	856	18.36

Adaptive modulation & coding

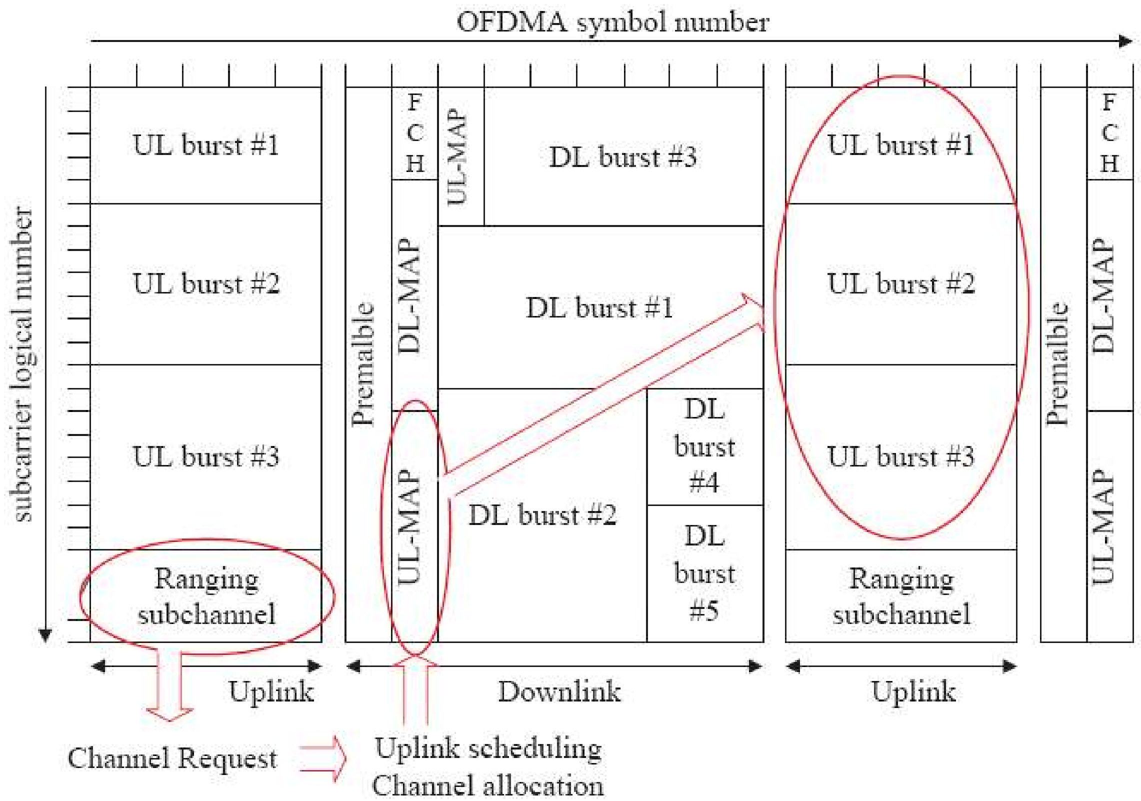
- One departure from the 802.11 standard is that 802.16 uses an outer Reed-Solomon (RS) block code concatenated with an inner convolutional code to achieve forward error correction (FEC).
- Naturally, interleaving is also employed to reduce the effect of burst errors.

Protocol stack



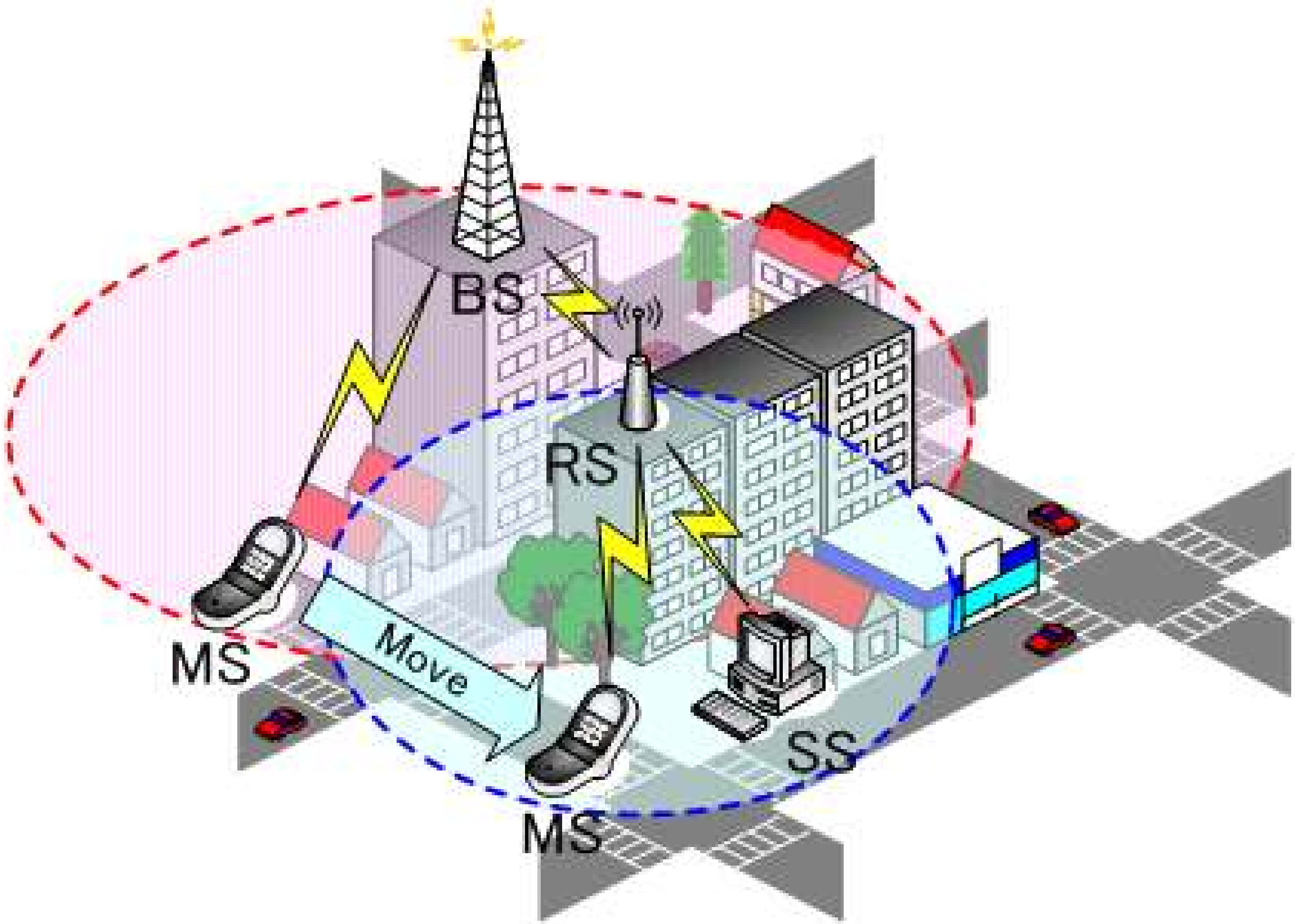
OFDMA TDD frame structure

- DL-MAP and UL-MAP indicate the current frame structure
- BS periodically broadcasts Downlink Channel Descriptor (DCD) and Uplink Channel Descriptor (UCD) messages to indicate burst profiles (modulation and FEC schemes)



Task Group on 802.16j

- Allow relay stations added to extend reach/coverage



*Reference: C802.16-005/013

IEEE 802.16j

- Backward compatible frame structure supporting both relay frames and legacy frames
- Definition of RF requirements including the relay link frequency, duplexing and channel B/W
- Relay shall support network entry for the mobile station and mobile station handover
- The support of more than one relay hop between MMR-BS and MS
- This task group is currently in the process of finishing IEEE 802.16j

Task group 802.16m

- Provide Gigabit WiMAX using advanced MIMO technology
- Advanced Air Interface: data rates of 100 Mbit/s for mobile applications and 1 Gbit/s for fixed applications
- Cellular, macro and micro cell coverage
- Currently no restrictions on the RF bandwidth
- Status: completion of the standard by December 2009 for approval by March 2010

3GPP
LTE
(Long Term Evolution)

LTE overview

- 3GPP work on the Evolution of the 3G Mobile System started in November 2004. Standardized in the form of Release-8.
- LTE-Advanced
  - More bandwidth (up to 100 MHz).
  - Backward compatible with LTE.
  - Standardization in progress (targeted for Rel-10).
- Multiple access scheme
  - DL OFDMA: same as WiMAX
  - UL Single Carrier FDMA (SC-FDMA): power efficient modulation in the uplink
- Adaptive modulation and coding
  - DL/UL modulations: QPSK, 16QAM, and 64QAM
  - Convolutional code and Rel-6 turbo code
- Advanced MIMO spatial multiplexing techniques
  - (2 or 4)x(2 or 4) downlink and uplink supported.
  - Multi-user MIMO also supported
- Support FDD and TDD (FDD dominant)

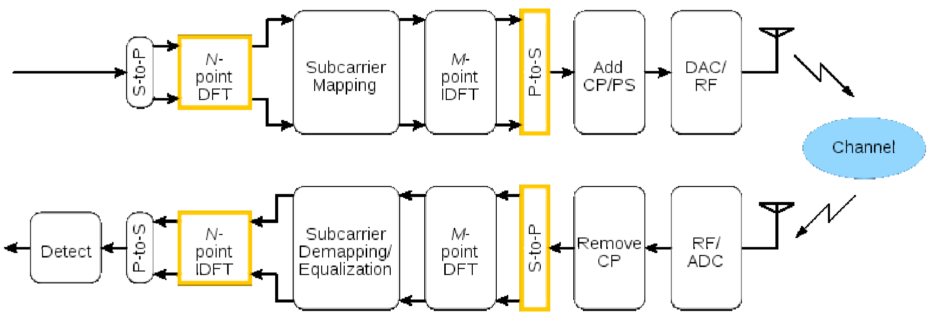
System requirement

- Peak data rate
  - 100 Mbps DL/ 50 Mbps UL within 20 MHz bandwidth.
- • Up to 200 active users in a cell (5 MHz)
- • Less than 5 ms user-plane latency
- • Mobility
  - Optimized for 0 ~ 15 km/h.
  - 15 ~ 120 km/h supported with high performance.
  - Supported up to 350 km/h or even up to 500 km/h.
- • Enhanced multimedia broadcast multicast service (E-MBMS)
- • Spectrum flexibility: 1.25 ~ 20 MHz
- • Enhanced support for end-to-end QoS

Why SC-FDMA uplink?

- In OFDM systems, the peak-to-average-power ratio (PAPR) is high.
  - Power efficiency is low.
  - Requires high dynamic range amplifier on the transmitter side.

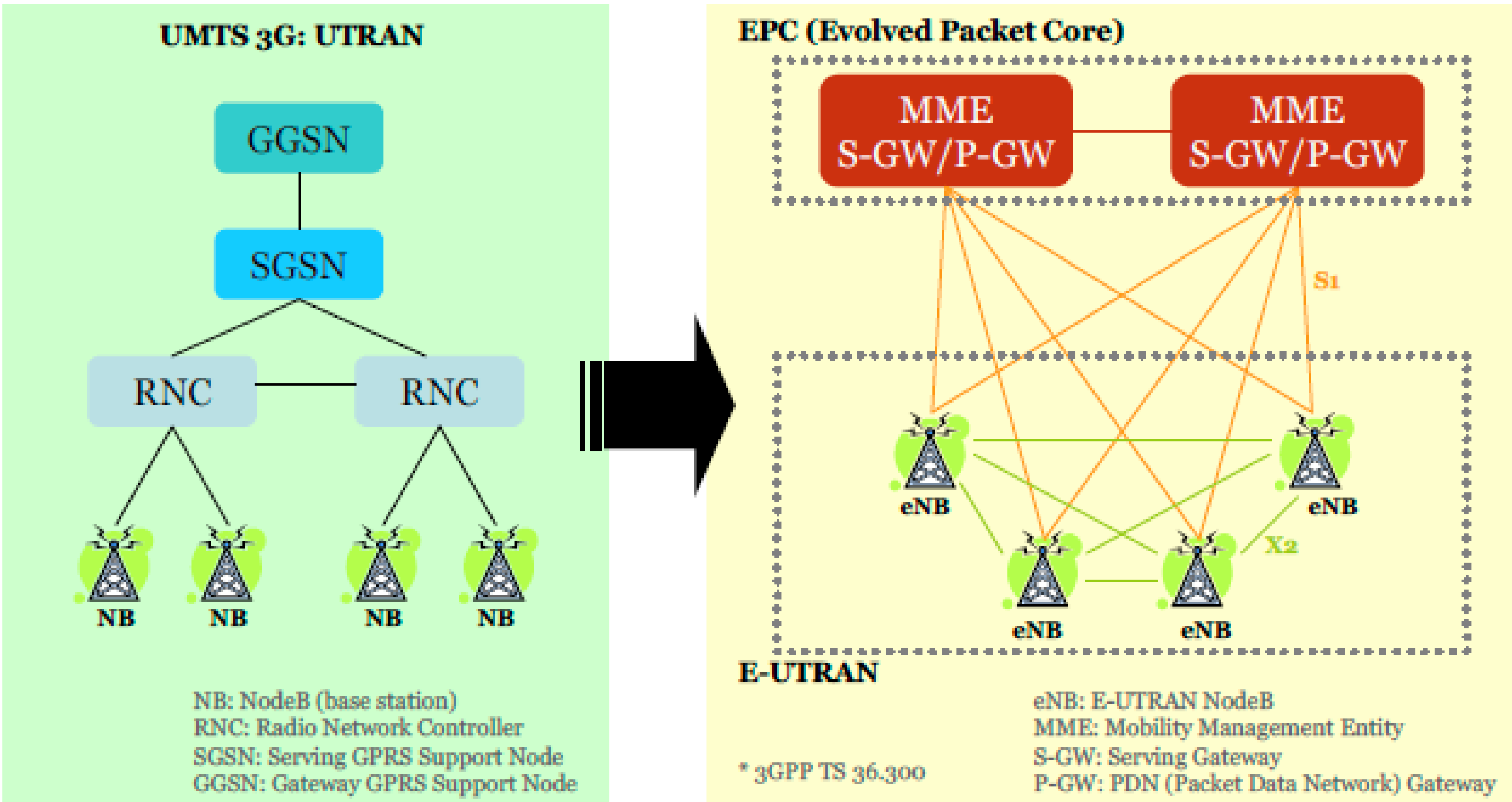
- SC-FDMA is a new single carrier multiple access technique which has similar structure and performance to OFDMA.
  - It is based on an OFDMA transceiver.
  - The data are pre-processed (FFT) before send to the OFDM transmitter.



