Slide supporting material

Lesson 10: WiFi and WiMAX MAC Analysis

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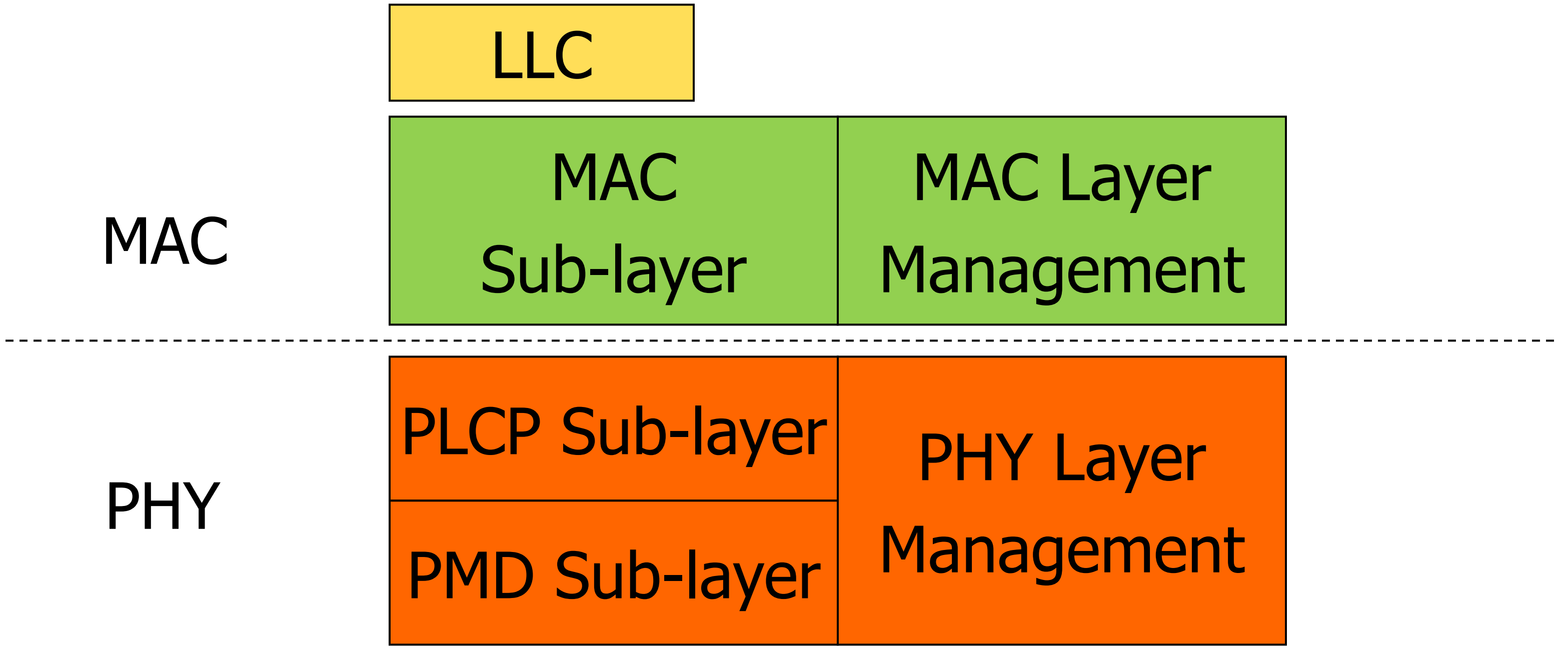
WiFi Description

802.11 Scope & Modules

To develop MAC and PHY specifications for wireless connectivity for fixed, portable, and moving terminals in a local area.



ISM Frequency Bands

- Industrial, Scientific, and Medical (ISM) bands were originally reserved for the use for industrial, scientific and medical purposes other than communications. An example of use is microwave ovens. The emissions of these devices can create electromagnetic interference with radio communications using the same frequency.
- The most common ISM bands for wireless systems are:
  - 2.4 - 2.4835 GHz
  - 5.725 - 5.875 GHz

The Classical IEEE 802.11 Wireless System

- The **classical IEEE 802.11 system** (1997) is characterized by a channel bit-rate of 1 or 2 Mbit/s in the ISM frequency band at 2.4-2.4835 GHz with two different wireless transmission techniques:
  - Direct Sequence Spread Spectrum (DSSS),
  - Frequency Hopping Spread Spectrum (FHSS).
- **These spread spectrum techniques are used to reduce the interference produced by other devices that use ISM frequencies (e.g., microwave ovens, cordless phones, Bluetooth and other appliances).**
- There is also the possibility of infrared transmissions with a wavelength in the range from 850 and 950 nm.

IEEE 802.11a/b/g/n/ac

- The **IEEE 802.11a standard (1999)** operates in the frequency bands 5.15-5.35 GHz, 5.725-5.825 GHz and has a physical layer based on Orthogonal Frequency Domain Multiplexing (OFDM), with a transmission capacity up to 54 Mbit/s.

- The **IEEE 802.11b standard (1999)** is an improvement of the DSSS physical layer, named High-Rate DSSS (HR-DSSS) in the 2.4 GHz ISM band, delivering up to 11 Mbit/s. Note that IEEE 802.11b supports both DSSS mode for lower bit-rates at 1 and 2 Mbit/s and the HR-DSSS mode for higher bit-rates at 5.5 and 11 Mbit/s.

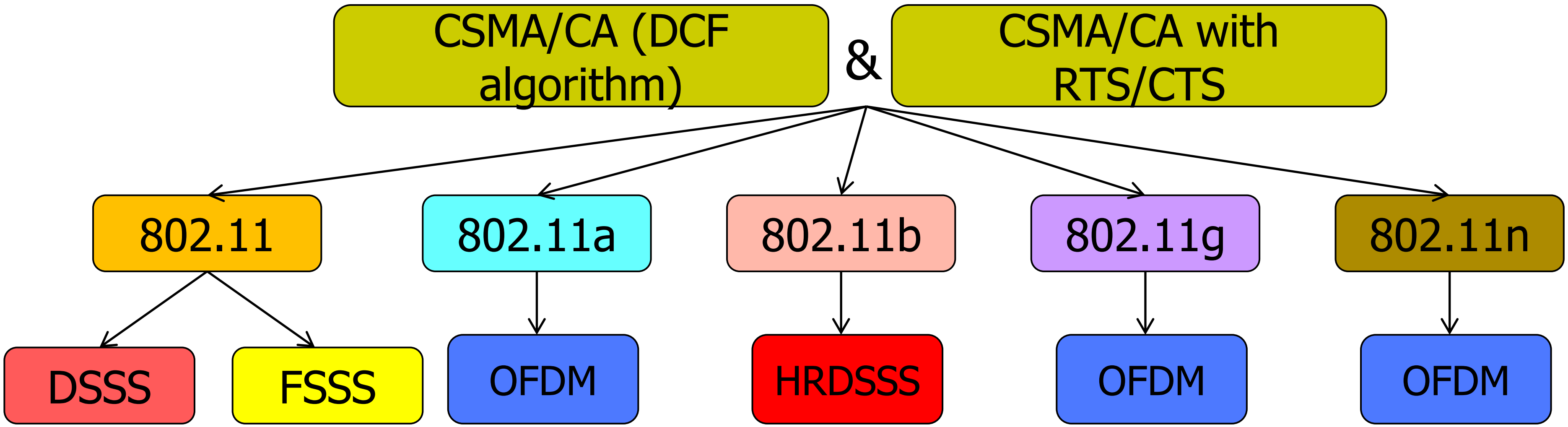
IEEE 802.11a/b/g/n/ac (cont'd)

- The **IEEE 802.11g amendment (2003)** is a standard for WLANs still in the 2.4 GHz band, which achieves high bit-rate transmissions (the maximum bit-rate is 54 Mbit/s) with an OFDM-based physical layer. IEEE 802.11g is fully interoperable with IEEE 802.11b.

- **IEEE 802.11n (2009)** is a new standard with an OFDM air interface and Multiple Input -Multiple Output (MIMO) antennas. 802.11n operates in both 2.4 GHz and 5 GHz ISM bands. The maximum data rate goes from 54 Mbit/s up to 600 Mbit/s (10 times faster than IEEE 802.11g).

- The new **IEEE 802.11ac standard** further increases the link throughput above 500 Mbit/s, operating in the 5 GHz ISM band.

