A Introduction of Wireless MAC Protocol

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Agenda

- Wireless MAC Protocol Classification
- Wireless Communication Technologies
- Multiplexing
- Basic MAC Protocol
- RFID
- IEEE 802.11 MAC protocol
- IEEE 802.15 MAC protocol
- IEEE 802.16 MAC protocol
- WINNER system
- Summary and Conclusion

Wireless MAC Protocol Classification

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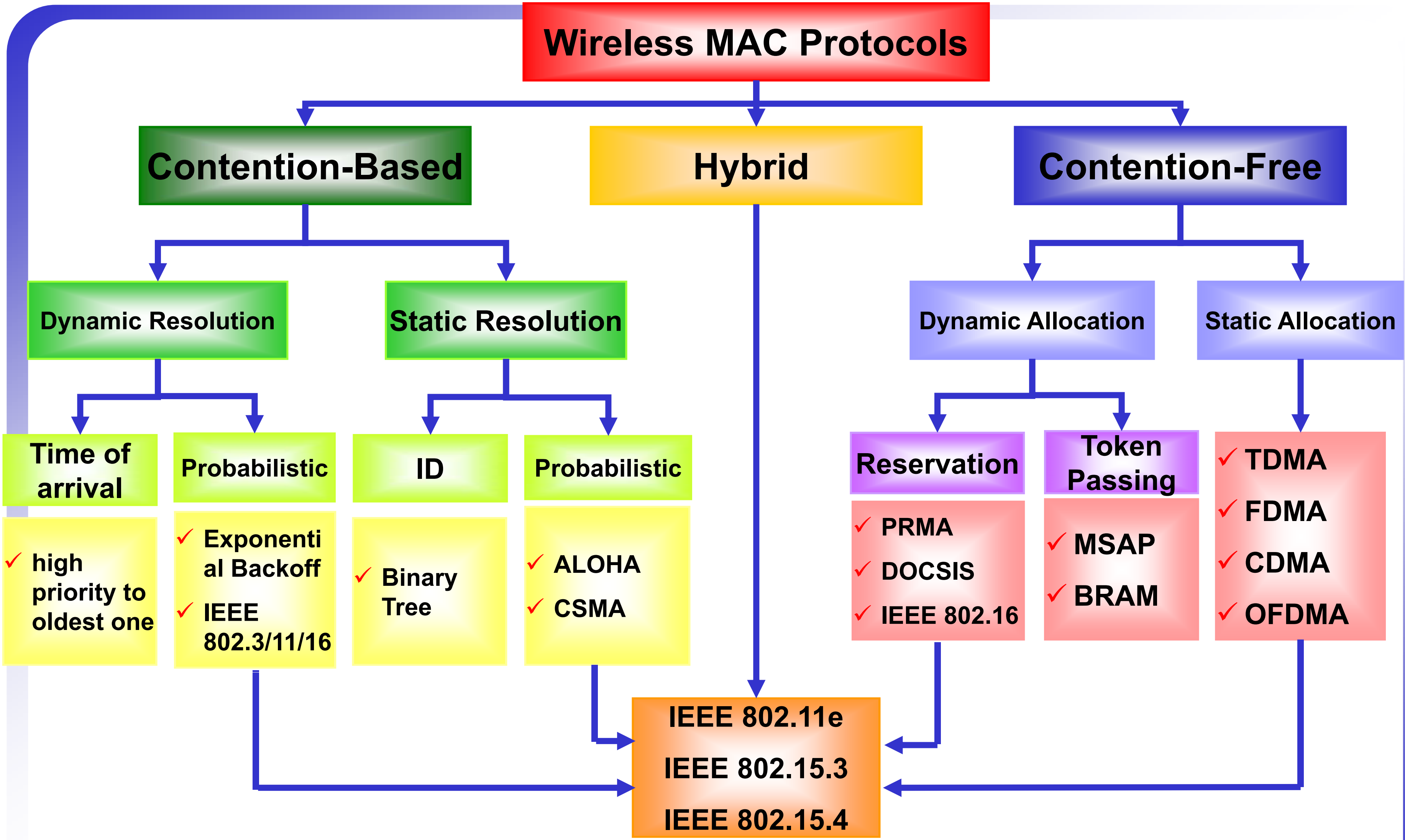
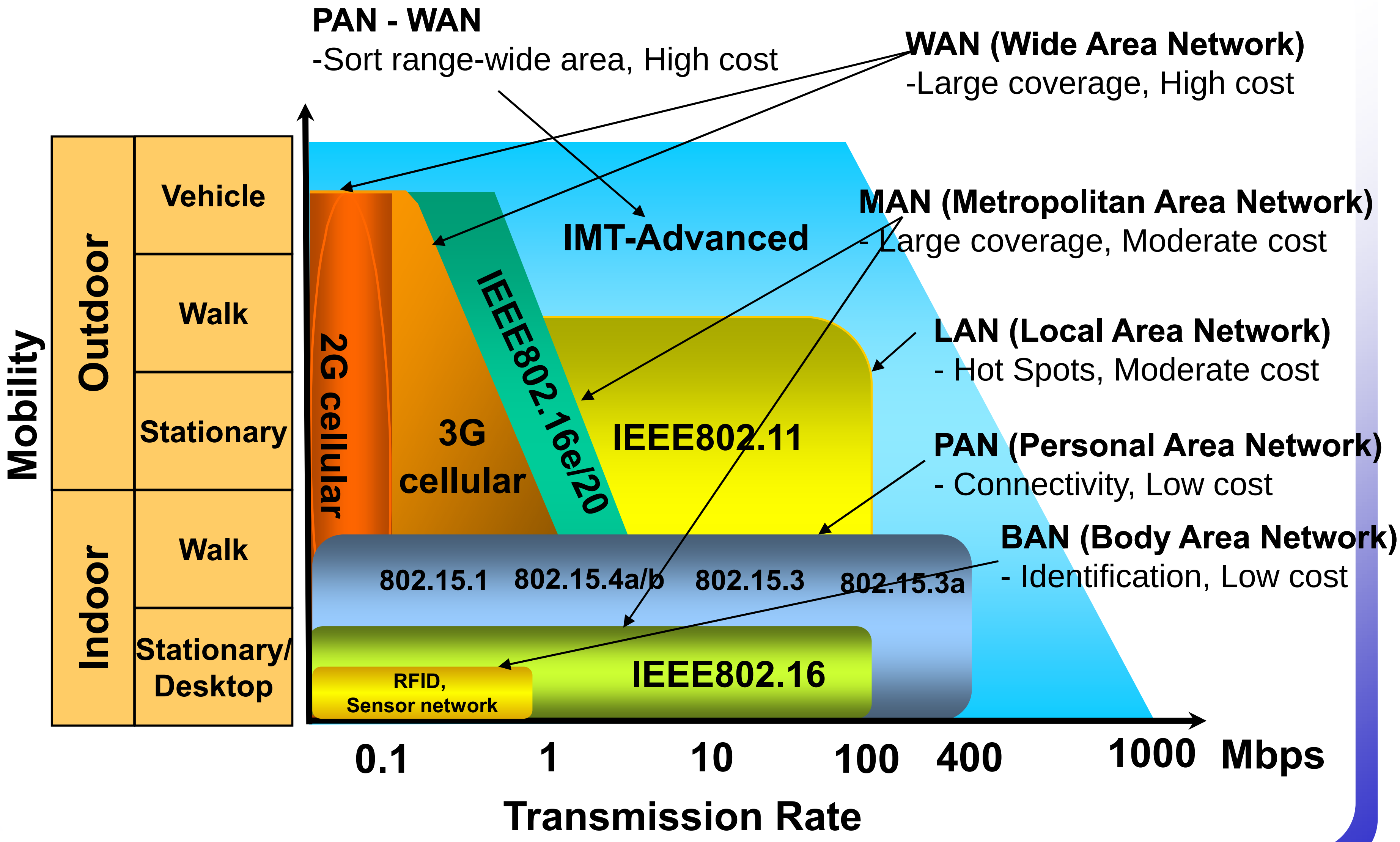