- Compared to OFDMA, SC-FDMA signals have much lower PAPR.
  - Requires less expensive linear amplifier, suitable for UE equipment.
  - Power efficient.

LTE network architecture

- E-UTRAN (Evolved Universal Terrestrial Radio Access Network)



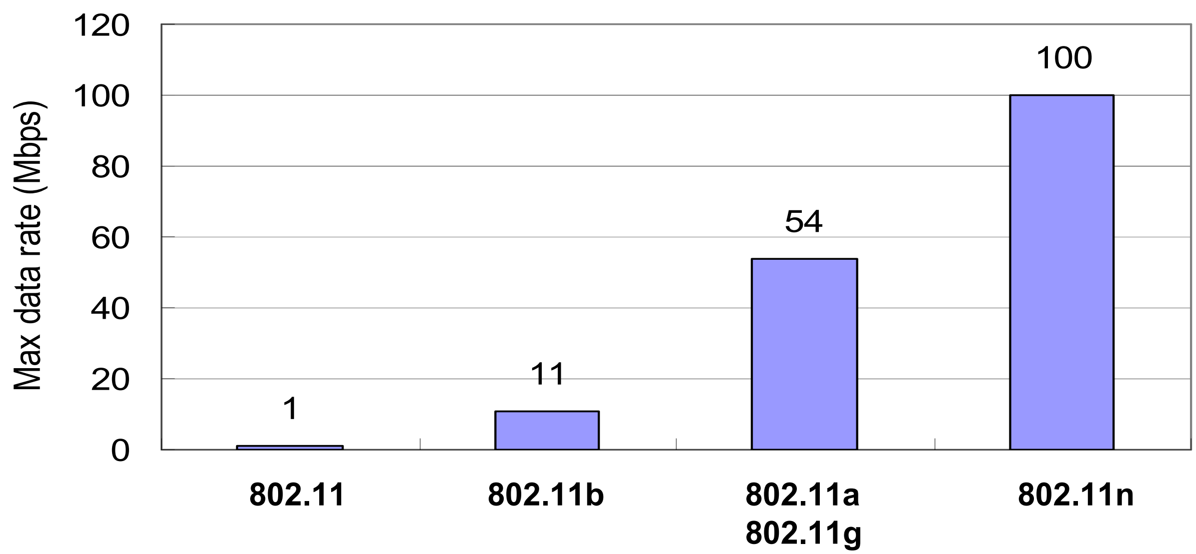
IEEE 802.11 Wireless Local Area Network

IEEE 802.11 Wireless Local Area Network (WLAN)

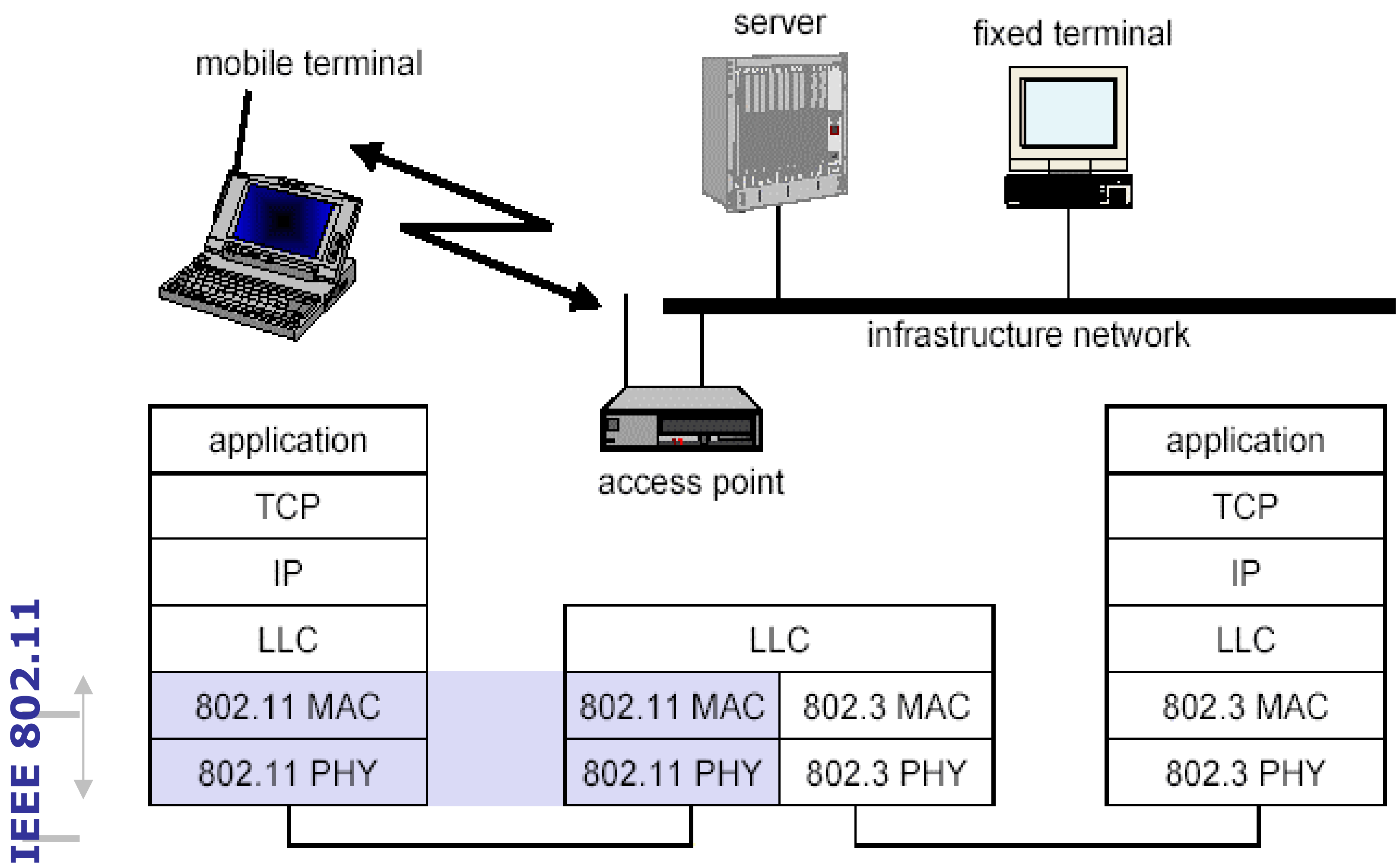
- Basic standard first ratified in 1997
- Primary (original) function:
  - Wireless replacement for Ethernet
- Frequency band: Unlicensed band
  - 2.4 GHz: 11 channels, 3 of which are non-overlapping
  - 5 GHz: 12 non-overlapping channels
- Basic data rate
  - 1, 2, 5.5, 11, . . ., 54Mbps
- Range
  - Indoor: 20 ~ 25 meters
  - Outdoor: 50~100 meters
- Specify protocols for MAC and PHY layers only
  - 802.11 has defined many new amendments
    - PHY: 802.11b, 802.11a, 802.11g, 802.11n…
    - MAC: 802.11e, 802.11i, …
- Application
  - Enterprise and campus networking
  - Ad hoc networking
  - Public access in “hot spots”
  - Home networking

IEEE 802.11: basics

Standard	Freq	Supported Rate	Number of Channels	Published	Market Introduction
802.11	2.4GHz	1, 2	11	1997	N/A
802.11b	2.4GHz	1, 2, 5.5, 11	11	1999	1999
802.11a	5GHz	6, 9, 12, 18, 24, 36, 48, 54	12	1999	2002
802.11g	2.4GHz	1, 2, 5.5, 11, 6, 9, 12, 18, 24, 36, 48, 54	11	2003	2003
802.11n	2.4/5GHz	100Mbps above MAC SAP	N/A	Expected 2009	Pre-N 2005

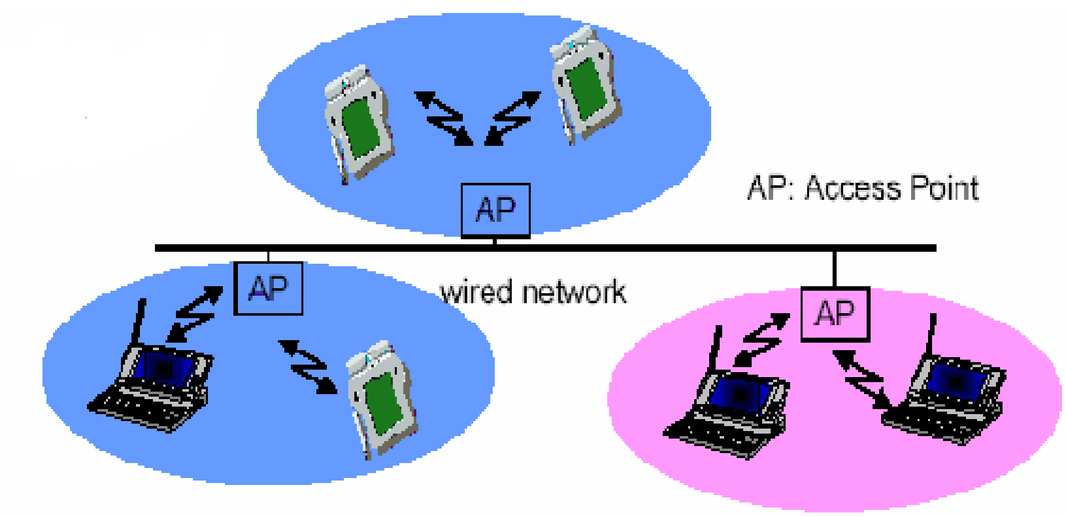


Protocol stacks



Network architecture

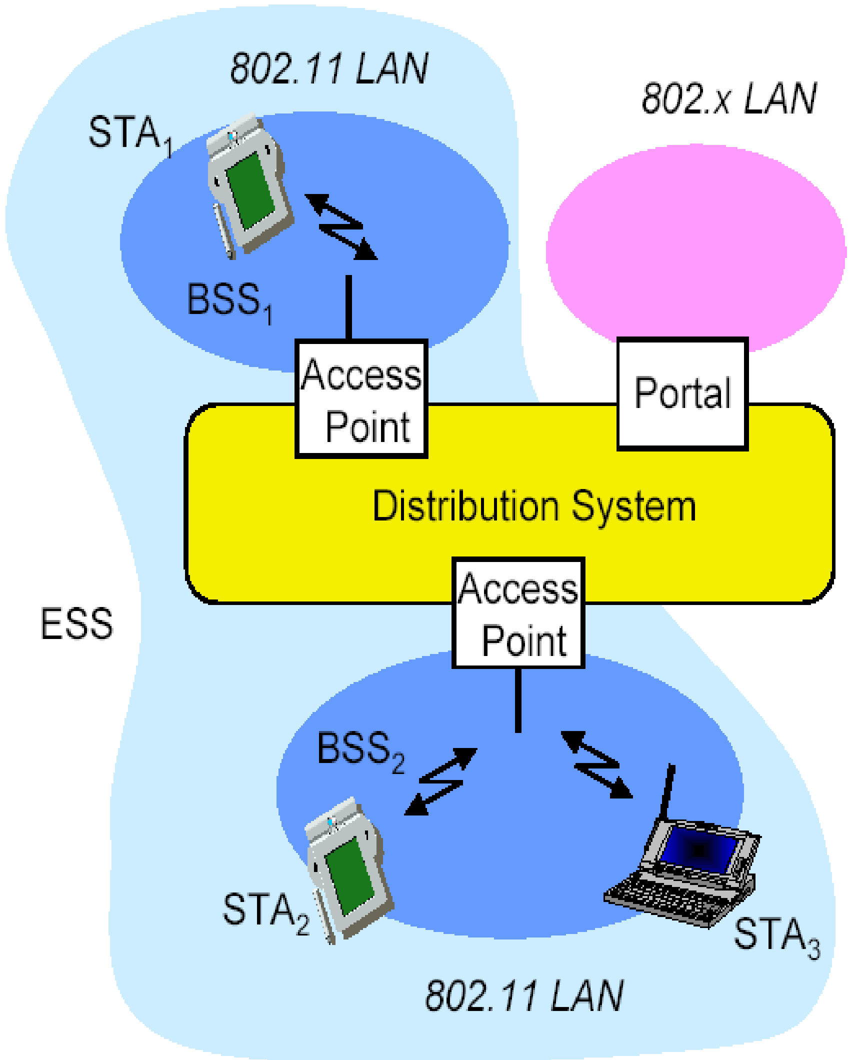
- Two configurations
  - Infrastructure basic service set