WiFi PHY Options



- 1 Mbit/s
- 2 Mbit/s

- 1 Mbit/s
- 2 Mbit/s

- 6 Mbit/s
- 12 Mbit/s
- 24 Mbit/s
- 54 Mbit/s

- 5 Mbit/s
- 11 Mbit/s

- Up to 54 Mbit/s

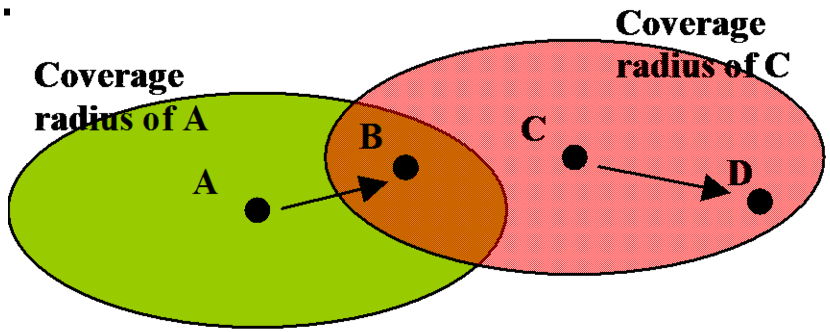
- Up to 600 Mbit/s

WiFi Topologies

- Three different network topologies are available for WiFi as follows:
  - **Independent Basic Service Set (IBSS)**
  - **Basic Service Set (BSS)**
  - **Extended Service Set (ESS).**
- An IBSS consists of a group of WiFi terminals communicating directly each other in an ad hoc mode (peer-to-peer operation mode). A BSS is a group of terminals, which do not communicate directly with each other, but only through the **Access Point (AP)**, a specialized station. Many APs with the related BSSs can be interconnected to a backbone system; the set of BSSs and DS forms the Extended Service Set (ESS).

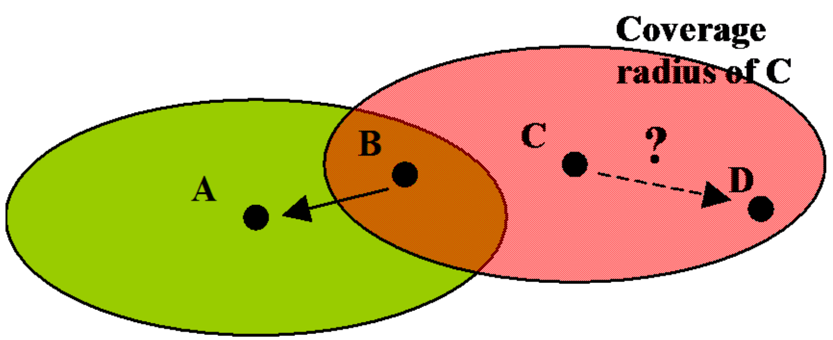
Interf. from Adjacent Cells: Hidden Terminal Problem

- Let us assume to use a generic carrier sense multiple access protocol in a wireless LAN: a terminal listen to the channel before transmitting to avoid interference.
- While node (terminal) A is transmitting to node B, node C verifies that there is no concurrent transmission and decides to send a message to node D. However, the transmissions of A and C **collide** to terminal B that, therefore, cannot correctly receive the message sent by A.
- The problem is that **terminal C (i.e., hidden terminal)** cannot 'see' the simultaneous transmission of A since C is beyond the radius of coverage of A.



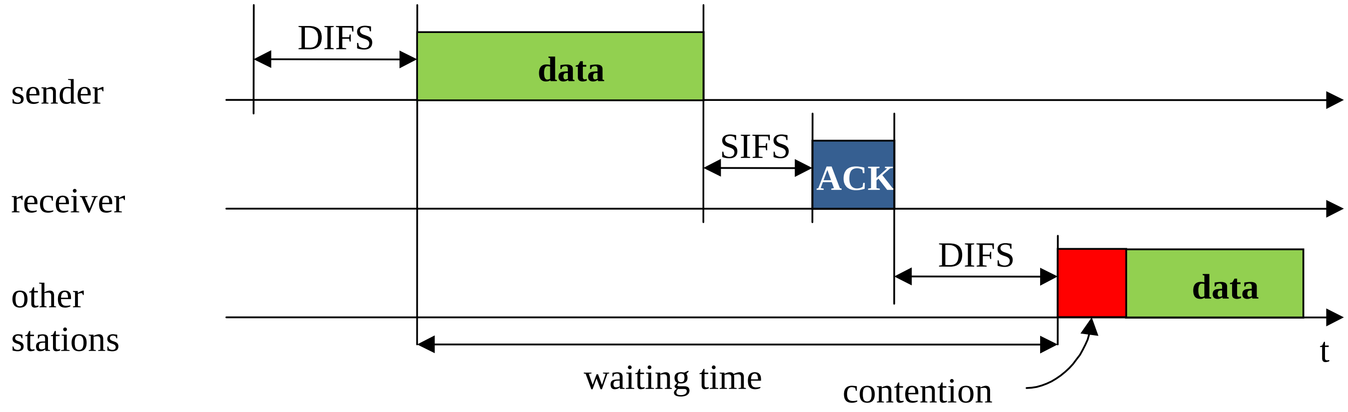
Interf. from Adjacent Cells: Exposed Terminal Problem

- While B is transmitting to node A, terminal C would like to send data to node D, but C does not transmit since C perceives an occupied channel due to the transmission of B (false carrier sense). Hence, C does not transmit to D even if could do so without generating any collision with the transmission to A. **Terminal C is the exposed terminal**.



MAC: Distributed Coordination Function (DCF)

- A Station (STA), needing to transmit a frame, senses the medium to determine if another STA is transmitting:
  - If idle, the STA verifies that the medium is idle for a specific time, DIFS (DCF Inter-Frame Space). Once DIFS elapses, a transmission is made.
  - If busy, STA shall defer until the end of the current transmission.
    - STA waits for another DIFS. If the medium is still idle, the STA selects a random backoff interval and decrements this backoff counter while the medium is idle.
    - Finally, if the medium is idle, the STA transmits.



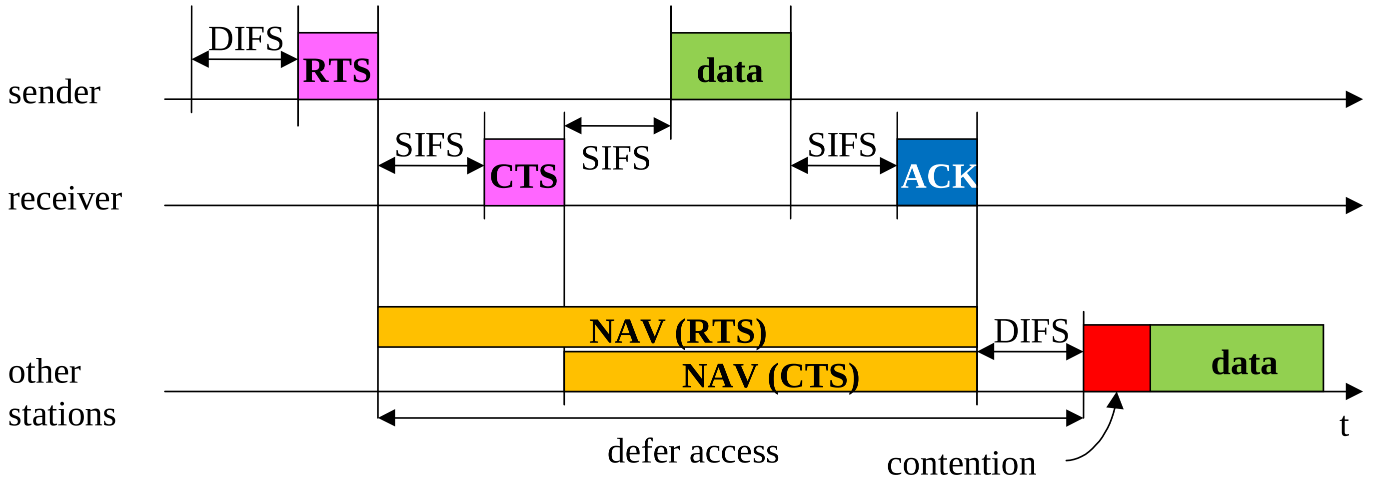
DCF Algorithm: Carrier Sensing

- In IEEE 802.11, carrier sensing is needed to determine if the medium is available. There are two methods:
  - A **physical carrier-sense function** is provided by the PHY layer and depends on the medium and modulation used.
  - A **virtual carrier-sense mechanism** is provided by the Network Allocation Vector (NAV), a ‘parameter’ managed by the MAC layer.
- The channel is busy if one of the two above mechanisms indicate it to be.
- If a terminal experiences a packet collision, the backoff window is doubled at the next attempt.

Enhanced DCF Algorithm: CSMA/CA with RTS/CTS

The Request-to-Send/Clear-to-Send (RTS/CTS) scheme to enhance the basic DCF scheme is described as follows:

- It could happen that some STAs are in the range of the AP, but neither of them is in the range of each other. If these STAs transmit at the same time, the carrier-sense mechanism fails and there is a collision.
- To solve the **hidden terminal problem**, the DCF protocol is enriched with the RTS/CTS signals to clear out an area. Once the RTS/CTS exchange is complete, the sender transmits its frame without risk of collisions.



The RTS/CTS scheme is convenient only for sufficiently long data messages.