- CSMA : Carrier Sense Multiple Access
-PRMA : Packet Reservation Multiple Access
-BRAM : Broadcast Recognition Access Method
- DOCSIS : Data Over Cable Service Interface Specification
-MSAP : Mini Slotted Alternating Priority

Wireless Communication Technologies



Wireless Communication Technologies

	802.11	802.15	802.16	RFID	WINNER
Coverage Area	LAN < 100 m	PAN, Access < 10 m	MAN < 1Km	Access < 10m (M/W)	Wide-area >1km Metropolitan < 1km Short-range <100m
Spectrum	Unlicensed ISM band	Unlicensed	Licensed/ Unlicensed	Licensed/ Unlicensed	Licensed/ Unlicensed
Frequency	2.4 GHz, 5 GHz	868/902MHz 2.4 GHz 3.1~10.6GHz	10-66 GHz 2-11 GHz	0.125/13.56 MHz 860-930MHz 2.4/ 5GHz	2.7~5.0 GHz
Mobility	Portable Local Roaming	Personal Space	Fixed Area	Access Space	High and low mobility
LOS vs. NLOS	NLOS	NLOS	LOS(10-66GHz) NLOS(2-11GHz)	LOS	LOS NLOS
MAC Protocol	CSMA/CA	CSMA/CA, TDMA S-ALOHA	TDMA/TDD W-DOCSIS	SDMA/FDMA/ TDMA/ Binary search Aloha based	TDD/FDD Cellular, P2P communication
Data Rate	1 – 54 Mbps	< 1Mbps <480Mbps 15.3a	< 50 Mbps	< 1 Mbps 200 tag/antenna	Up to 1 Gbps/ 1-100 Mbps
Cost	Low	Low	Moderate	Very Low	High