  - Independent basic service set: ad hoc mode

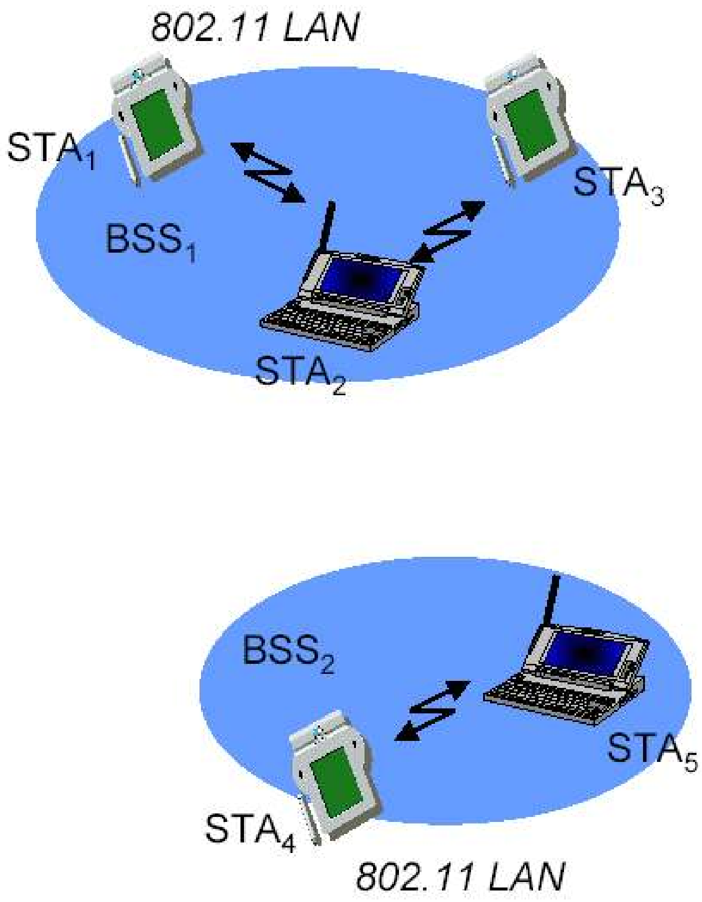
Infrastructure mode

- **Station (STA)**
  Not allowed to communicate with each other directly in infrastructure mode. Any traffic must go through the access point.
- **Access Point (AP)**
  Provide access to DS and act as a STA as well.
- **Portal**
  A logical point at which non-IEEE 802.11 MSDU enter the IEEE 802.11 DS.
- **Distribution System (DS)**
  Interconnect BSSs to form one logical network



MAC Service Data Unit (MSDU): Information that is delivered as a unit between MAC SAPs.

Ad Hoc mode

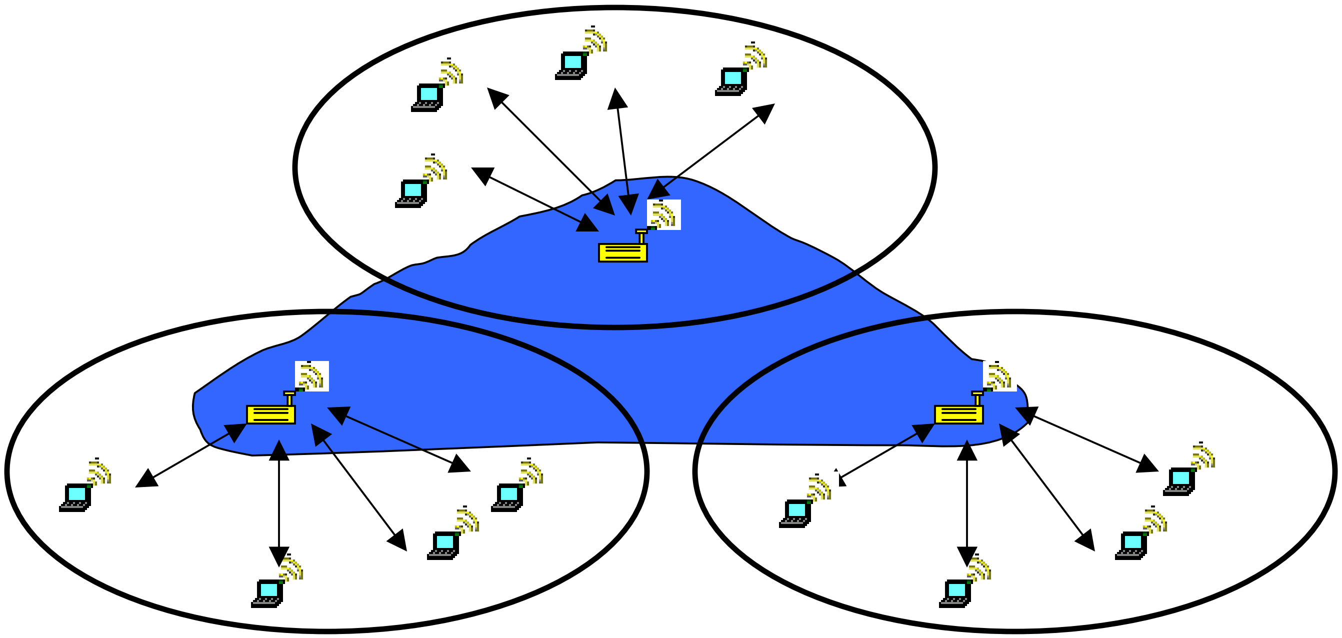


- **Station (STA)**

  Direct communication within a limited range, no relay function.

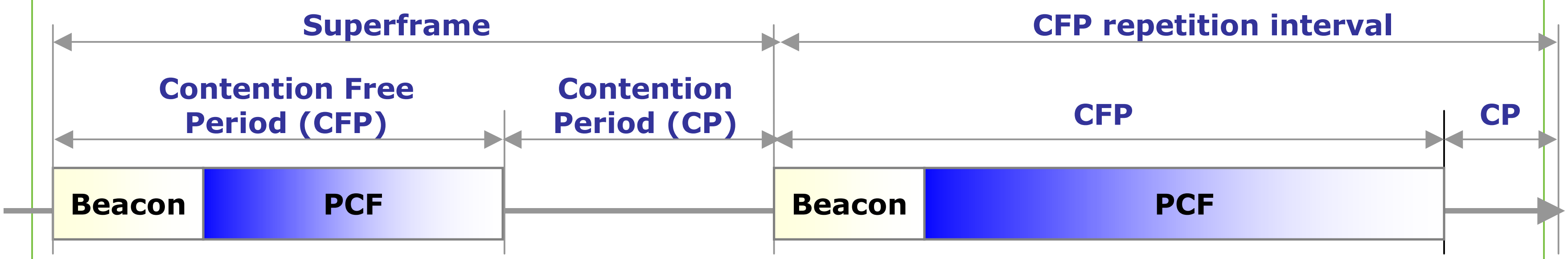
Service set

- Basic Service Set (BSS)
  - Basic building block of an IEEE 802.11 WLAN
  - A set of stations controlled by a single coordination function
- Extended Service Set (ESS)
  - Wireless network of arbitrary size and complexity, consists of a set of BSSs interconnected by DS.
  - All stations of the ESS appear to be in a single MAC layer
  - APs communicate with each other to forward traffic through wired or wireless network



MAC protocol: overview

- Superframe structure
  - Consists of both contention period and contention-free period
    - These two periods are of variable length. Their duration depends on the traffic load at the AP and at the mobile hosts.
  - DCF is used in contention period
  - PCF is used in contention-free period
  - PCF has higher access priority than DCF
  - Each superframe is started by a Beacon
  - Each contention-free period is terminated by a CF-End message transmitted by the access point (AP).



Contention period protocol

DCF: CSMA/CA

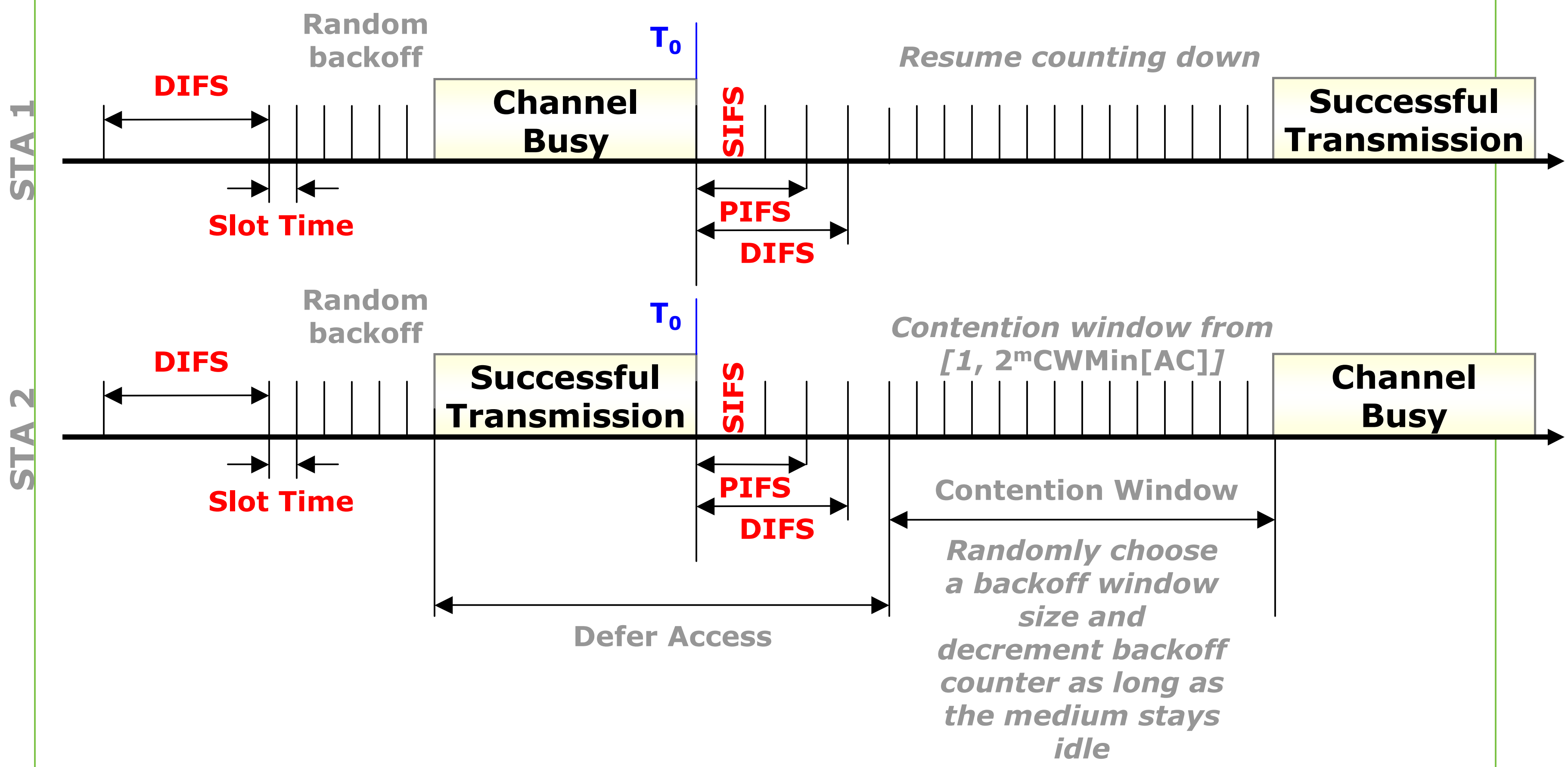
- **Algorithm**
  - **Station which is ready to send starts sensing the channel**
  - **If the channel is free for the duration of a DCF Inter-Frame Space (DIFS), station transmits immediately.**
  - **If the channel is busy, the station has to wait for a free DIFS, then the station must additionally wait for a random backoff time (collision avoidance, multiple of slot-time) before transmission**
  - **The receiving station has to acknowledge the reception of the packet after waiting for a SIFS period, if the packet is received correctly (CRC).**
  - **If no ACK is received after a timeout period at transmitting station, it reschedules a new transmission time for the packet, with a round of backoff**
  - **When the number of retransmissions exceeds RetryLimit (e.g. 6), the packet is dropped at the transmitting station.**
    - **Assume the upper layer retransmission mechanism will take care of this dropped packet.**

Inter-frame spaces

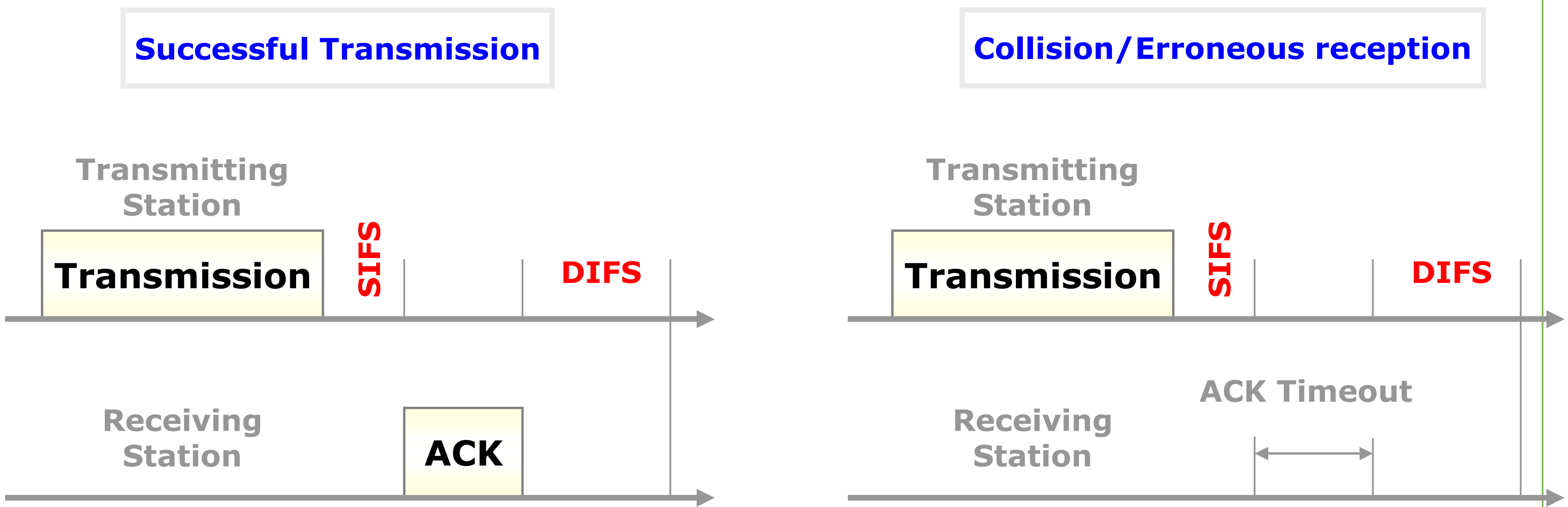
- IEEE 802.11 has defined different inter frame spaces
  - SIFS (Short Inter Frame Spacing)
    - Highest priority, for ACK, CTS, Polling response
  - PIFS (PCF IFS)
    - PIFS = SIFS + slot time
    - Medium priority, for time-bounded service using PCF
  - DIFS (DCF IFS)
    - DIFS = SIFS + 2 x slot time
    - Lowest priority, for asynchronous data service
  - EIFS (Extended IFS)
    - SIFS + ACK_Transmission_Time + DIFS
    - Used after an erroneous frame reception
  - SIFS < PIFS < DIFS < EIFS