IEEE 802.11e: Enhanced MAC for QoS Support in WiFi

- The main problem with DCF is that all traffic flows are managed as **best effort**: real-time traffic cannot be supported with adequate Quality of Service (QoS) levels since collisions delay transmissions.
- Point Coordination Function (PCF) is an optional contention-free access scheme for time-bounded delay-sensitive transmissions used in combination with DCF. Even if PCF avoids time wasted in collisions, PCF cannot assure a good QoS level, because there are unpredictable beacon delays and unknown transmission durations of the polled STAs.
- These are the reasons why the IEEE 802.11e standard has been proposed to provide QoS support in WiFi (IEEE 802.11 a/b/g/n). At MAC layer, the Hybrid Coordination Function (HCF) mechanism is considered.
  - HCF has two modes: a contention-based access method, called Enhanced Distributed Channel Access (EDCA) and a contention-free (polling-based) transfer, called HCF Controlled Channel Access (HCCA).
  - EDCA and HCCA operate together according to a superframe structure.
  - **A new feature of HCF is the concept of transmission opportunity (TXOP)**. The aim of TXOP is to limit the time interval for which an **STA (now called QoS-enabled STA, QSTA)** is allowed to transmit frames.

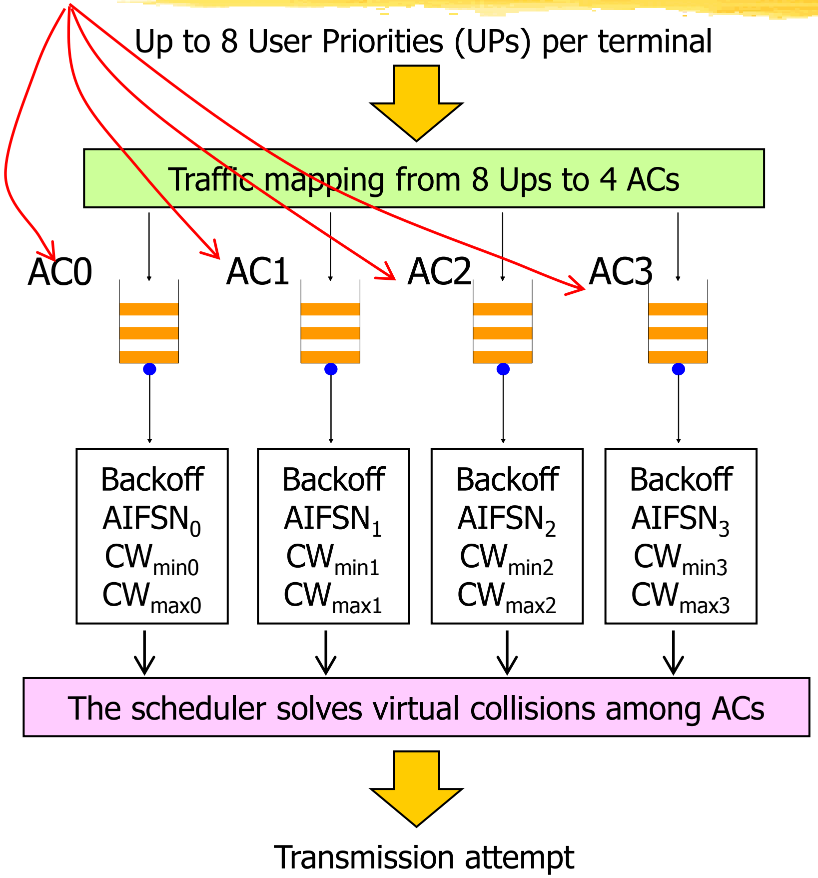
S. Mangold, Choi Sunghyun, G.R. Hiertz, O. Klein, B. Walke, "Analysis of IEEE 802.11e for QoS support in wireless LANs", *IEEE Wireless Communications*, Vol. 10, No. 6, pp. 40-50, Dec. 2003.

IEEE 802.11e: Enhanced MAC for QoS Support (cont'd)

- EDCA access is an extension of the DCF mechanism to include **eight priority levels** and **four Access Categories** (ACs), typically voice, video, best effort, and background (different priority levels can be used within an AC).
  - **The following quantities depend on AC: minimum and maximum contention window value, the maximum TXOP value (TXOP$_{lim}$) and the IFS time interval between the transmissions of frames**, now called, Arbitration Inter Frame Space (AIFS), substituting the DIFS interval of legacy WiFi.
- After a collision, a new Contention Window (CW) value is calculated on the basis of the Persistence Factor (PF).
- Priority mechanisms:
  - Shorter backoff intervals can be considered for high-priority traffic so that they successfully contend.
  - If two QSTAs need to transmit at the same time, the QSTA with the shorter AIFS will obtain a successful access.
  - In the classical 802.11 standard, CW is always doubled after any unsuccessful transmission, whereas 802.11e uses PF to increase the CW for each AC.
- **EDCA has a queue for each AC at the QSTA. Each queue (implementing the EDCA contention algorithm) provides frames to an independent channel access function.**
- HCCA uses a Hybrid Coordinator (HC) to centrally manage the medium access according to a polling-like approach.

QoS Classes in 802.11e

4 MAC layer queues for QoS differentiation



AC3 and AC2 are used for real-time applications (e.g., voice or video transmissions); AC1 and AC0 are used for best effort and background traffic (e.g., file transfer, email).

ACs map directly from Ethernet-level Class of Service (CoS) priority levels.

Priority	UP, User Priority (Same as 802.1d)	802.1D Designation	802.11e AC (Access Category)	Service type
lowest	1	Background (BK)	0	Best Effort
	2	Not defined	0	Best Effort
	0	Best Effort (BE)	0	Best Effort
	3	Excellent Effort (EE)	1	Video Probe
	4	Controlled Load (CL)	2	Video
	5	VI (Video<100 ms latency and jitter)	2	Video
	6	VO (Video<10 ms latency and jitter)	3	Voice
highest	7	Network Control (NC)	3	Voice

Parameters for EDCA of IEEE 802.11e

- The appropriate selection of the AC parameters is an interesting task that has to be related to the characteristics of higher layers protocols, the adopted applications, the related QoS requirements, the number of users and the traffic load.

- The AP can use beacon frames to update the QSTAs about the new values for AIFS, CW_{min}, CW_{max} and $TXOP_{lim}$ for the different ACs to cope with varying system conditions.

Parameters for EDCA of IEEE 802.11e (cont'd)

- The CW_{min} and CW_{max} values have a coarse granularity; their values must belong to the set $\{2^X - 1\}$, where X is a number with four binary digits. Correspondingly, CW_{min}, CW_{max} belong to the set {0, 1, 3, 7, 15, 31, 63, 127, 255, 511, 1023, 2047, 4095, 8191, 16383, and 32767}.
- $TXOP_{lim}$ is a multiple of 32 μs in the range [0, 8160] μs. A $TXOP_{lim}$ equal to 0 denotes that one single packet can be transmitted at any rate.
- The minimum AIFSN value is 2. The AIFS values are obtained from AIFSN according to the following formula: AIFS [μs] = AIFSN x slot_time + SIFS. The value of slot_time depends on the PHY type.

Default Values

- An allocation scheme for the different parameters (e.g., CW_{min}, CW_{max}) of the four ACs has been defined in the standard:

AC	CW_{min}	CW_{max}	AIFSN	$TXOP_{lim}$ (802.11g)
AC_BK	aCW_{min}	aCW_{max}	7	0
AC_BE	aCW_{min}	aCW_{max}	3	0
AC_VI	$(aCW_{min}+1)/2-1$	aCW_{min}	2	3.008 ms
AC_VO	$(aCW_{min}+1)/4-1$	$(aCW_{min}+1)/2-1$	2	1.504 ms

- Example of numerical configuration:

AC	Cw_{min}	CW_{max}	AIFSN	$TXOP_{lim}$ (802.11g)
AC_BK	31	1023	7	0
AC_BE	31	1023	3	0
AC_VI	15	31	2	3.008 ms
AC_VO	7	15	2	1.504 ms

WiFi Analysis

Bianchi's Model for WiFi (Saturation Analysis)

- This study has been carried out for both the basic CSMA/CA access scheme and the RTS/CTS scheme.
- Assumptions:
  1. **Ideal channel conditions** (i.e., no hidden terminals and capture).
  2. **Finite number of terminals** *n*.
  3. **Perfect channel sensing** by every station (collision may occur only when two or more packets are transmitted within the same time slot).
  4. **Saturation assumption**: the transmission queue of each station is assumed to be always non-empty: after each packet transmission each station has soon available another packet that has to undergo a backoff procedure to be transmitted.
  5. **Constant and independent collision probability** *p* of a packet transmitted by each station, regardless of the number of retransmissions already made.
  6. **No retry limit**.
  7. **ACK timeout time** is neglected.

G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function", *EEE Journal Sel. Areas. in Comms.*, Vol. 18, No. 3, pp. 535-547, 2000.

Definitions and Notations

- **Saturation throughput is the maximum load that the system can carry.**
- S denotes the normalized system throughput, that is the percentage of time the channel is used to successfully transmit a packet.
- σ denotes the **slot duration** in the backoff phase. σ depends on the PHY type of WiFi.
- H denotes the packet header length, including PHY and MAC headers.
- δ denotes the (max) propagation delay in a WiFi cell.
- Parameter τ **denotes the stationary probability that a station transmits a packet in a generic 'slot time'**.
- W is the minimum window size used at the first transmission attempt with the backoff procedure. At each reattempt the window size doubles. We consider m **stages**, so that the windows size can vary from W up to $2^m W$.