Multiplexing

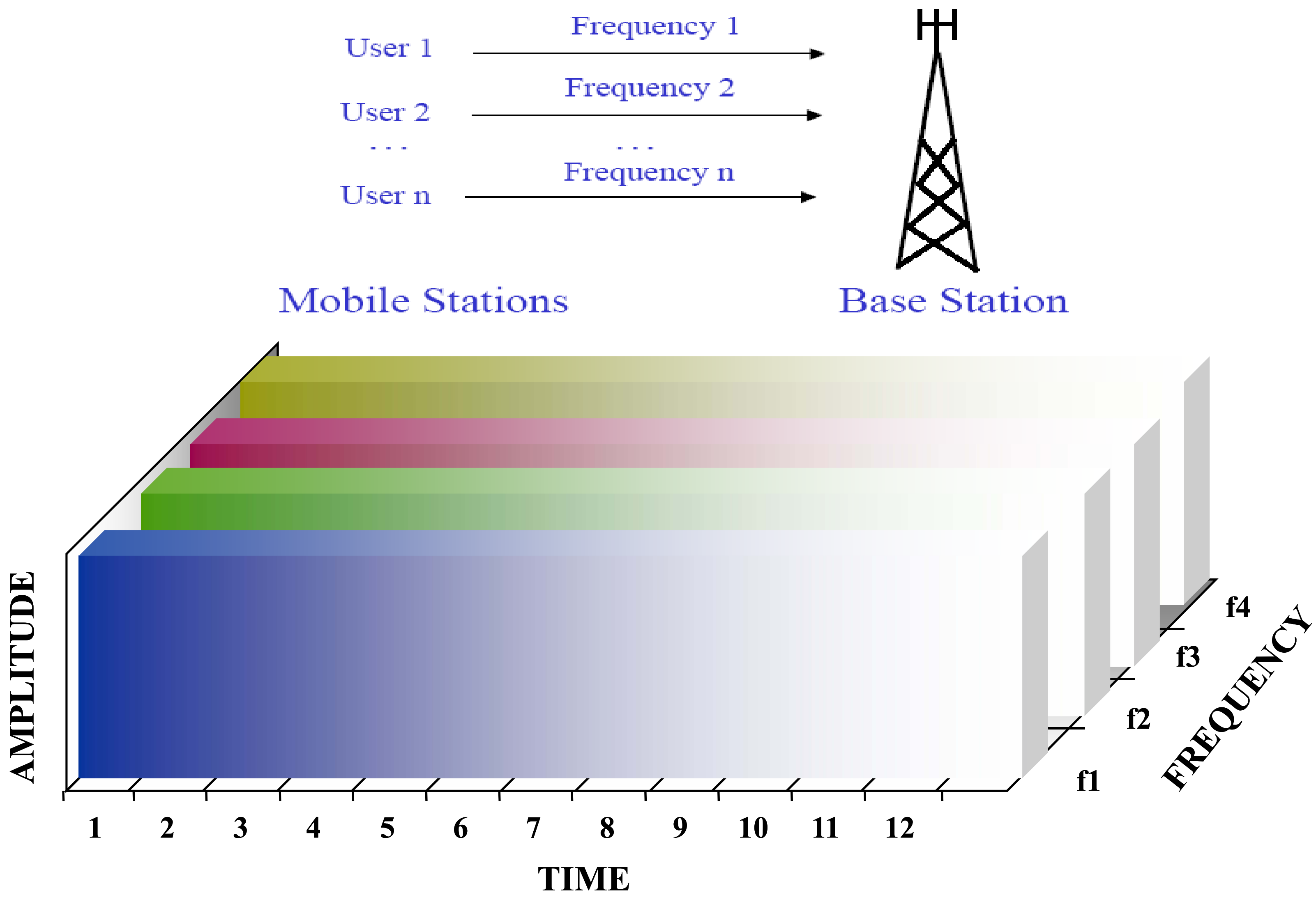
-. FDMA

-. TDMA

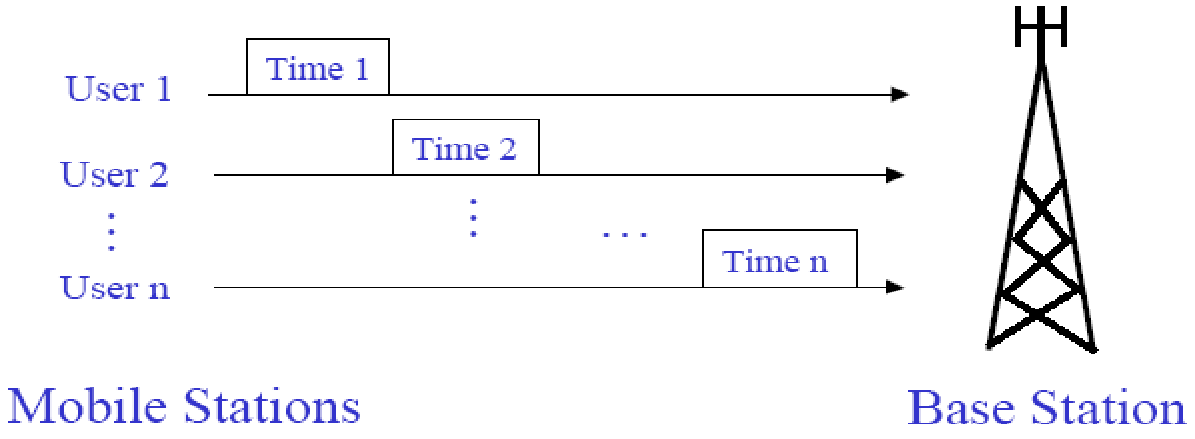