- Values of IFS and slot time are PHY dependent.
  - 802.11b (DSSS)
    - Slot time = 20us, SIFS = 10us
  - 802.11a
    - Slot time = 9us, SIFS = 16us

Basic DCF: an illustration



Basic DCF: an illustration

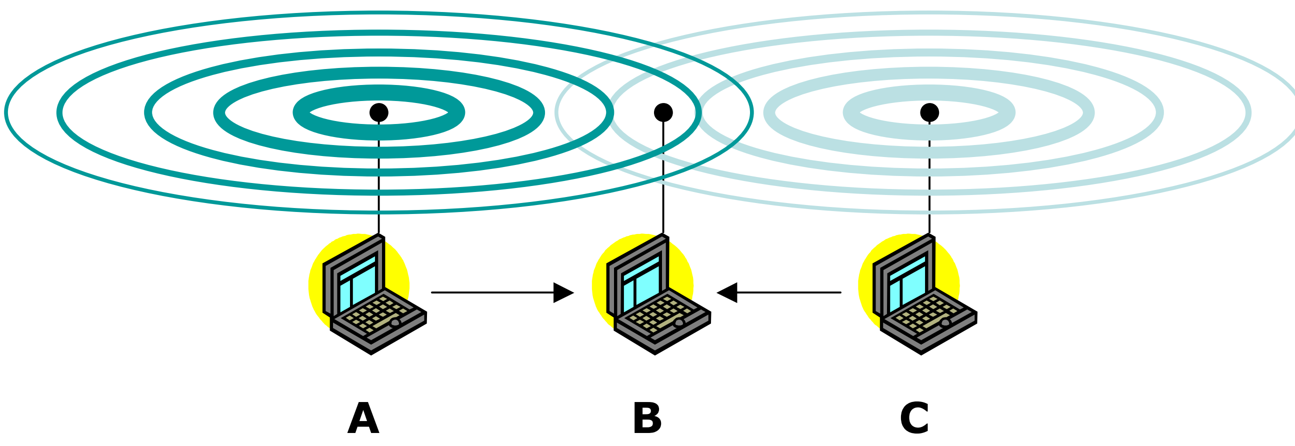


Exponential backoff: more detail

- To begin the backoff procedure:
  - Choose a random number in [0, CWMin-1] from a uniform distribution
  - Listen to determine if the channel is busy for each time slot
  - Decrement backoff time by one slot if channel is idle
  - Suspend backoff procedure if channel is busy in a time slot
  - Resume backoff when the channel becomes idle again.
  - When the backoff counter value becomes 0, STA starts transmission.
- When experiencing collision
  - Choose a new random number according to uniform distribution within interval [0, min{ 2^ixCWMin-1, CWMax-1}]
  - Repeat the steps described above for backoff.
- When you hit the ceiling: retransmission time = RetryLimit (e.g. 6)
  - Drop the packets
  - Most of the time, upper layer protocol will take care of the packet drop and initiate retransmission.

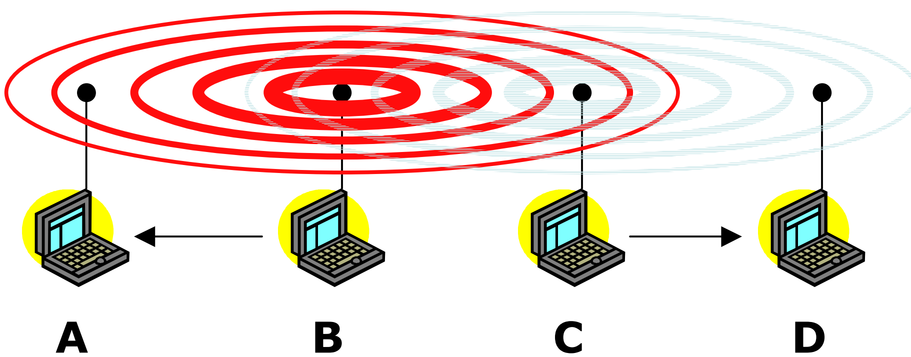
Hidden terminal problem

- A and C are two STAs far away from each other.
- A sends to B, C cannot hear A
- C wants to send to B
- If use CSMA/CA:
  - C senses a “free” medium, thus C sends to A
  - Collision at B, but A cannot detect collision
- Therefore, A is “hidden” for C



Exposed terminal problem

- B sends to A, C wants to send to D
- If use CSMA/CA
  - C senses an “in-use” medium, thus C waits
  - But A is outside the radio range of C, therefore waiting is not necessary
- Therefore, C is “exposed” to B



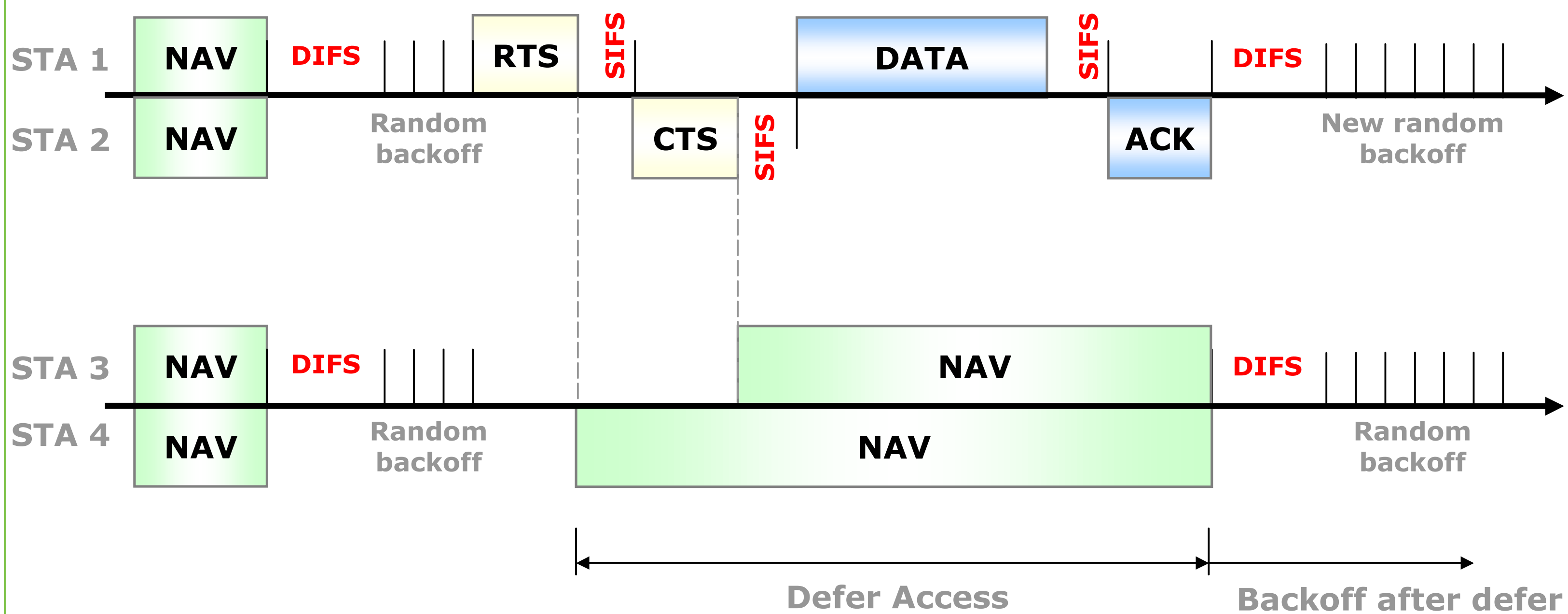
Solution: DCF with RTS/CTS

- Request To Send/Clear To Send (RTS/CTS)
  - Address the hidden terminal problem
  - But can’t tackle exposed terminal problem

- Detailed algorithm
  - When a station wants to send a packet, it first sends a RTS.
  - The receiving station responds with a CTS.
  - Stations that can hear the RTS or the CTS then mark that the medium will be busy for the duration of the request (indicated by Duration ID in the RTS and CTS).
  - Stations will adjust their Network Allocation Vector (NAV)
    - Time that must elapse before a station can sense channel for idle status
  - This is called virtual carrier sensing.
  - RTS/CTS are smaller than long packets that can collide

RTS/CTS: illustration

- **Usually RTS/CTS mechanism is disabled in the product.**
- **When should it be enabled?**
  - **When data frame is long enough to justify the overhead caused by the exchange of RTS/CTS messages.**
  - **RTS threshold is adjustable in the WLAN card.**



IEEE 802.11n (draft standard)

- Amendment which improves upon the previous 802.11 standards by adding multiple-input multiple-output (MIMO) and many other newer features.
- Frequency of 5 GHz or 2.4 GHz
- The current 802.11n draft provides for up to four spatial streams, even though compliant hardware is not required to support that many.
- Much higher throughput
  - Improves the peak throughput to at least 100Mb/s, measured at the MAC data SAP
  - Data rate of 74 – 284 Mbps
  - Allow multi-stream HD video streaming
- Backward compatible at MAC layer
  - Keeping the existing IEEE 802.11 MAC SAP interface

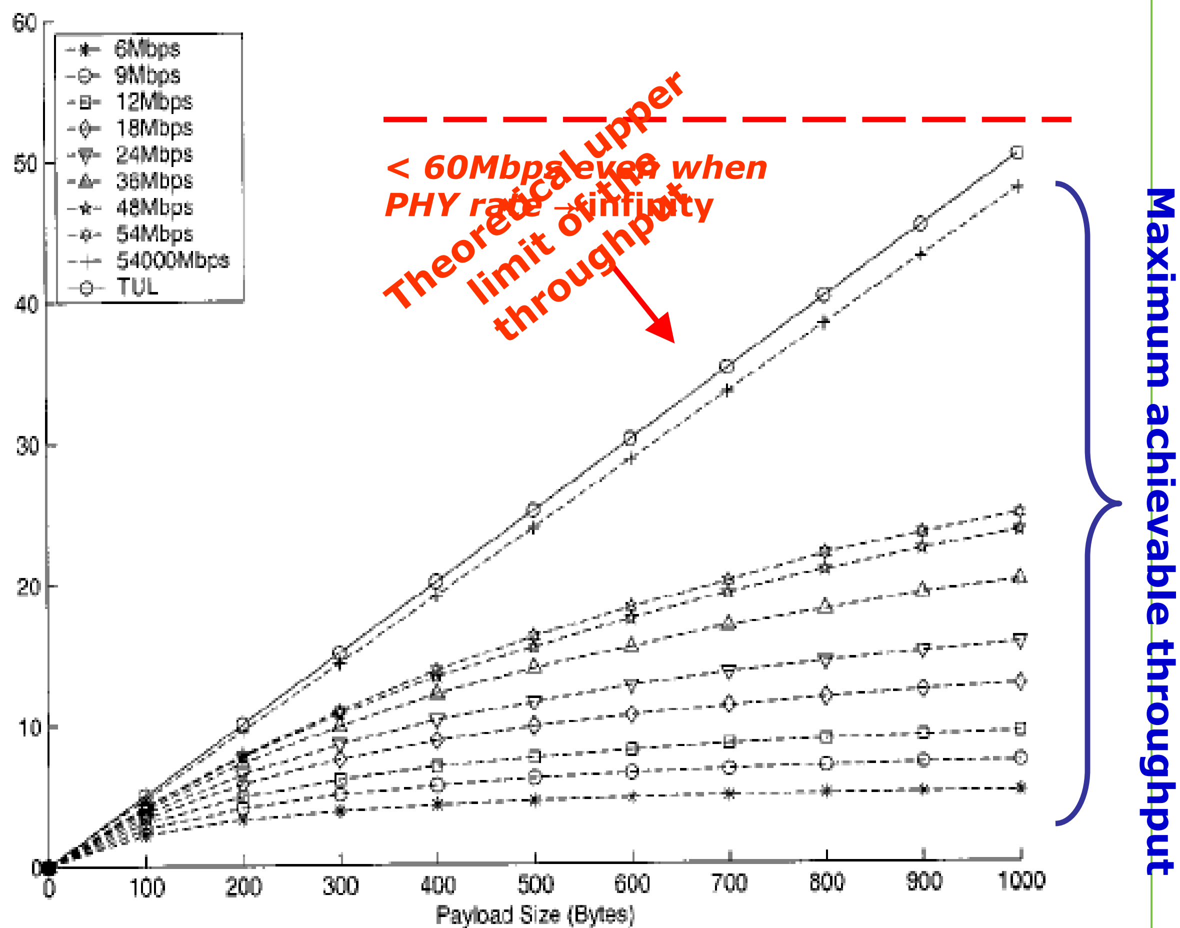
802.11n mode of operations

- 40 MHz operation (channel bonding. *optional*)
  - Primary channel plus secondary (upper/lower) channel
  - Primary for management frames, both channels for data frames (opportunistically)
  - Higher bandwidth, higher data rates!
  - …but higher interference
  - Only one non-overlapping channel in 2.4 GHz