Model of the Backoff Procedure

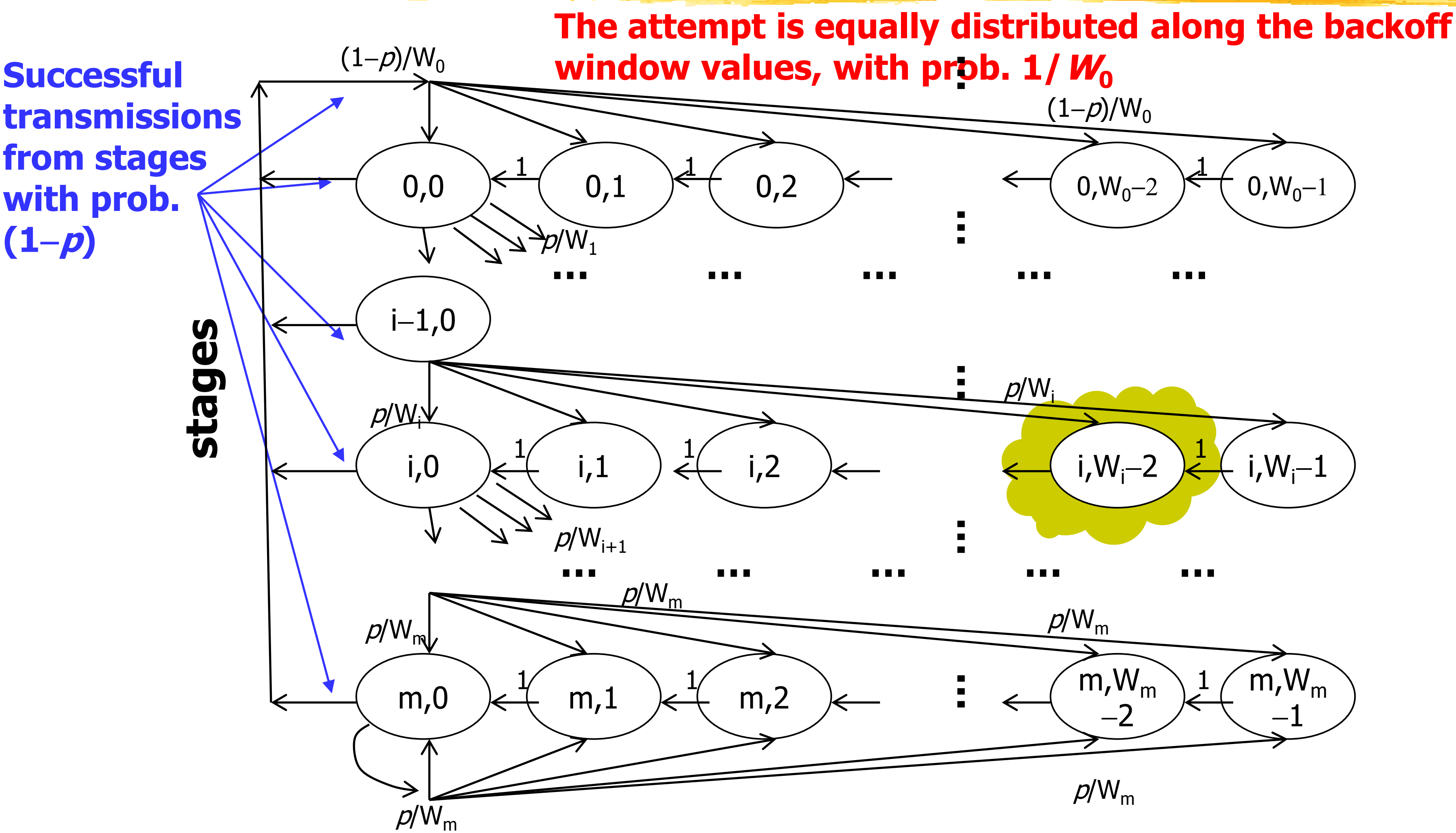
- **As soon as a station ends to transmit a packet, a new backoff procedure is started since another packet is soon available (saturation assumption**, maximum load condition).

- We consider the system evolving on a **suitable time slot basis: in this study a time slot denotes the variable time interval between two consecutive backoff time counter decrements.** This slot time is not the PHY slot time σ since the backoff time decrement is stopped when the channel is sensed busy (this slot time may be bigger than σ).

- We consider an **imbedded system (at the time slot level)** that allows a 2D state to be defined depending on the **stage level** $i \in \{0, 1, \ldots, m\}$ and on the **backoff counter value** $k \in \{0, 1, \ldots, W_i - 1\}$.

- Let $b_{i,k}$ denote the probability that a station is in the state $\{i, k\}$. We obtain the state diagram shown in the next slide.

Model of the Backoff Procedure (cont'd)



Solution of the State Diagram

- Equilibrium conditions are written for each state equating the input rate to the output one; for instance for the state *i*, $W_i - 2$ we may write:

$$b_{i,W_i-2} = b_{i,W_i-1} + p b_{i-1,0} / W_i$$

- We sum the equilibrium conditions (member to member) along a row and we obtain the state probabilities:

$$b_{i,0} = p^i b_{0,0} \quad 0 < i < m \qquad b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \quad 0 < i < m$$

$$b_{m,0} = \frac{p^m}{1-p} b_{0,0} \qquad b_{0,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW\left[1-(2p)^m\right]}$$

Solution of the State Diagram (cont'd)

- We can now express the probability τ that a station transmits in a randomly-chosen slot time. As any transmission occurs when the backoff time counter is equal to zero, regardless of the backoff stage level i, we have:

$$\tau = \sum_{i=0}^{m} b_{i,0}$$

- To find the value of *p* it is sufficient to note that the probability that a transmitted packet encounters a collision, is the probability that, in a time slot, at least one station of the $n - 1$ remaining ones transmits.

$$p = 1 - (1 - \tau)^{n-1}$$

Solution of the State Diagram (cont'd)

- A system of non-linear equations in the unknown *p* and τ is obtained:

$$\begin{cases} \tau = \dfrac{2(1-2p)}{(1-2p)(W+1)+pW\left[1-(2p)^m\right]} \\ p = 1-(1-\tau)^{n-1} \end{cases}$$

The numerical solution of this p – τ system is provided in Lesson No. 19 by means of Matlab®.

- This system admits a single solution that depends on parameters: *W*, *n*, and *m*. We can thus implicitly consider that $\tau = \tau(W, n, m)$. **Note that *n* is a given parameter, while *W* and *m* could be tuned to optimize the throughput of the WiFi access protocol.**

WiFi Throughput

- The normalized throughput *S* can be obtained as the ratio of the average payload size successfully transmitted in a slot time and the average duration of a slot time (considering that it can be idle, successful, or affected by collisions):

$$S = \frac{P_s P_{tr} E[P]}{(1-P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1-P_s) T_c}$$

where P_s is the probability that a transmission occurring in the channel is successful, P_{tr} is the probability that there is at least a transmission in the slot, T_c is average time the channel is sensed busy in a slot with a collision, T_s is the average time the channel is sensed busy in a slot with a successful transmission, $E[P]$ is the average payload length.

$$P_{tr} = 1-(1-\tau)^n \quad \text{and} \quad P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}}$$

WiFi Throughput (cont'd)

- T_c and T_s parameters for the basic CSMA/CA scheme and the RTS/CTS one are computed as follows:

$$\begin{cases} T_s^{bas} = H + E[P] + SIFS + \delta + ACK + DIFS + \delta \\ T_c^{bas} = H + E[P^*] + DIFS + \delta \end{cases}$$

$$\begin{cases} T_s^{rts} = RTS + SIFS + \delta + CTS + SIFS + \delta + H + E[P] + SIFS + \delta + ACK + DIFS + \delta \\ T_c^{rts} = RTS + DIFS + \delta \end{cases}$$

Note that SIFS, DIFS and σ values depend on the WiFi PHY type.

Maximum WiFi Throughput

- The S expression depends on τ and many parameters, like T_s, T_c, σ, and $E[P]$.