-. CDMA

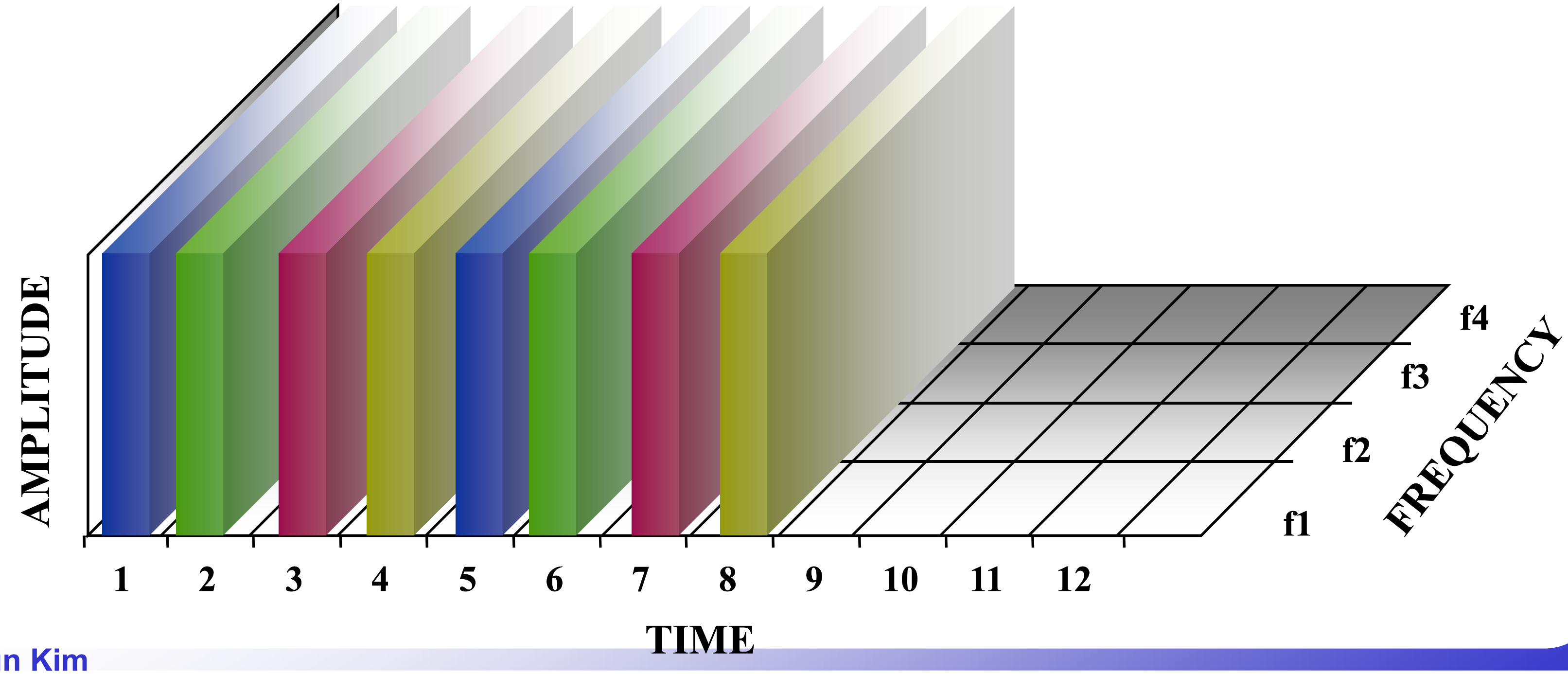
-. OFDM/OFDMA

FDMA (Frequency Division