- Backward compatibility (distinguished by their PLCP headers)
  - Mixed
    - Full support for legacy clients
    - Broadcast control frames always in 20 Mhz
    - Performance degradation for .11n stations
  - Greenfield
    - No backward compatibility
    - Short & more efficient PLCP format
    - No performance degradation for .11n devices

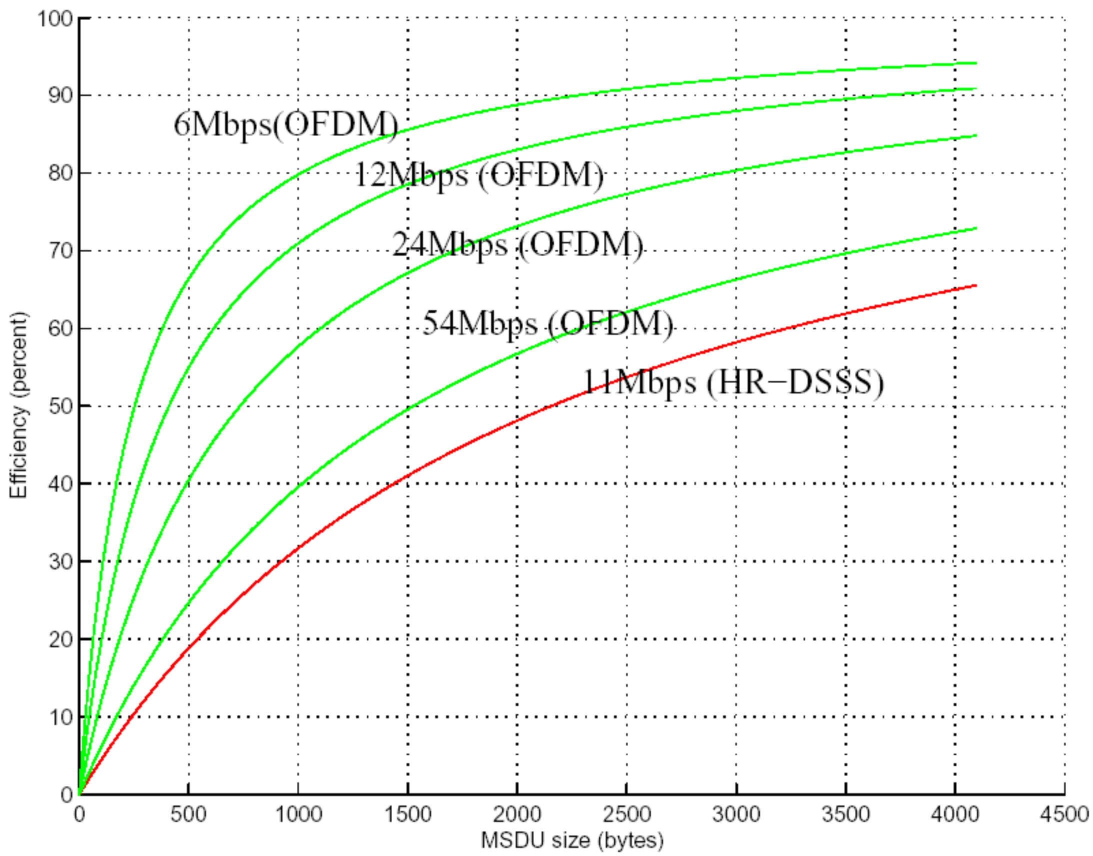
Inefficiency of DCF MAC

- The current DCF MAC imposes an inherent limit on network throughput above MAC layer.
- Regardless of the physical data rate, we can ***NEVER*** reach the 100Mbps, if we use the DCF.



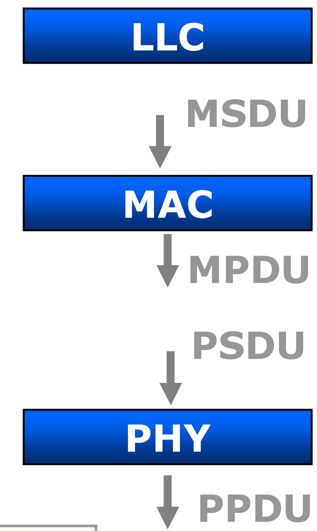
Inefficiency of DCF

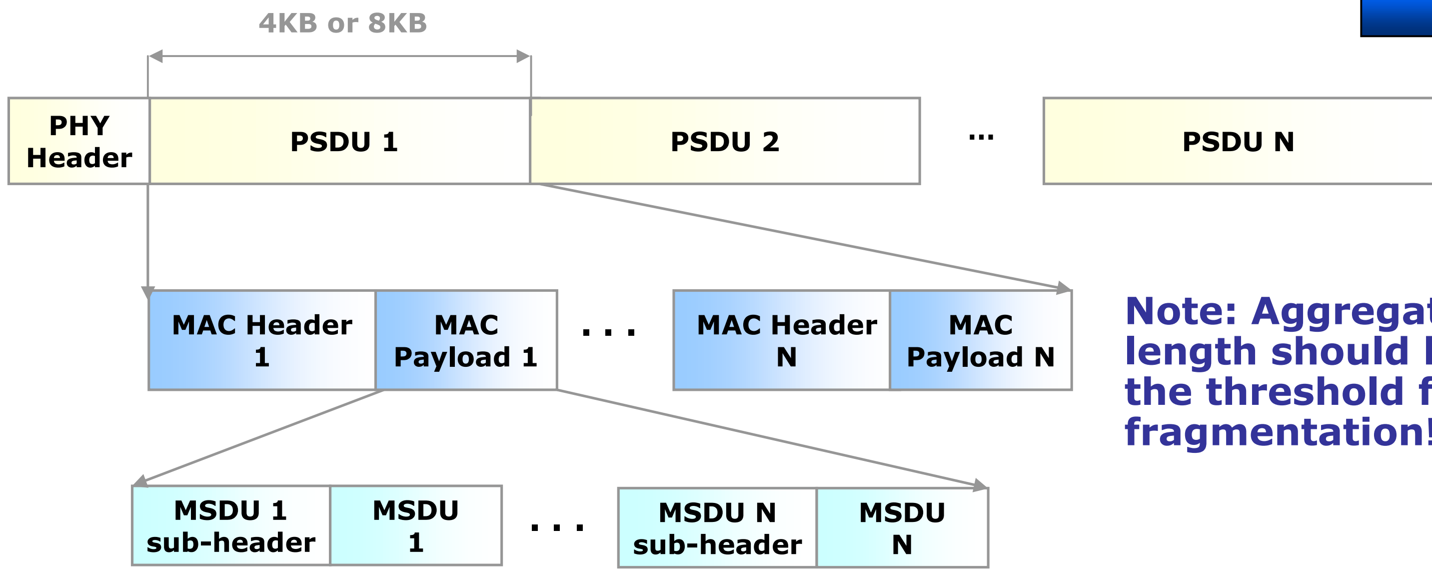
- As the PHY layer rate increases, the observable throughput at MAC-SAP does not grows proportionally
- The MAC protocol efficiency in fact drops!
- Given the legacy MAC protocol and parameters, upper limit of throughput exists, no matter how fast the PHY layer transmits.



802.11n solution: frame aggregation

- Frame aggregation
  - MSDU level
  - PSDU level
- Increase maximum frame size
- Header compression

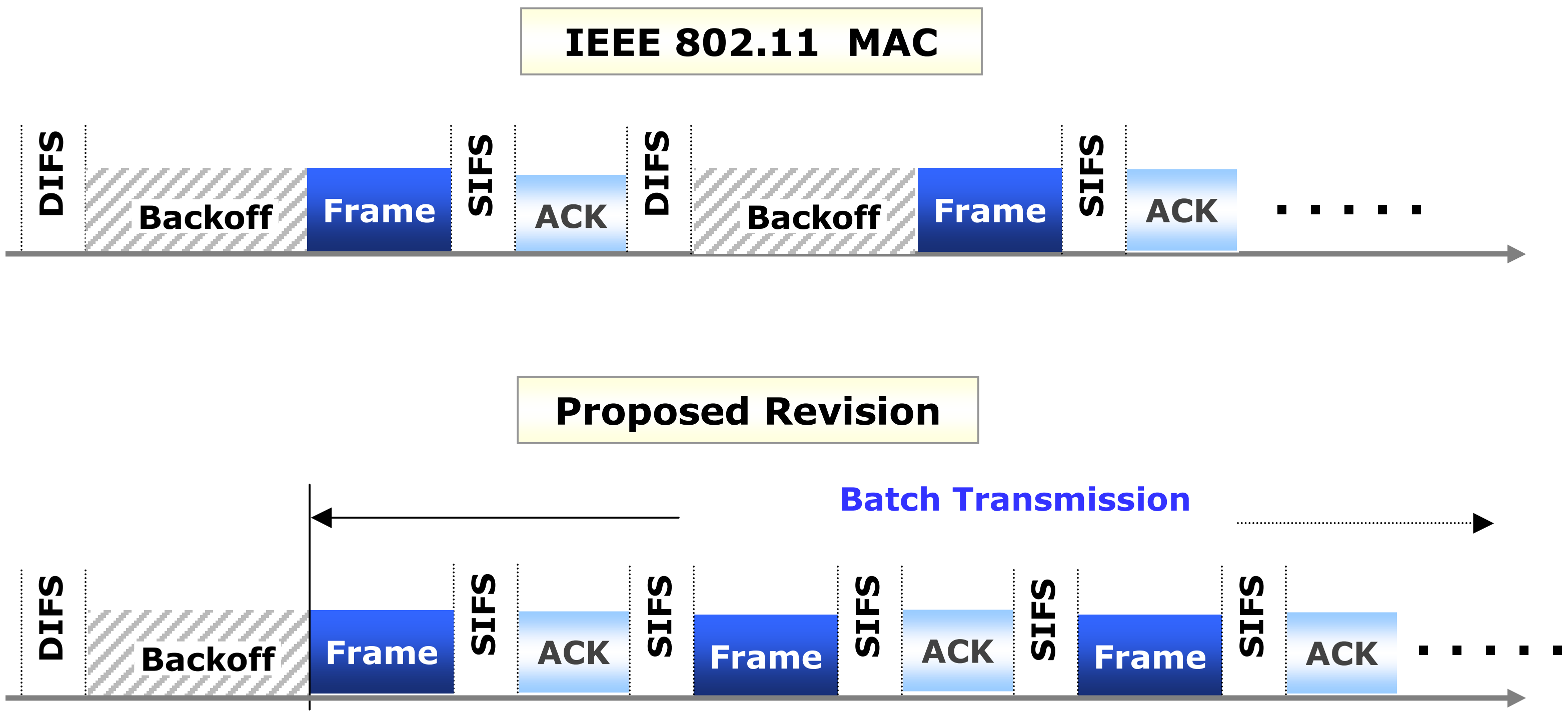




Note: Aggregation length should be below the threshold for fragmentation!

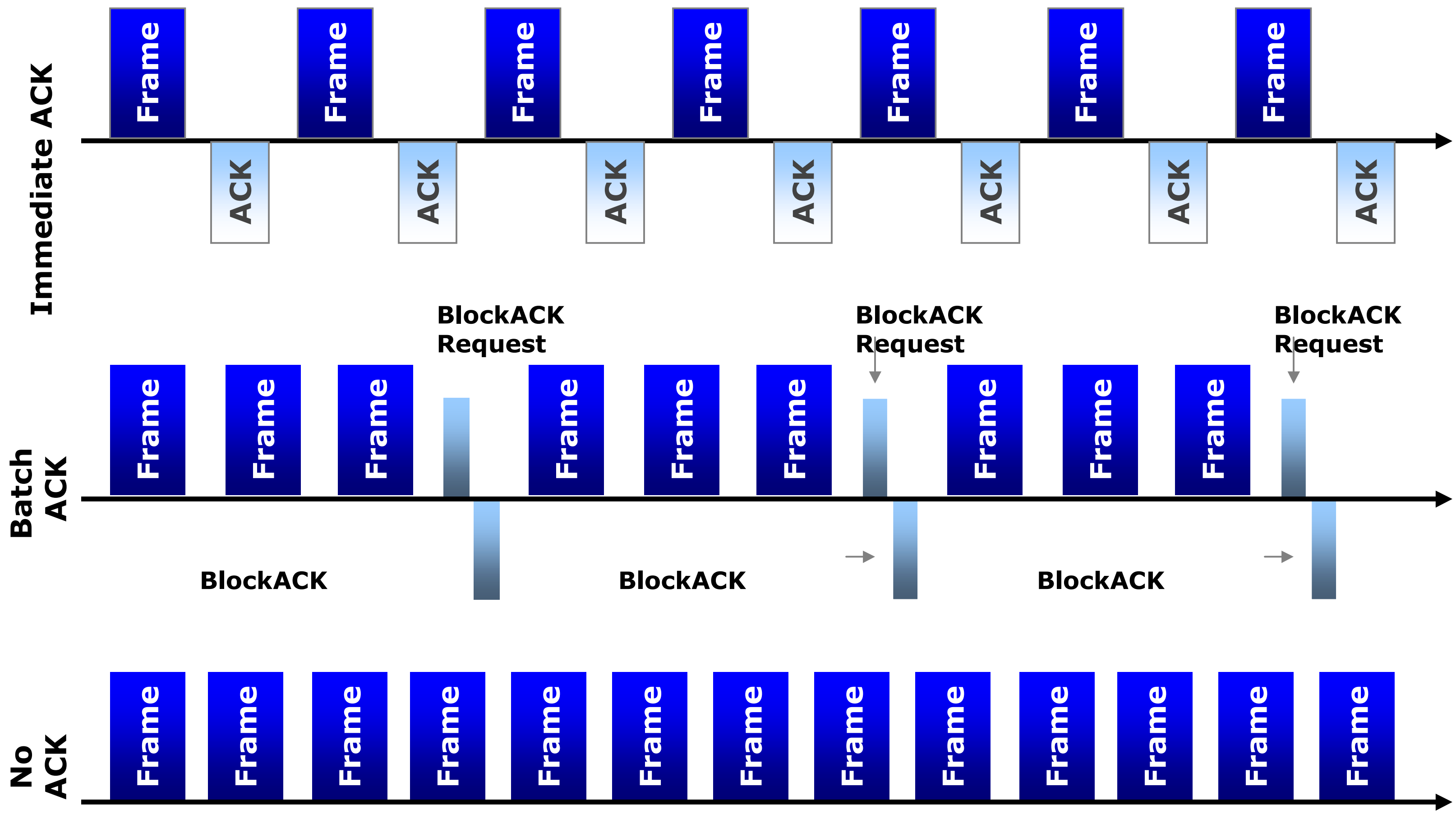
802.11n solution: burst transmission

- Burst/batch transmission:
  - For one channel contention (e.g., backoff, deference, etc), multiple frames, instead of a single frame will be transmitted.