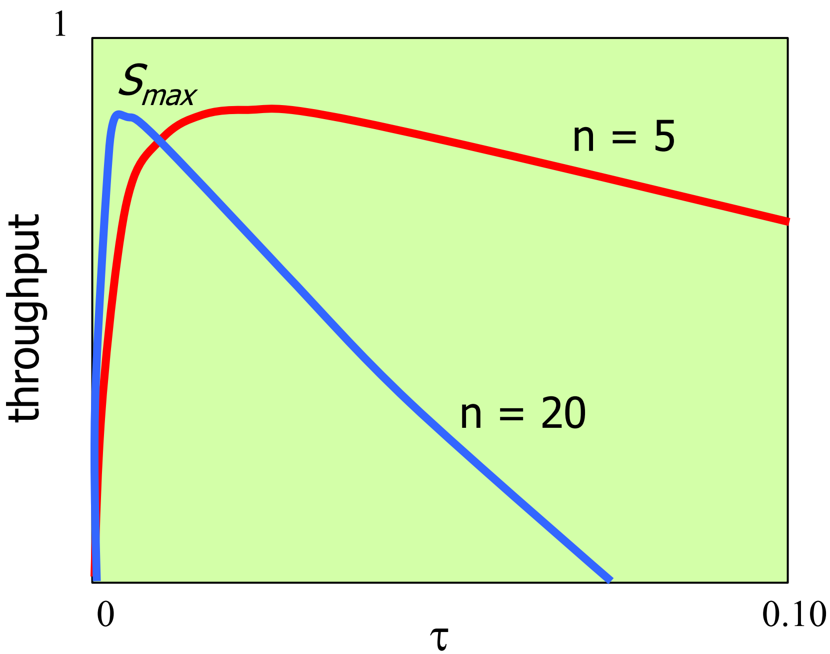
- We select τ to maximize S. We thus obtain the following condition to determine the optimal τ value as a function of W and m:

$$\tau = \frac{\sqrt{\left[n + 2(n-1)(T_c^* - 1)\right]/n} - 1}{(n-1)(T_c^* - 1)} \approx \frac{1}{n\sqrt{T_c^*/2}}$$

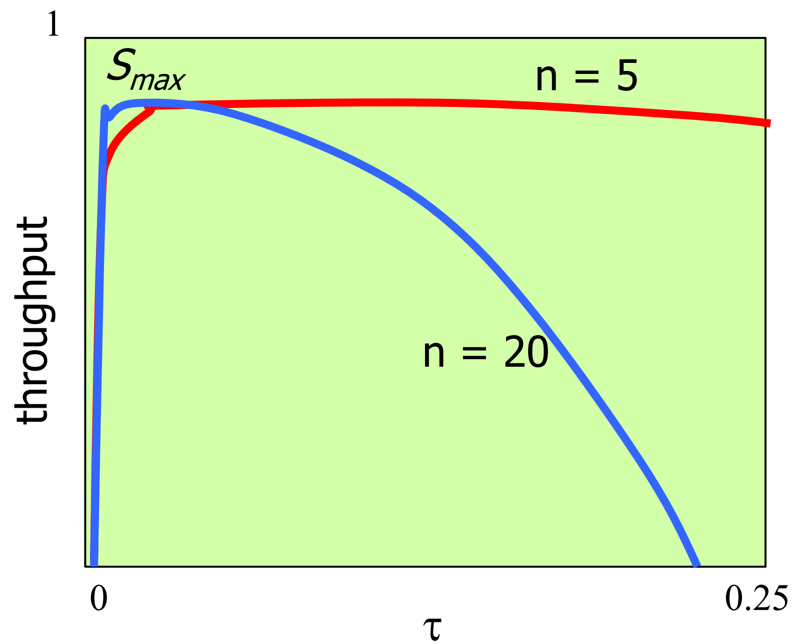
- For sufficiently-large n, the maximum S, S_{max}, can be approximated as:

$$S_{\max} = \frac{E[P]}{T_S + \sigma K + T_c\left[K\left(e^{1/K} - 1\right) - 1\right]}$$

WiFi Throughput Behavior



Basic CSMA/CA scheme



RTS/CTS scheme

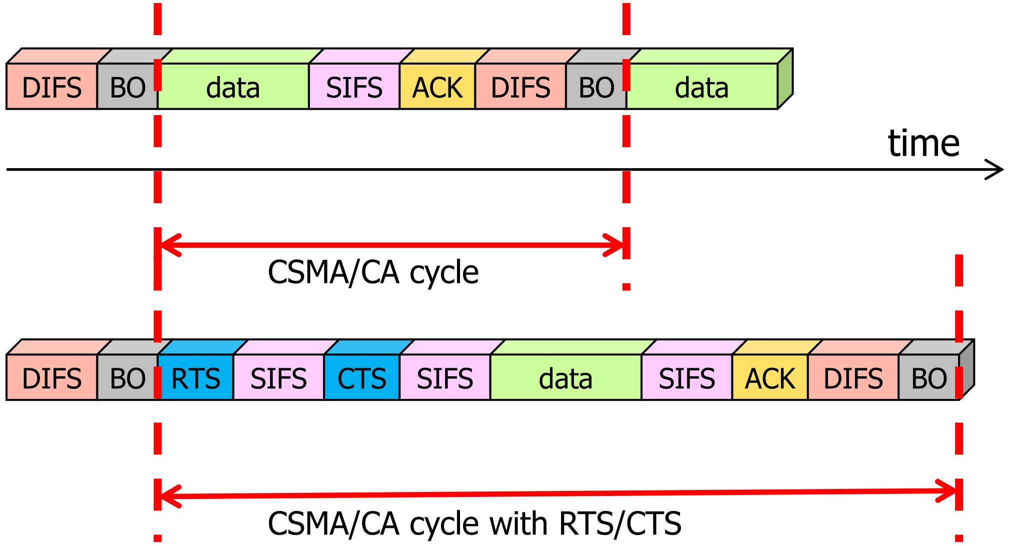
Comments on the WiFi Throughput Performance

- The maximum throughput S_{max} is practically independent of the number of stations n.
- The choice of m does not practically affect the system throughput, as long as m is greater than 4 or 5.
- The maximum throughput achievable by the basic CSMA/CA access mechanism is very close to that achievable by the RTS/CTS mechanism. In this study, however, we neglect hidden terminals (only one cell is considered) that would be a situation where RTS/CTS would show advantages with respect to the classical mechanism.
- RTS/CTS is able to better manage collisions, so that the increase in n has a milder impact on throughput.
- The throughput of the RTS/CTS scheme is less sensitive to the transmission probability τ.
- The RTS/CTS scheme is less sensitive to the use of low W values ($W < 64$).

Simplified Analysis of the WiFi Channel Capacity

- We define the **upper bound to the throughput (i.e., the throughput without collisions)** that can be achieved by an IEEE 802.11 network as its *Theoretical Maximum Throughput* (TMT).
- TMT is computed as the ratio of the MSDU size divided by the time needed to transmit it:

$$TMT = \frac{MSDU \ \ size}{Delay \ \ per \ \ MSDU}$$



J. Jun, P. Peddabachagari, M. Sichitiu, "Theoretical Maximum Throughput of IEEE 802.11 and its Applications", in Proc. of the *2nd IEEE International Symposium on Network Computing and Applications 2003 (NCA'03)*, Cambridge, MA, pp. 249–56, Apr. 2003.

Simplified Analysis of the WiFi Channel Capacity (cont'd)

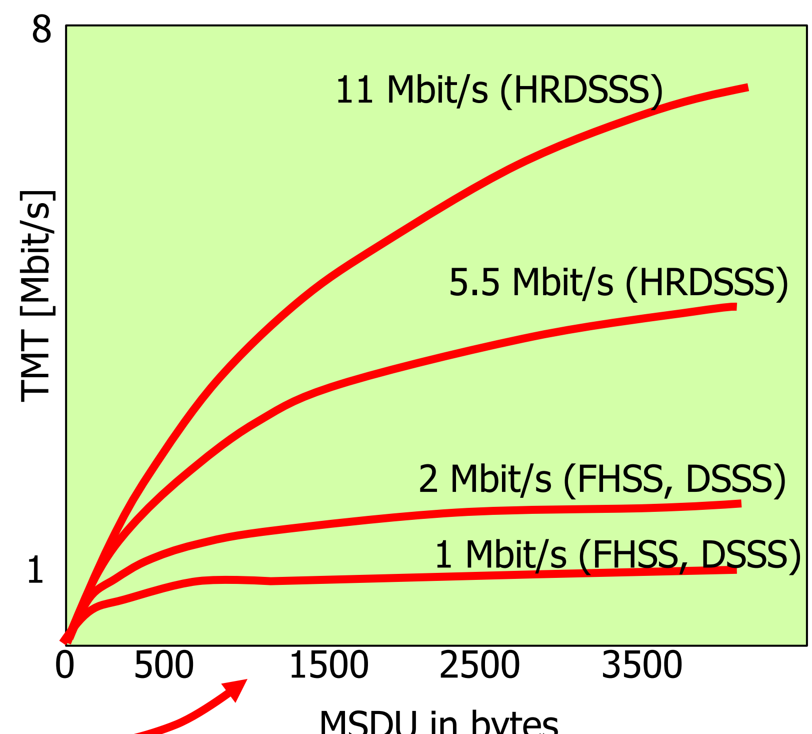
Let us refer below to IEEE 802.11 b with RTS/CTS:

$$Delay\ \ per\ MSDU = T_{DIFS} + T_{SIFS} + T_{BO} + T_{RTS} + T_{CTS} + T_{ACK} + T_{DATA}$$

We consider the average window at the first attempt for the backoff time, as if there is **no collision**: $T_{BO} = C_{Wmin}/2$.

Parameter	Value	Parameter	Value
Data Rate (PHY)	1,2,5.5,11 Mbit/s	Retry limit	4, 7
Time slot	20 μs	PHY header	48 bits
SIFS	10 μs	PLCP preamble	72, 144 bits
PIFS	30 μs	MAC header	224, 272 bits
DIFS	50 μs	RTST threshold	2400 bits
EIFS	304 μs	MAC ACK	112 bits
CW_{min}	31	RTS	160 bits
CW_{max}	1023	CTS	112 bits

data for IEEE 802.11b



The MSDU size has a certain impact on the efficiency of the WiFi air I/F: the shorter the packet the lower the efficiency, since RTS, CTS, DIFS and SIFS have lengths that are independent of the packet size.