Multiple Access)



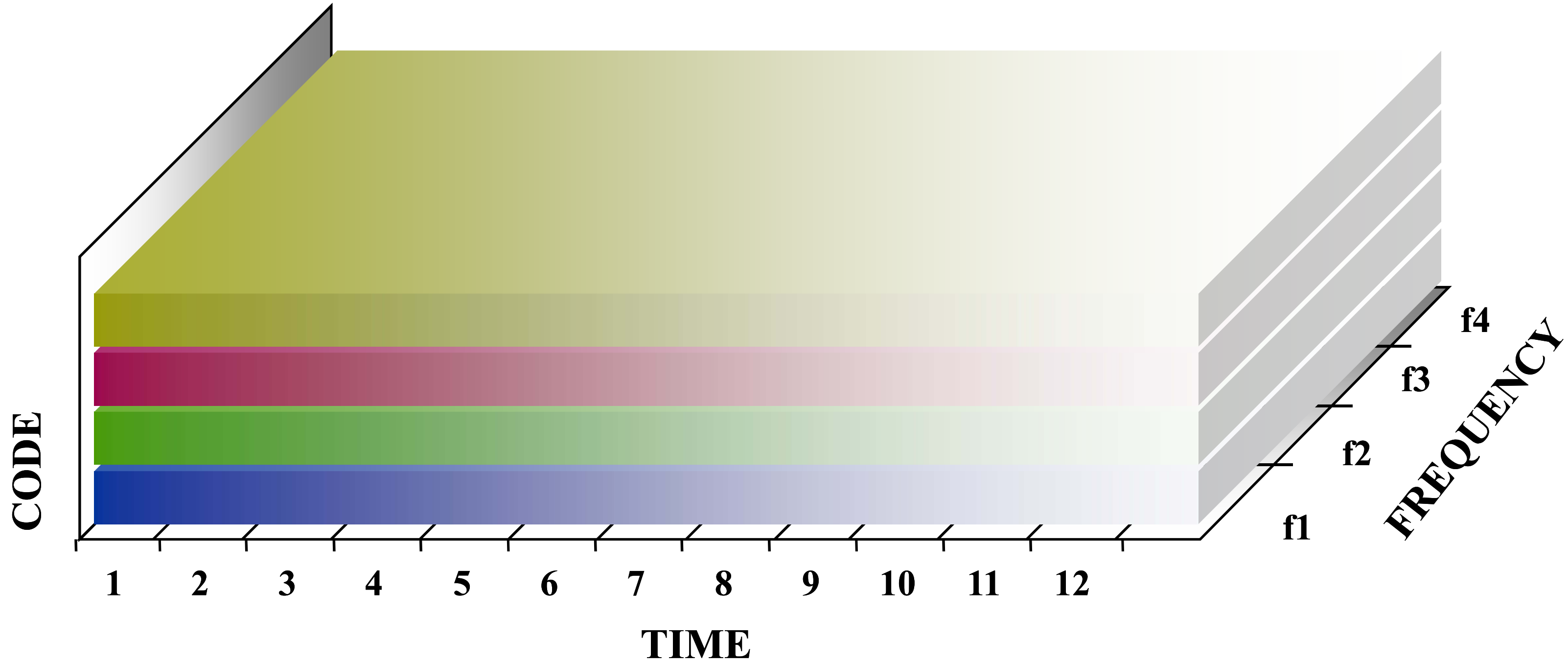
TDMA (Time Division Multiple Access)