802.11n solution: block acknowledgement

- Block Acknowledgement (BlockACK)
  - Use one ACK message to acknowledge multiple received frames



Cooperative Communications

Motivation

- Wireless channels
  - Bandwidth and power limited
  - Multi-user interference
  - Unreliable due to signal fading
  - Vulnerable to attacks
- Multimedia applications
  - High data rates
  - Error sensitive, delay intolerant
- We need
  - Higher transmission rates, reliability and security at the physical layer
  - End-to-end performance metrics
  - Cross-layer optimization

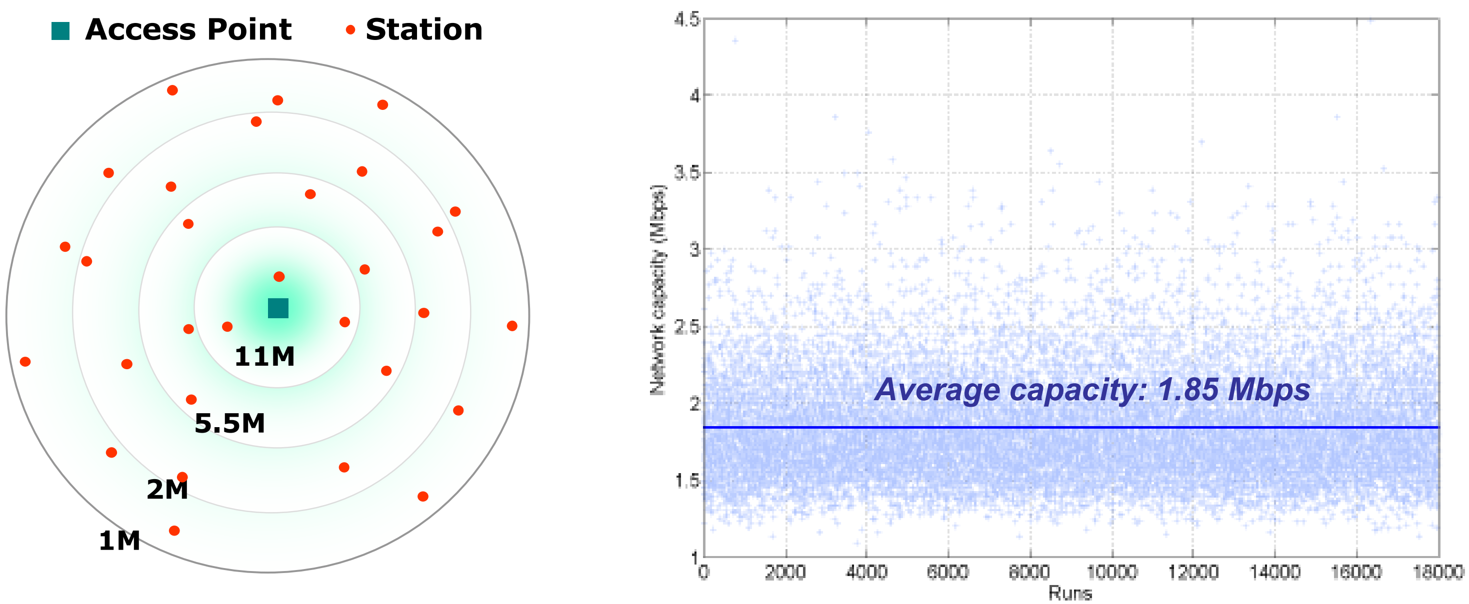
Cell edge problem

- Stations at the edge transmit at a much lower rate than stations in the center, 9Mbps vs 54Mbps for 802.11g networks.
- Packet transmission for station at the edge takes much longer time (around 9 times for 802.11g).
- Higher packet loss due to worse channel condition.
- Higher interference level at the cell edge.
- Cooperative communication can greatly improve the cell edge problem.

Service anomaly

- If a station transmits packets at low data rate, it needs much more channel time than the fast stations
- Each station has the same probability to grab the channel
- Low rate stations occupies the channel for most of the time
- Thus the aggregated network throughput is much lower than the highest supported rate

Service Anomaly in IEEE 802.11

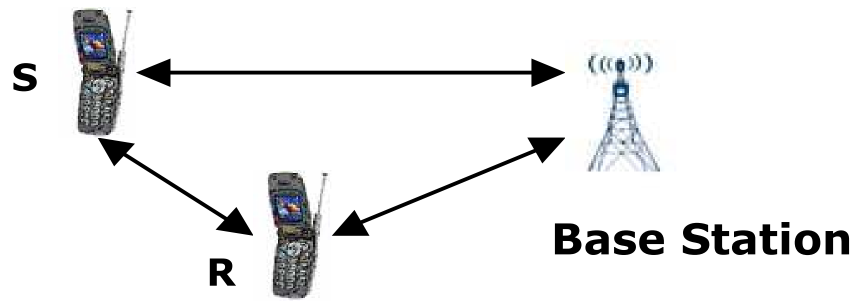


Cooperative networking

- Wireless devices helping each other communicate with other devices or fixed infrastructure

- Cooperation provides a good solution to many of the problems arising in wireless systems

How does cooperation work?



- Wireless antennas are omnidirectional
- Signals transmitted towards the destination can be “overheard” at the relay
- Relays process this overheard information and re-transmit towards the destination
  - Total resources (energy, bandwidth) are same as non-cooperative case
- Destination processes signals from both mobiles

Benefits of cooperation

- Higher spatial diversity
  - Resistance to shadow and small scale fading
- Opportunistic use of network energy and bandwidth
- Higher data rates, fewer retransmissions so less network delay
- Higher QoS
- Lower total transmitted energy which reduces interference and extends the battery life
- Extended coverage

Background

- Simple three terminal network
  - Information theoretic analysis:

  Van der Meulen (1971), Cover & El Gamal (1979)
- Applications to wireless
  - *Sendonaris, Erkip, Aazhang (1998, 2003)*
  - *Laneman, Tse, Wornell (2000, 2003)*

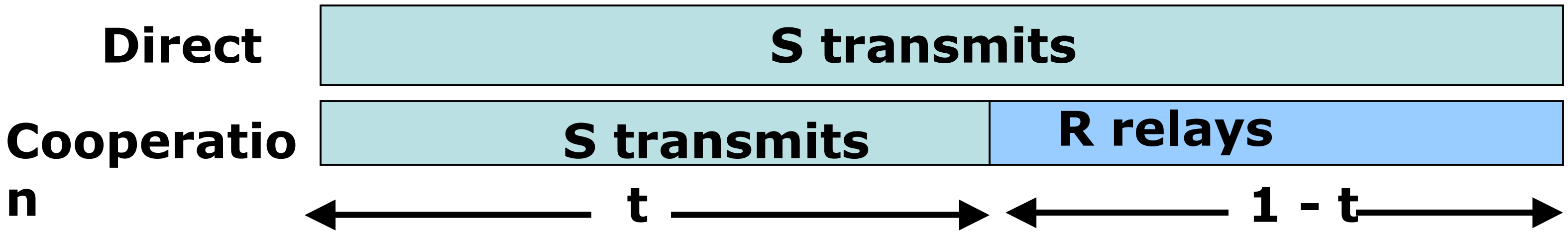
  …and many others
- Currently a “hot” research topic
- Also interest in industry, standardization (WiMAX, WiFi)

Cooperative networking

- Goal
  - A complete network solution utilizing cooperation at the physical, MAC, network and application layers and study cross-layer design
  - Security in cooperative networks
- Research topics
  - Physical layer / Information theory
  - Cooperative MAC
  - Cooperative multimedia
  - Cooperative security
  - Implementation

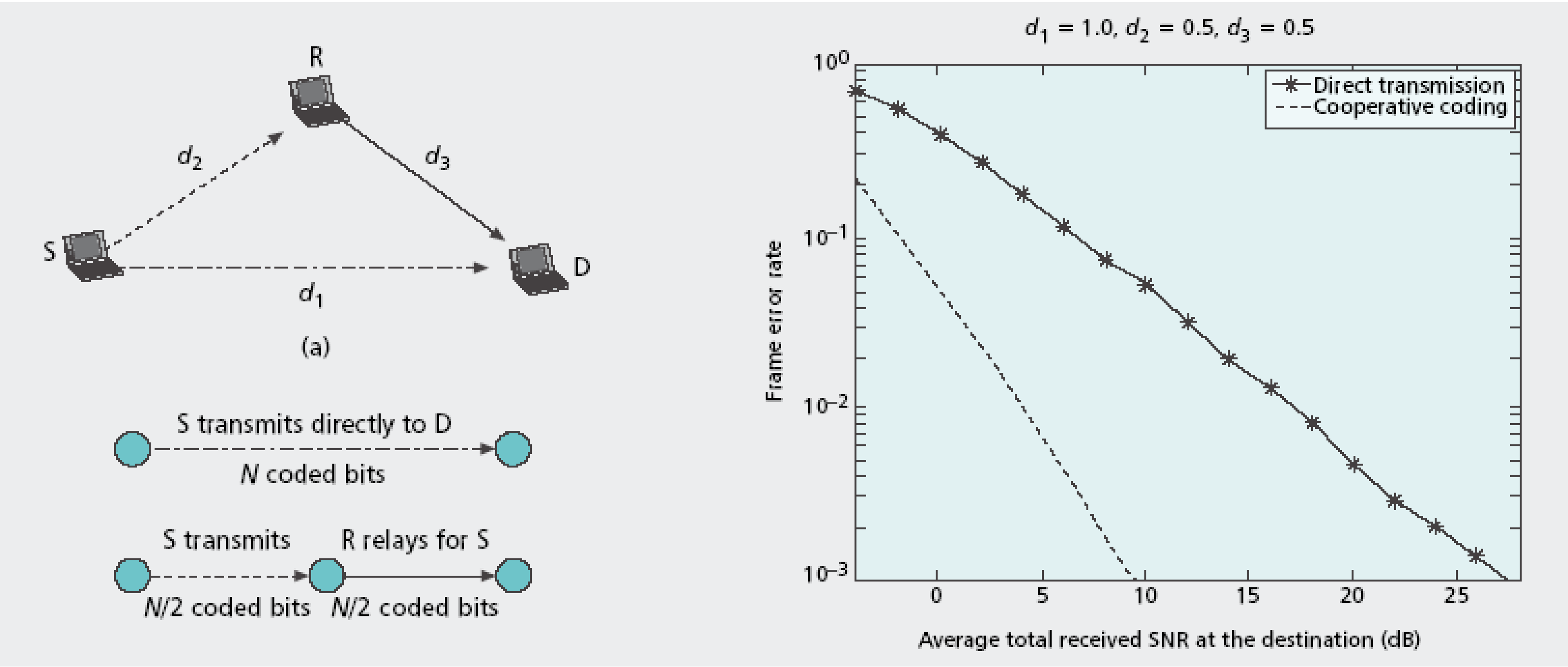
Cooperation protocols

- Simple orthogonal model



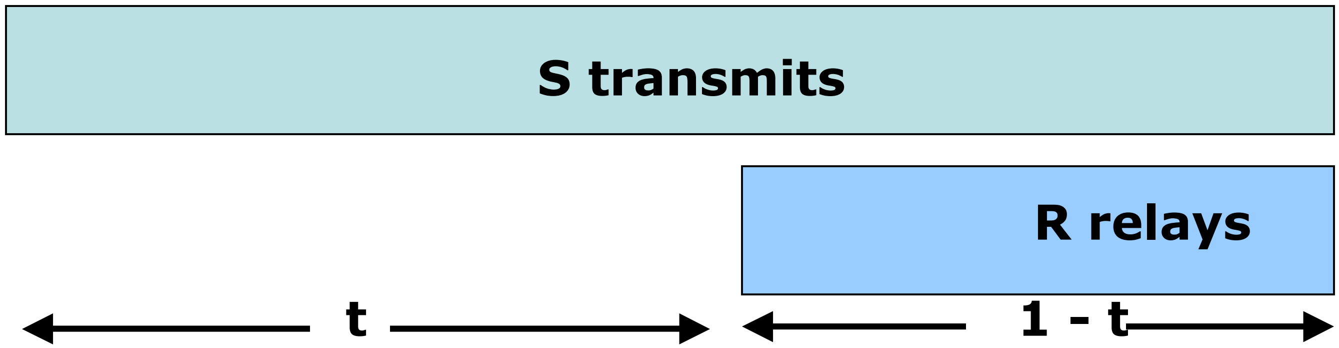
- Y_R: Received signal at the relay,
- $Y_D^{(i)}$: Signal at the destination for slot i, i=1,2
- Relay can
  - **Decode and forward (DF)** or **Cooperative Coding**
    - Repeat or transmit new parity bits
  - **Amplify and forward (AF)**
    - Forward Y_R (analog), t=1/2
  - **Compress and forward (CF)**
    - Compress Y_R using side information at the destination $Y_D^{(1)}$