WiMAX Description

What is WiMAX?

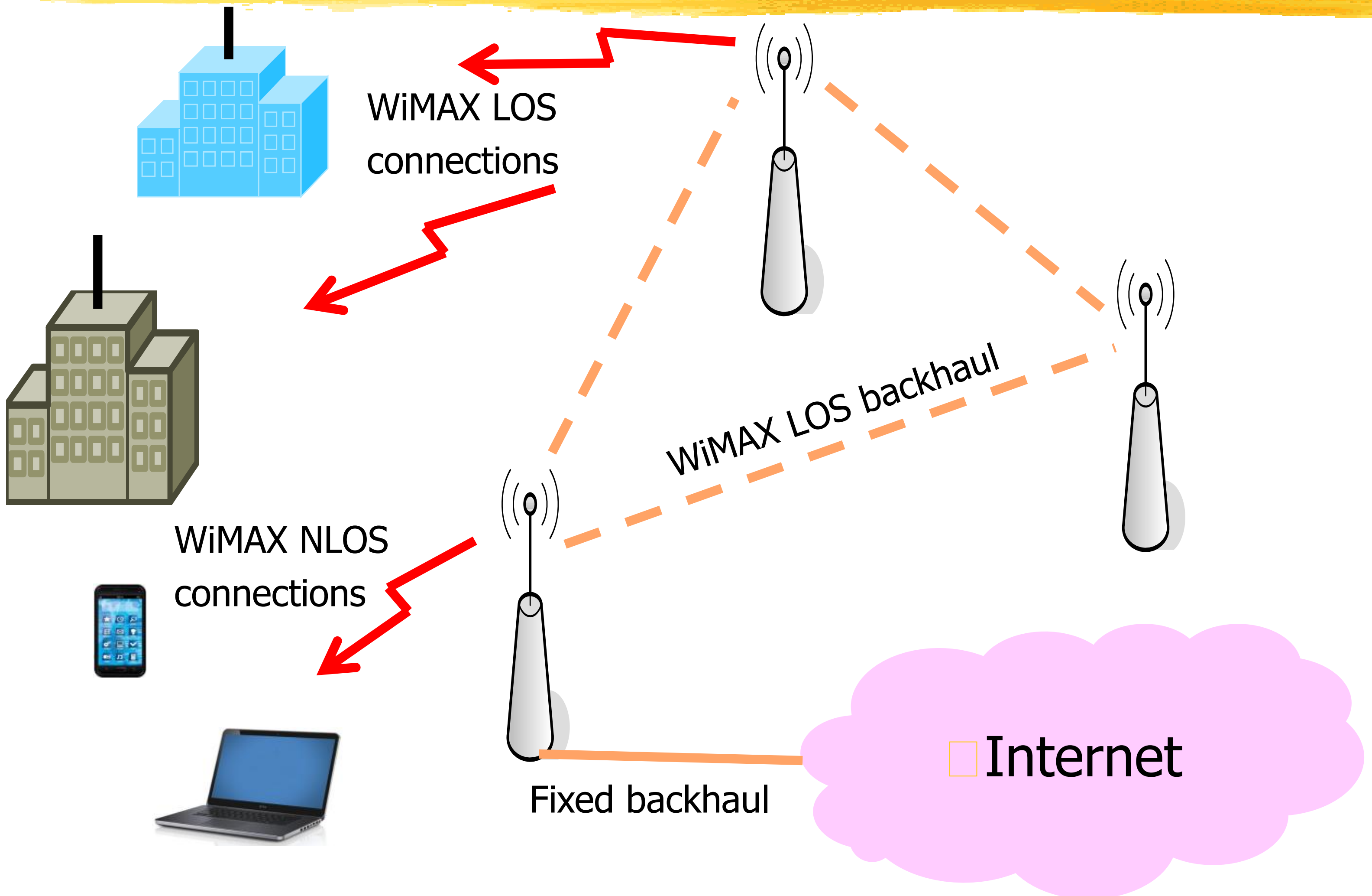
- WiMAX (Worldwide Interoperability for Microwave Access) is a standard-based technology enabling last mile wireless broadband access as an alternative to cable and DSL.
- WiMAX Forum is a non-profit industry body for promoting the adoption of this technology and ensuring that different vendors' products will interoperate.
- WiMAX technology is specified by the Institute of Electrical and Electronics Engineers (IEEE) as the **IEEE 802.16 standard**.
  - Korea's telecoms industry has developed its own standard, **WiBro**. In late 2004, Intel and LG Electronics have agreed on interoperability between WiBro and WiMAX.

WiMAX LOS and NLOS Cases

WiMAX can provide 2 types of wireless coverage:

- **Non-Line-Of-Sight (NLOS) conditions**, where a small antenna on a computer connects to the tower where the base station antenna is located.
  - Use of the lower frequency range (2 to 11 GHz).
- **Line-Of-Sight (LOS) conditions**, where a fixed antenna points straight at the WiMAX tower from a rooftop or pole (point-to-point link with possible directional antennas). The LOS connection is stronger and more stable, so it is able to send a lot of data with fewer errors.
  - Possible use of higher frequencies with ranges reaching 66 GHz.

WiMAX LOS and NLOS Cases (cont'd)



Evolution of WiMAX

Standard	802.16	802.16d (fixed WiMAX)	802.16e (mobile WiMAX)	802.16m
Year	2003	2004	2005	2011
Mobility	Fixed users	Fixed users or low mobility	Mobile	Mobile
Propagation	LOS	NLOS	NLOS	NLOS
Frequency	2 – 11 GHz	2.6 and 3.5 GHz	2.6, 3.5, and 5.5 GHz	1.7, 2.1, 2.3, 2.6, 3.5, 5.5 GHz
Key features	OFDM, AMC, Single Carrier	OFDMA, AMC	SOFDMA, AMC	MIMO-SOFDMA

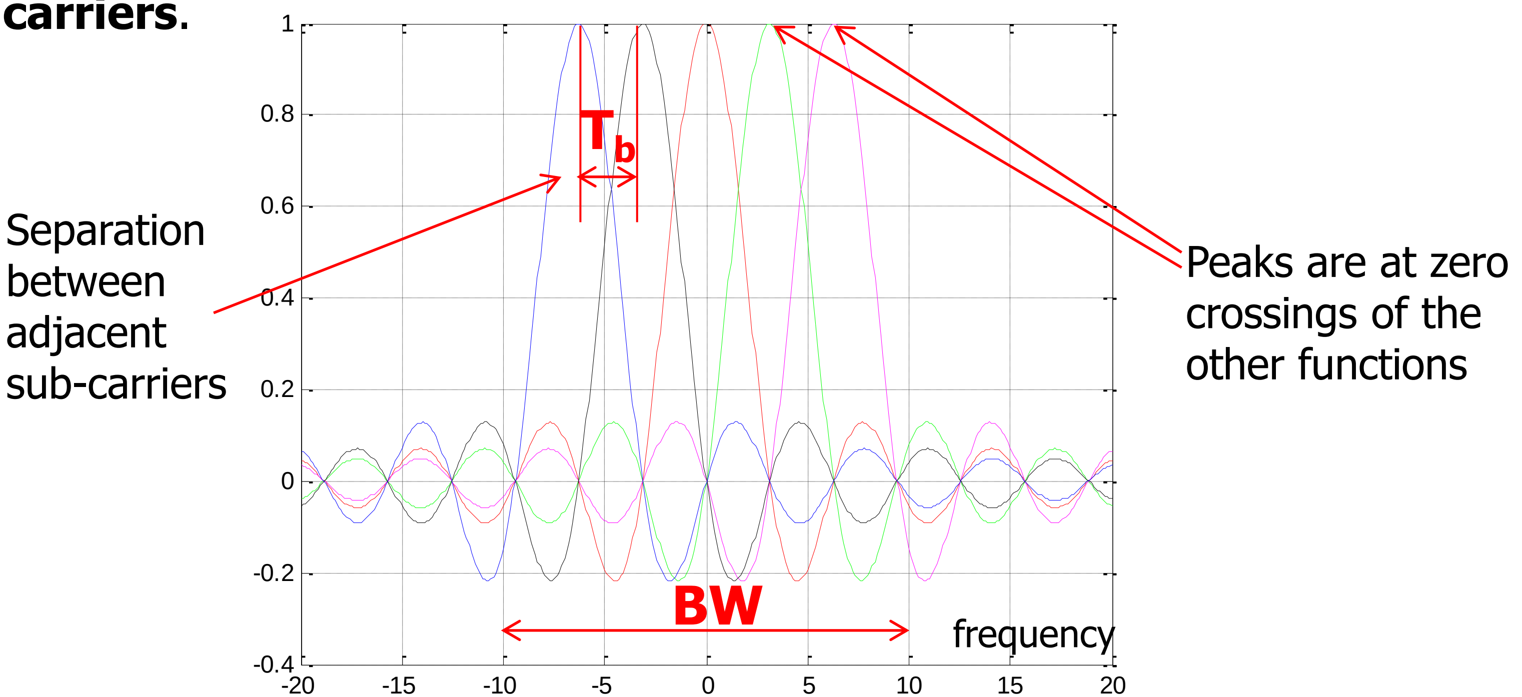
Duplexing Schemes

- Time-Division Duplexing (TDD)
  - Downlink & uplink share in time the same RF channel
  - Dynamic asymmetry
  - Does not transmit & receive simultaneously (low cost).
- Frequency-Division Duplexing (FDD)
  - Downlink & uplink on separate RF channels
  - Full Duplexing (FDX) to transmit & receive simultaneously
  - Half-Duplexing (HDX) subscriber stations (low cost) are supported.

OFDM PHY Characteristics

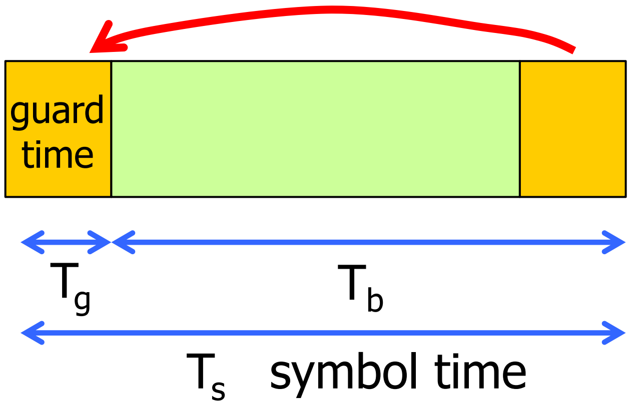
Orthogonal Frequency Division Multiplexing (OFDM):

- This is a Digital modulation technique
- It reduces the effects of the selective fading by splitting the broadband transmission in a number of low bit-rate transmissions on **orthogonal sub-carriers**.



OFDM PHY Characteristics (cont'd)

- **Time domain**: An OFDM symbol is divided between
  - Useful data part (Inverse FFT)
  - Cyclic prefix that is added at the beginning of each symbol to protect from Inter Symbol Interference (ISI)



- **Frequency domain**: an OFDM symbol is made of sub-carriers (the number is determined by the FFT size)
  - Data sub-carriers are used for data transmissions
  - Pilot sub-carriers are used for estimation purposes
  - Null sub-carriers are used as guard sub-carriers.

OFDM PHY Characteristics (cont'd)

- Licensed and unlicensed spectrum [2-11 GHz]
  - Several spectrum canalizations (BW) are possible: 1.5 MHz ~ 20 MHz; .16d: TDD and FDD duplexing; .16e: currently TDD duplexing only.
- Three physical layer technologies:
  - Single carrier modulation
  - COFDM with 256 point FFT (currently adopted by fixed WiMAX)
  - OFDMA with up to 2048 point FFT (currently adopted by mobile WiMAX, with scalability of the FFT size according to channel bandwidth)
- Support for smart antennas, MIMO, turbo codes in mobile WiMAX.
- High spectral efficiency: up to 3.75 bit/s/Hz (adaptive modulation)
  - but dimensioning in real NLOS case in the range of 2 bit/s/Hz
- Cell range very dependent on the environment (NLOS, LOS, Urban, Rural): LOS up to 30 km, NLOS 1 - 3 km.

WiMAX PHY Layer Resources

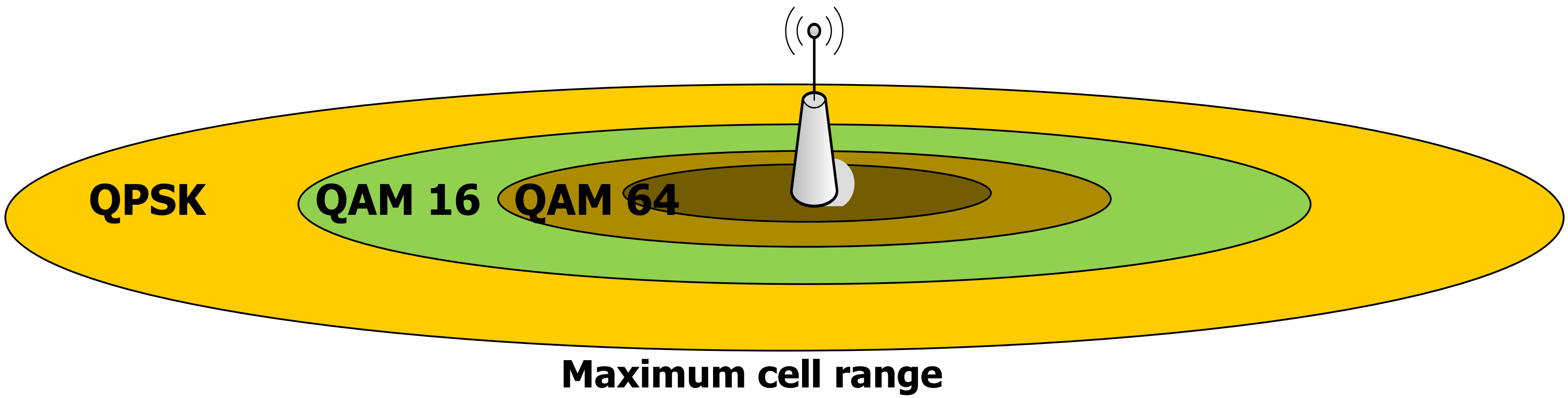
- The spectrum is split into a number of parallel orthogonal narrow-band sub-carriers. Sub-carriers are grouped to form sub-channels.
- **A <u>sub-carrier</u> is the smallest resource unit in the frequency domain; a <u>symbol</u> is the smallest resource unit in the time domain. The resource allocation is however made on the basis of <u>slots</u> having a number of sub-carriers and a given number of symbols.**
- The distribution of sub-carriers to sub-channels is done using three major permutation methods (IEEE 802.16e standard):
  - Partial Usage of the Sub-Channels (PUSC),
  - Full Usage of the Sub-Channels (FUSC),
  - Adaptive Modulation and Coding (AMC).
- In the first two methods, the sub-carriers of a sub-channel are pseudo-randomly distributed throughout the available spectrum; instead, sub-carriers are contiguous in the AMC case.

OFDMA Scalability

WiMAX supports a wide range of air interface configurations in terms of bandwidths (1.25-20 MHz), frames sizes (2-20 ms), etc.

Parameters	Values			
System Channel Bandwidth (MHz)	1.25	5	10	20
Sampling Frequency (MHz)	1.4	5.6	11.2	22.4
FFT Size (N_{FFT})	128	512	1024	2048
Number of Sub-Channels	2	8	16	32
Sub-Carrier Frequency Spacing	10.94 kHz			
Useful Symbol Time (T_b)	91.4 μs			
Guard Time ($T_g = T_b/8$)	11.4 μs			
OFDMA Symbol Duration ($T_s = T_b + T_g$)	102.9 μs			
Number of OFDMA Symbols per Frame (5 ms)	48			