Cooperative coding



Other protocols

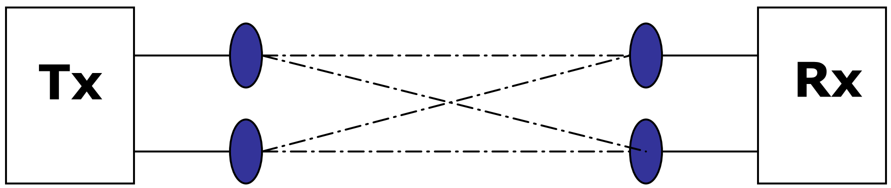
- Orthogonal: Spatial diversity, but loss in rate/spectral efficiency
- General half duplex



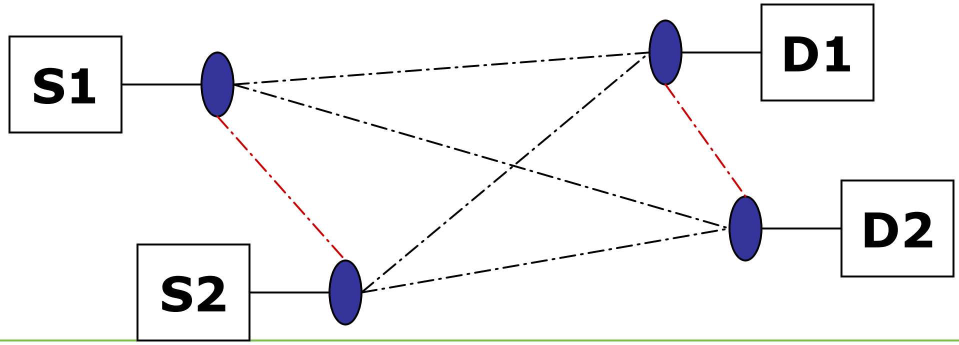
- Full duplex
  - Relay transmits and receives at the same time
- In general: What is the tradeoff between rate and reliability?

MIMO versus Cooperation

- **Multiple input-multiple output (MIMO)**
- **Spatial diversity and multiplexing gain**



- **Cooperation MIMO: Virtual MIMO, distributed antenna array**

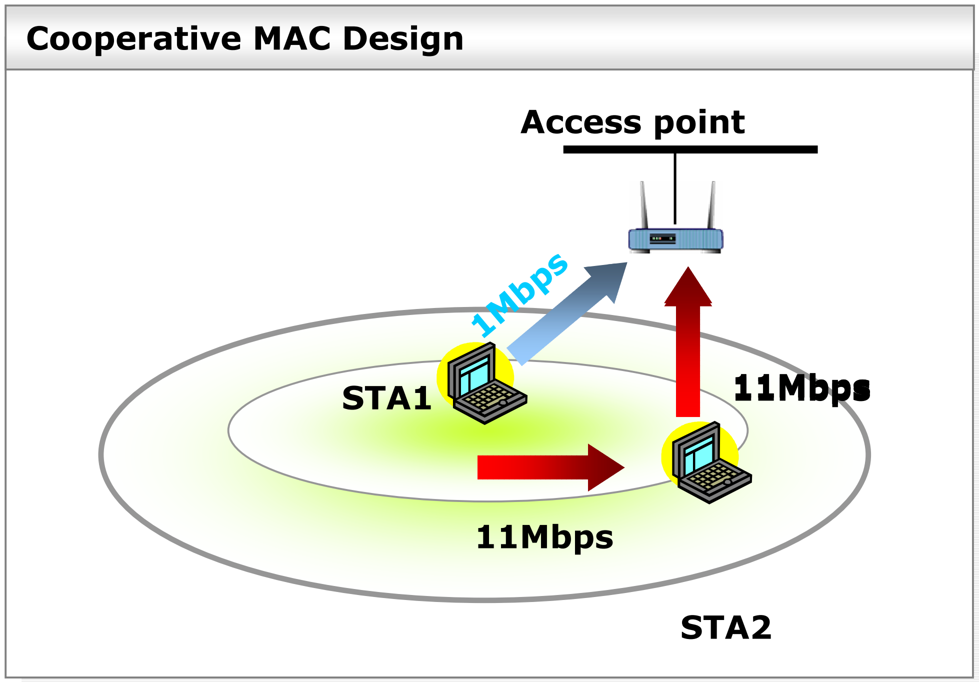


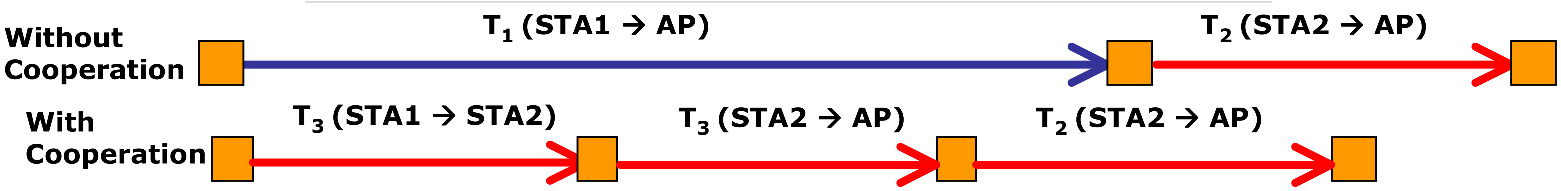
Cooperative MAC layer for IEEE 802.11

- What mechanism is required in the higher layer, such as MAC, to discover and fully utilize this technique?
- With the signaling overhead and limits, can we achieve these benefits?
- Will cooperative communications achieve benefit other than reliability, such as higher throughput, lower delay, etc?
- What benefits cooperative communications can bring to the whole network other than the nodes directly involved?

CoopMAC

- Leverage both the cooperation and multirate capabilities of the existing MAC protocol.
- By opportunistically cooperating between stations, it is possible to turn a Foe into a Friend

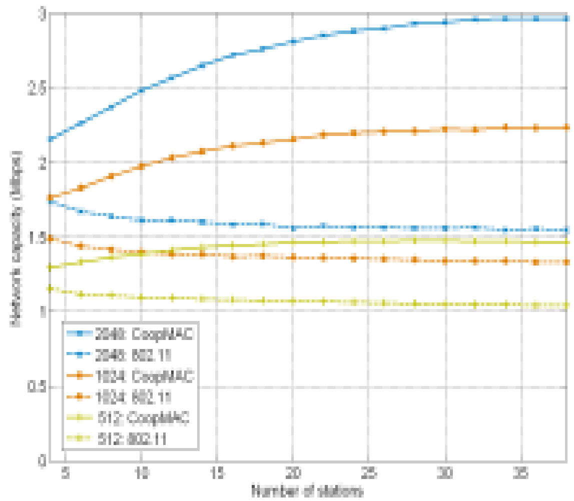




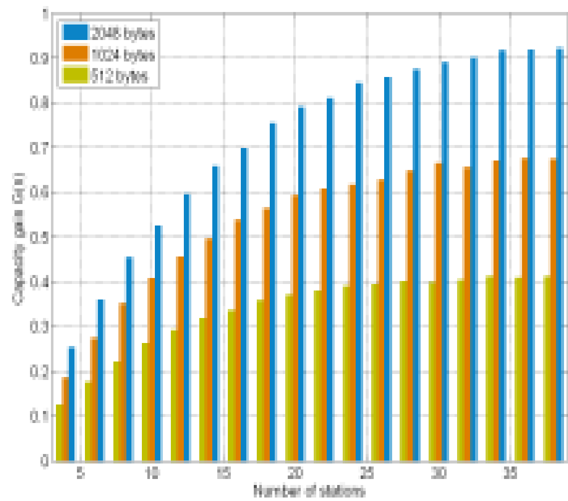
Performance improvement

- CoopMAC significantly boosts the network throughput.

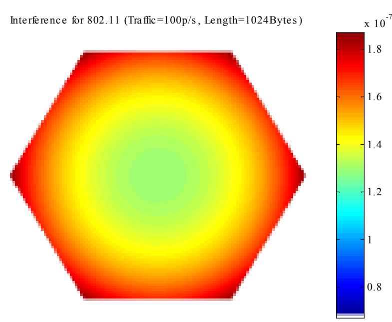
Capacity



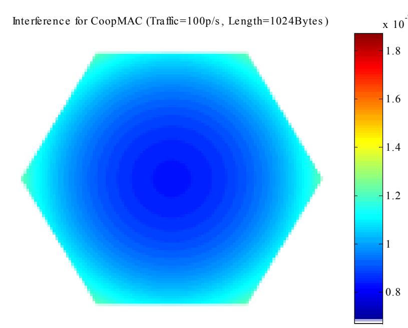
Capacity Gain



- Interference improvement.