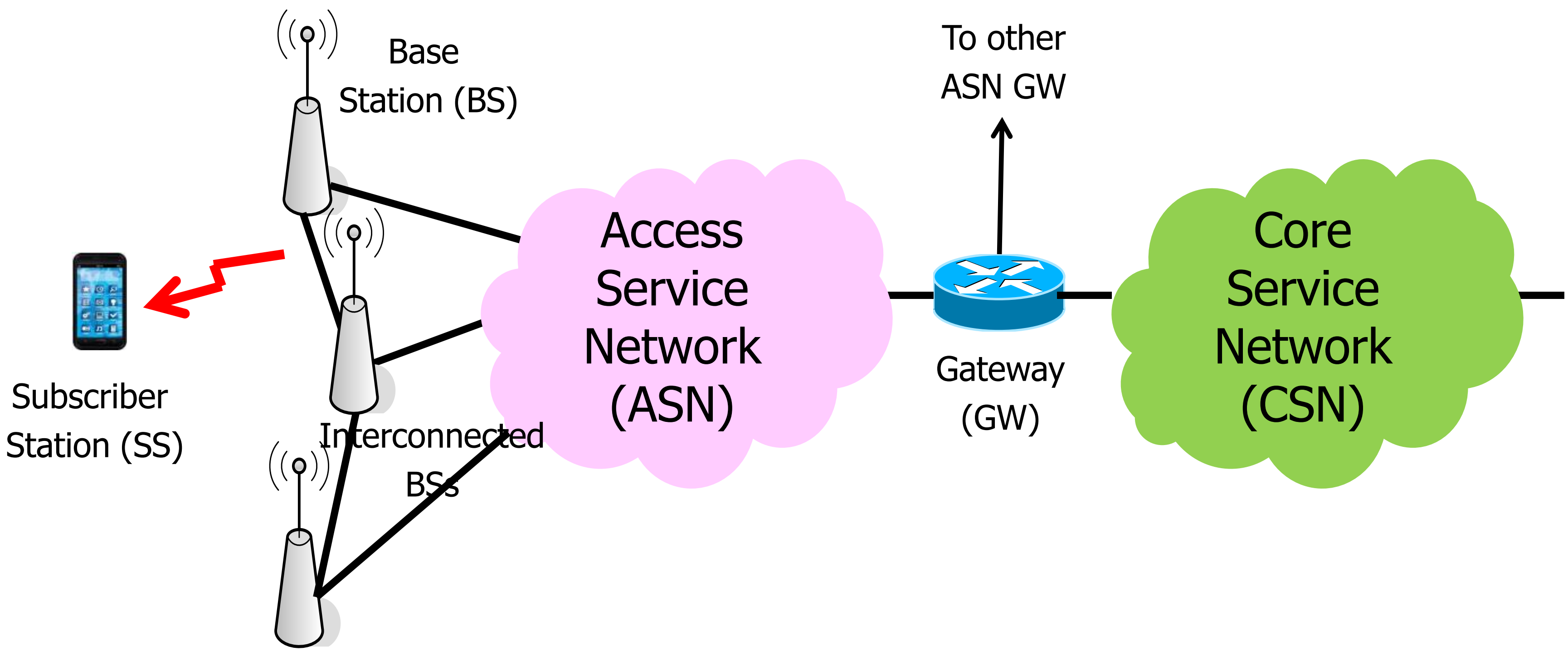
Adaptive PHY



Modulation and coding combinations in WiMAX: BPSK 1/2, QPSK 1/2, QPSK 3/4, 16QAM 1/2, 16QAM 3/4, 64QAM 2/3, and 64QAM 3/4.

The modulation order increases as we approach the base station. Signal to Interference and Noise Ratio (SINR) thresholds are adopted to decide the modulation and coding level used depending on the distance (path loss) from the base station.

WiMAX Network Architecture



MAC Layer Basic Characteristics

- **Connection-oriented MAC protocol**
  - **Connection:**
    - MAC level connection between BS and SS
    - Unidirectional mapping for the purpose of transporting the traffic of service flows
  - **Service flow:**
    - MAC channel for unidirectional transport where each packet has the same QoS characteristics.

WiMAX MAC Layer Resources

- The **number of resources (i.e., slots)** per **frame (i.e., scheduling interval)** with WiMAX depends on the number of symbols per frame, the number of sub-channels, and the permutation mode.

- **PUSC mode**: a slot is formed of two symbols and 24 data sub-carriers; depending on the frame length, we have from 19 to 198 symbols/frame and, depending on the available bandwidth, there are from 2 to 32 sub-channels (1 sub-channel = 24 data sub-carriers).

- **A slot carries a number of information bits depending on the modulation and code adopted**:
  - 24 information bits with BPSK 1/2 up to 216 information bits with 64QAM 3/4.

QoS Support in WiMAX

- The WiMAX standard envisages the following traffic classes with related resource allocation methods:
  - **UGS** (Unsolicited Grant Services): it supports constant bit-rate services (CBR) with specified max sustained rate, max latency tolerance, and jitter tolerance. UGS is suitable to support VoIP without silence suppression.
  - **rtPS** (real-time Polling Services): it is used for real-time services that generate variable size packets on a periodic basis such as streaming video and audio (MPEG video). The BS provides periodic unicast (uplink) request opportunities. rtPS offers a variable bit-rate with guaranteed minimum rate and delay.
  - **ertPS** (enhanced Real-Time Variable Rate), specified in 802.16e, is a combination of UGS and rtPS. Unsolicited unicast grants are provided by the BS, so in this way latencies caused by bandwidth requests are removed. Piggybacking is used to update the needs on a dynamical basis. It is used for VoIP services with variable packet sizes and voice activity detection.
  - **nrtPS** (non-real-time Polling Service): supports non-real-time variable size data packets, e.g., FTP.
  - **BE** (Best Effort services).

QoS Support in WiMAX (cont'd)

- The QoS support for the different traffic classes of WiMAX is detailed in the table below.

Scheduling Service	Maximum sustained traffic rate	Minimum reserved traffic rate	Request/ transmission policy	Tolerated jitter	Maximum latency	Traffic priority
UGS	●	●	●	●	●	
rtPS / ertPS	●	●	●		●	
nrtPS	●	●	●			●
BE	●		●			●

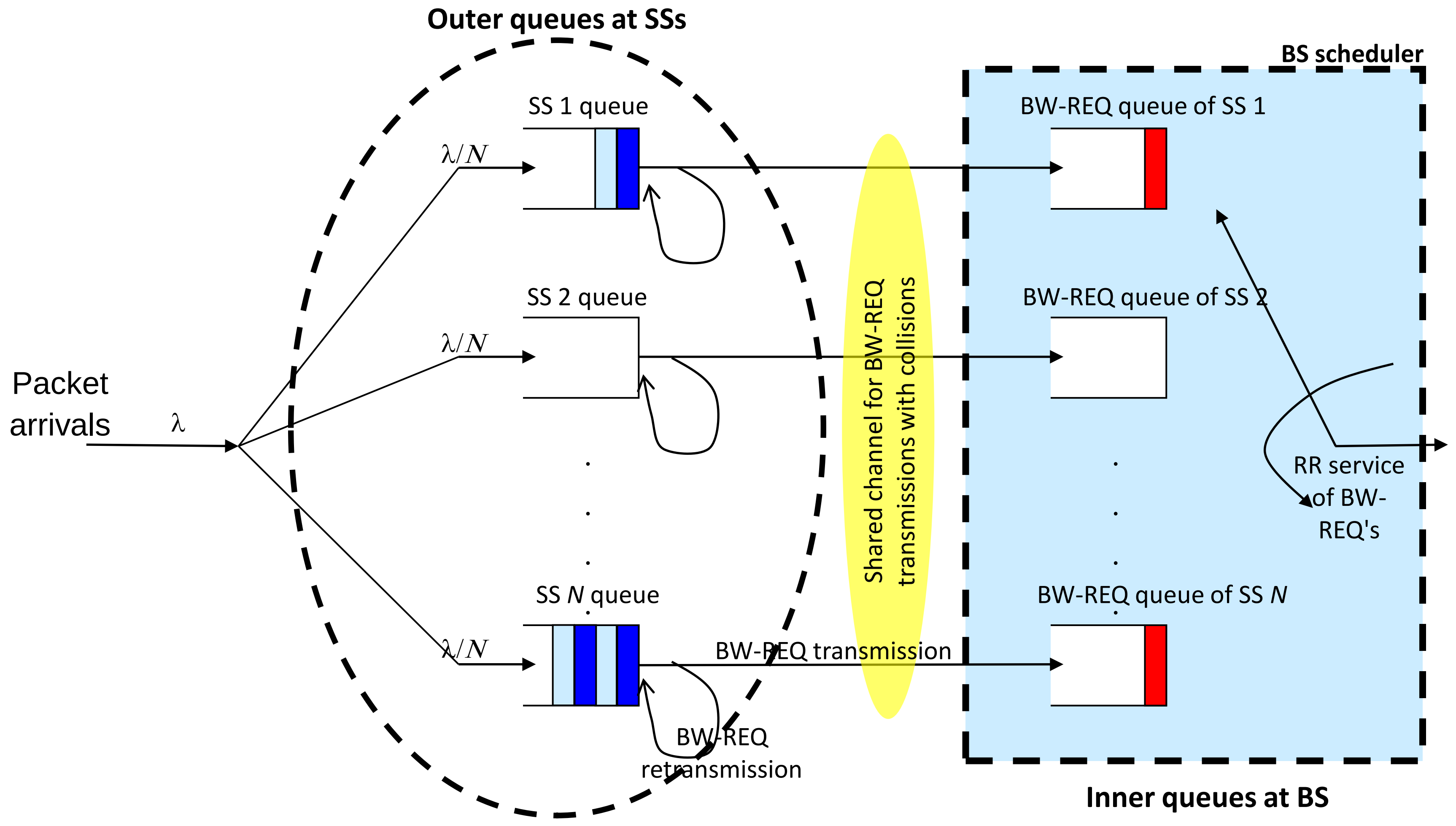
MAC: Uplink Resource Allocation

- IEEE 802.16 resource **request-grant mechanisms**:
  - **Unsolicited bandwidth grants**
    - Request is sent only once by the SS
    - BS allocates bandwidth periodically for the transmission of data;
    - This method is suitable for the UGS class
  - **Unicast polling**
    - BS provides some bandwidth in which SSs can make bandwidth requests
    - Used for rtPS or ertPS QoS classes
  - **Contention-based polling**
    - A certain amount of every uplink sub-frame is dedicated for sending contention-based bandwidth requests
    - Suitable for the BE class or even nrtPS.

MAC Layer: Uplink Queuing Model (BE Class)

- The MAC layer queuing architecture at the SSs and at the BS can be described as follows.
- We need to consider the sharing of resources among SSs in both the contention phase and the subsequent transmission phase using **two queue levels**:
  - Queues on the SS side (**outer queues**) for data transmission based on grants;
  - Queues on the BS side (**inner queues**) to store the requests (BW-REQs) received from the SSs, which need to be serviced by means of resource allocations (grants).

MAC Layer: Uplink Queuing Model (BE Class)



Thank you!

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