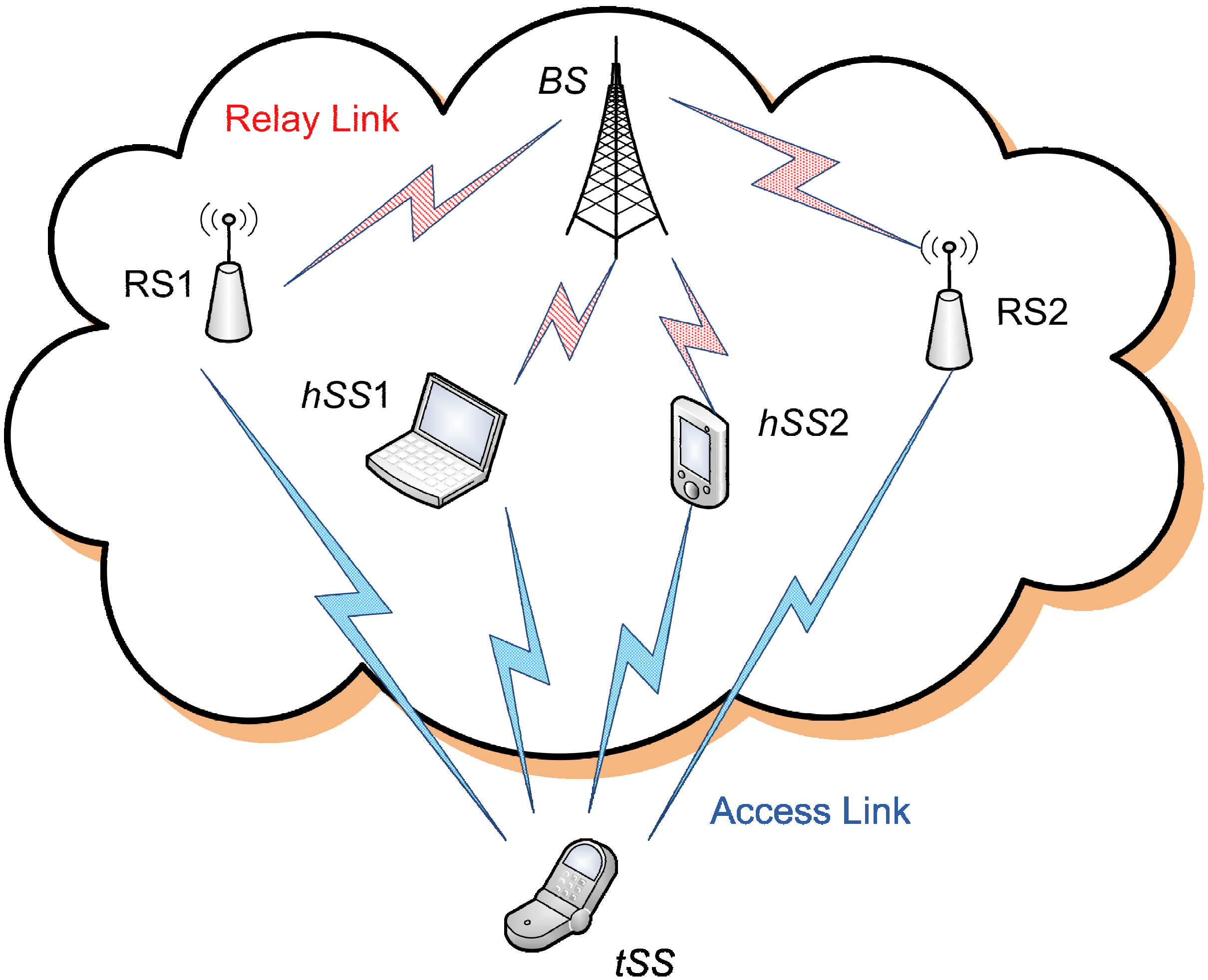


Non-cooperation



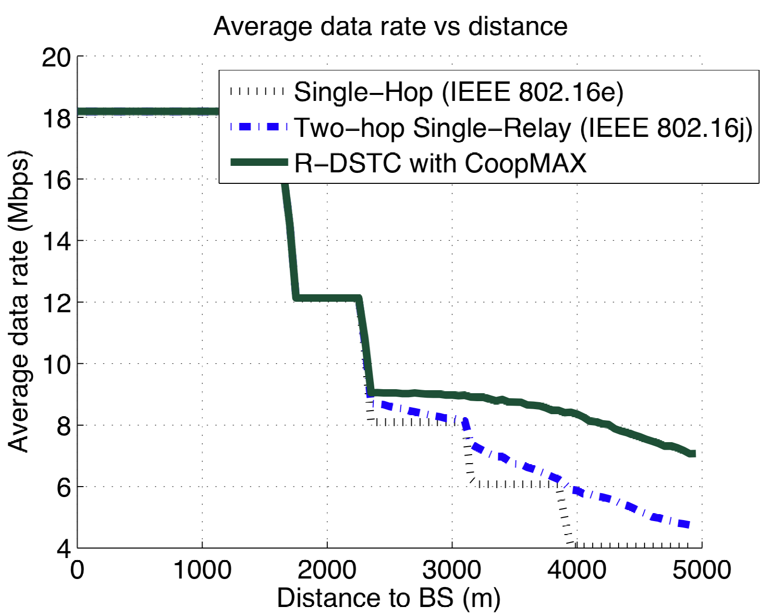
Cooperation

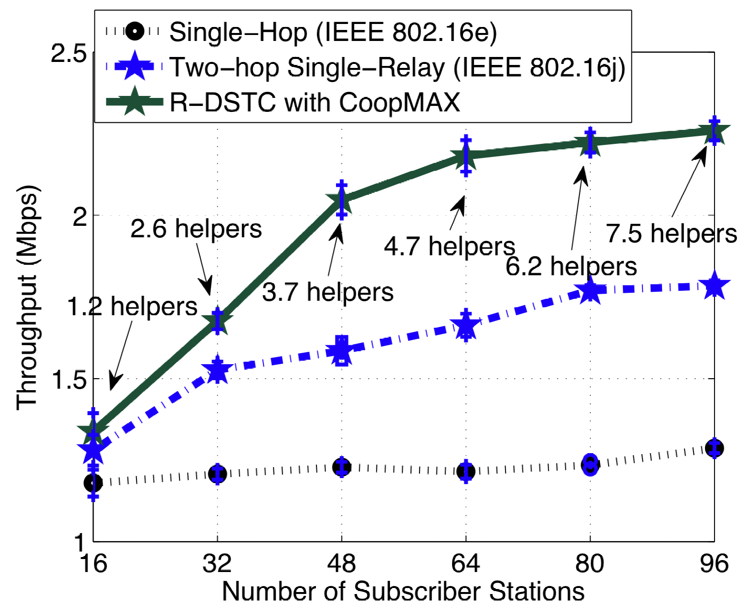
Cooperative MIMO in cellular network



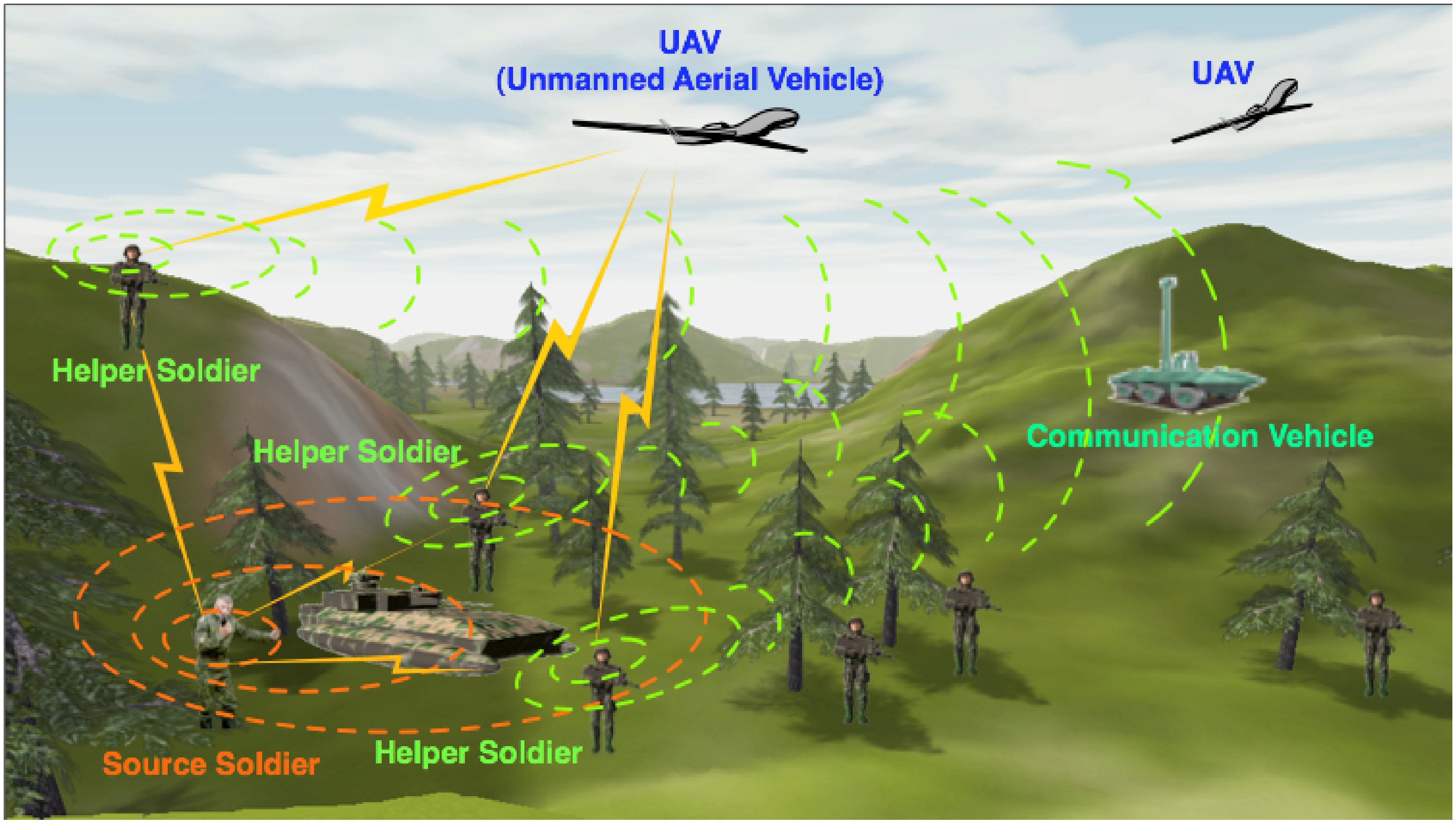
Cooperation in 802.16 WiMAX

- Cooperative MIMO using distributed space-time code





Cooperative MIMO in battlefield



Summary

- Enabling technologies for gigabit wireless network
  - MIMO
  - OFDM
  - Frequency domain equalization

- Efficient MAC/network layer for next generation wireless network
  - IEEE 802.16 (WiMAX)
  - 3GPP LTE
  - IEEE 802.11n (WiFi)

- Cooperative communications to improve spectrum efficiency and reliability
  - Cell edge improvement
  - Cooperative MIMO

Backup Slides

Motivation for QoS Capability

- Quality-of-Service (QoS) application over WLAN
  - Voice over IP (VoIP)
  - Video streaming
  - Wireless HDTV
  - Patient monitoring (wireless and mobile).
  - Home wireless networking devices (consumer electronic companies)

- Demand for consumer electronics (CE) connectivity is expected to increase by 5x by 2007 to $150 M (Park Associates)

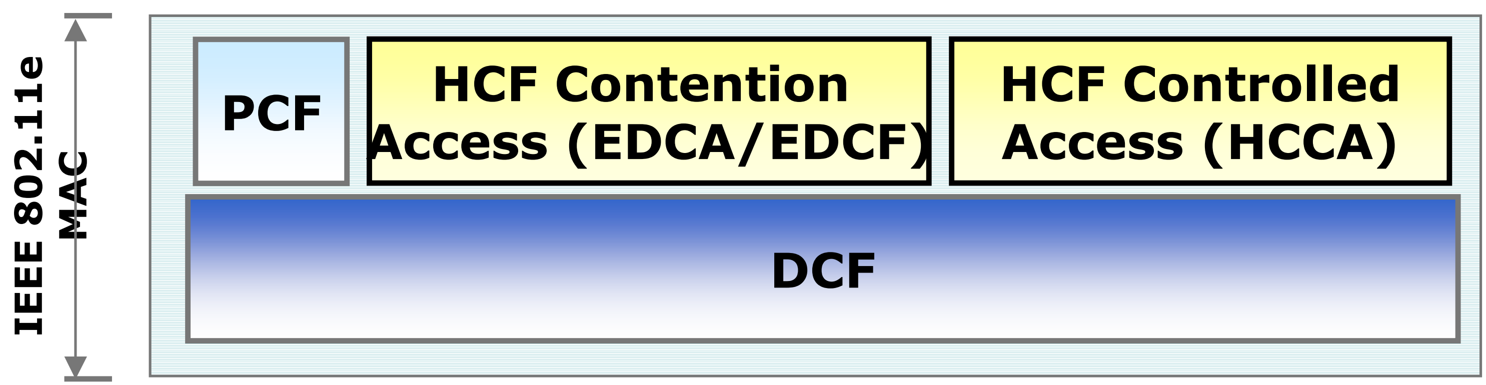
Legacy 802.11 Falls Short

Poor support for QoS in current 802.11, if exists at all!

- No QoS mechanism in DCF.
- Problems of PCF:
  - Unpredictable beacon delay: Ongoing transmission started in previous CP has variable length and may far exceed the time instance when next beacon is supposed to be sent.
  - Unknown transmission time of the polled station may affect other stations that are polled during the rest of CFP.
    - Variable length of the MSDU (up to the max of 2304 bytes, or 2312 bytes with encryption)
    - Different modulation and coding schemes, which is beyond the control of the PC.

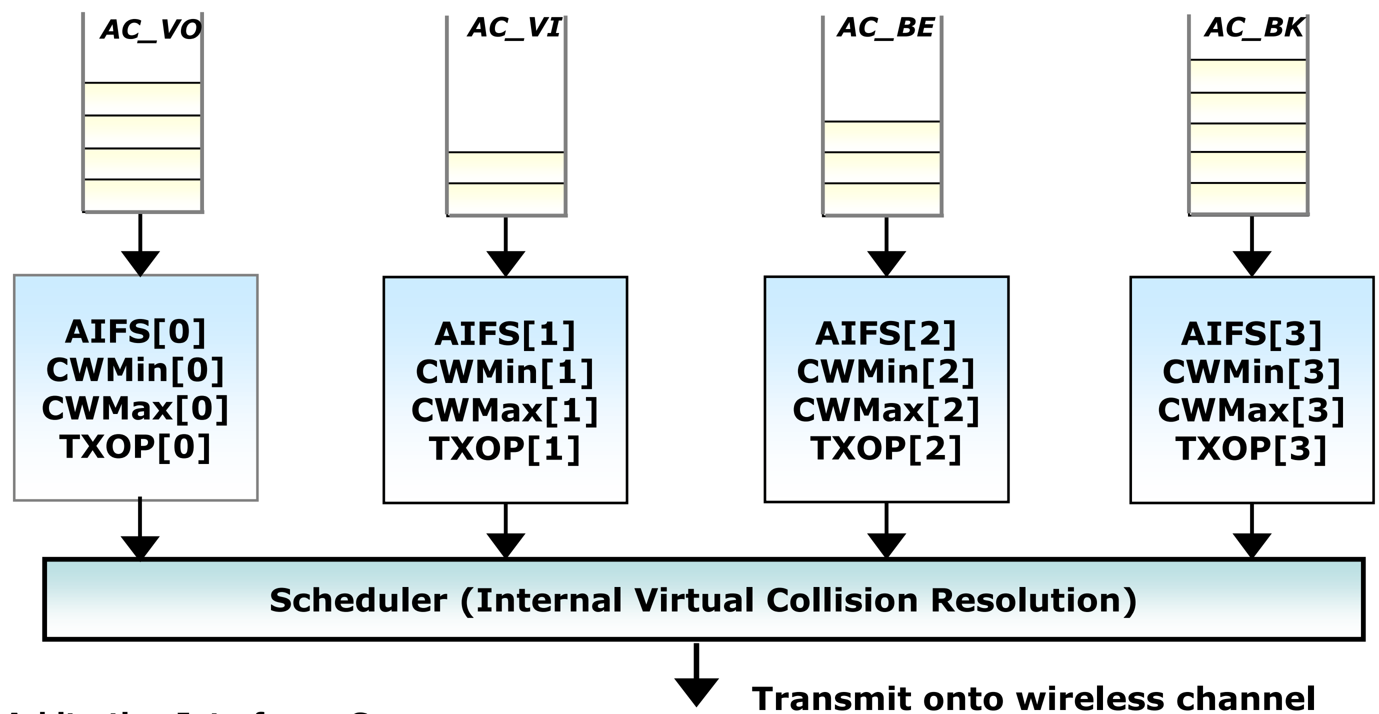
IEEE 802.11e: Overview

- The IEEE 802.11e working group was established to enhance the QoS capability of current WLAN.
- IEEE 802.11e modifies MAC layer only and defines an additional coordination function hybrid coordination function (HCF):
  - Combine DCF and PCF with some QoS-specific enhancements.
  - Contain
    - Enhanced Distributed Channel Access (*EDCA*), a.k.a Enhanced DCF mode (*EDCF*): Contention period.
    - HCF controlled channel access (*HCCA*): Contention-free period.



IEEE 802.11e: Multiple Queues

- Multiple FIFO queues in the MAC
  - Four access categories (AC), and eight priorities. (802.1D)
- Every queue is an independent contention entity with its own contention parameters
  - CWMin[AC], CWMax[AC], AIFS[AC], TXOP[AC]
- Internal virtual collision resolution mechanism



AIFS: Arbitration Interframe Space

IEEE 802.11e: An Illustration