CDMA (Code Division Multiple Access)

- DSSS(Direct Sequence Spread Spectrum)
- FHSS(Frequency Hopping Spread Spectrum)
- THSS(Time Hopping Spread Spectrum)

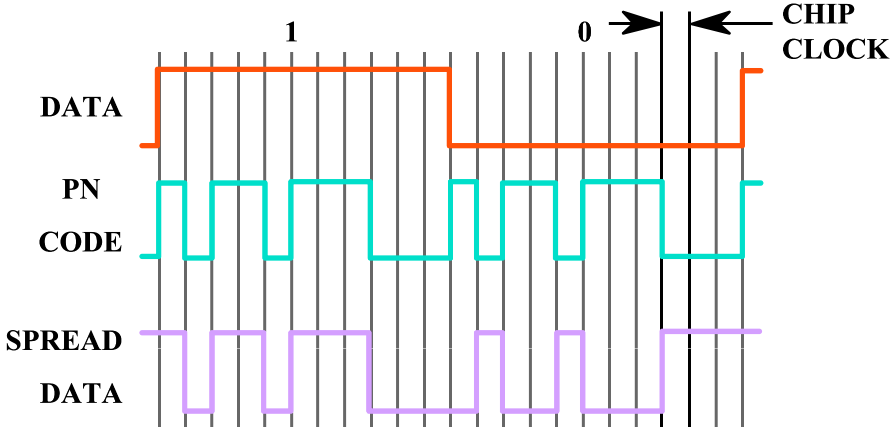


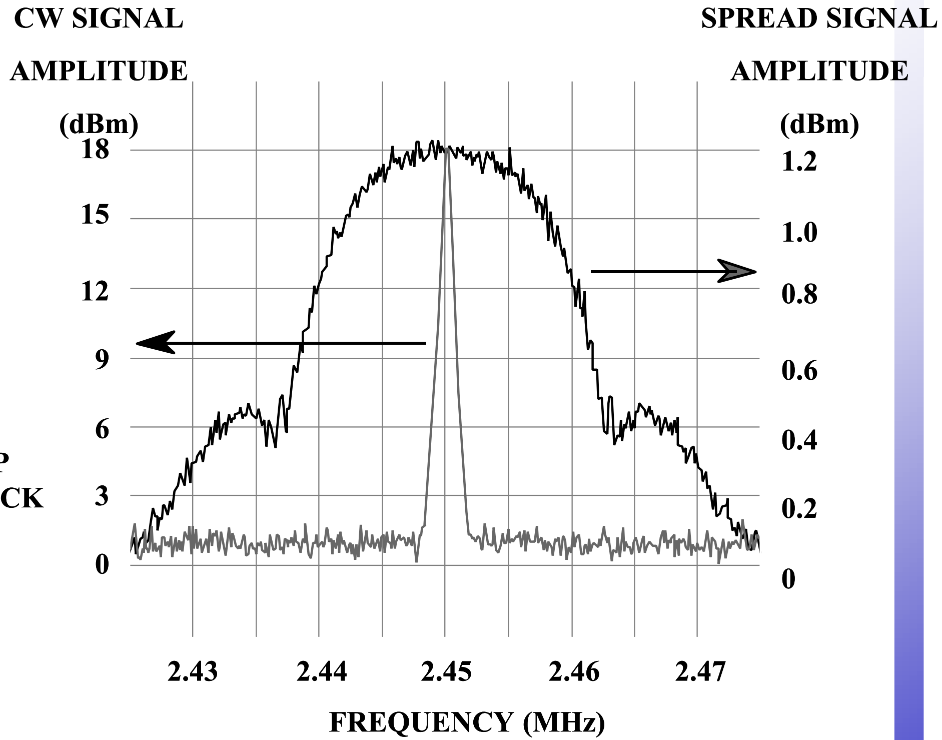
CDMA (Code Division Multiple Access)

DSSS

- DATA SIGNAL SPREAD BY A PN CODE
- PROPERTIES OF PN CODE
- CHIP RATE
- DS PROCESSING GAIN

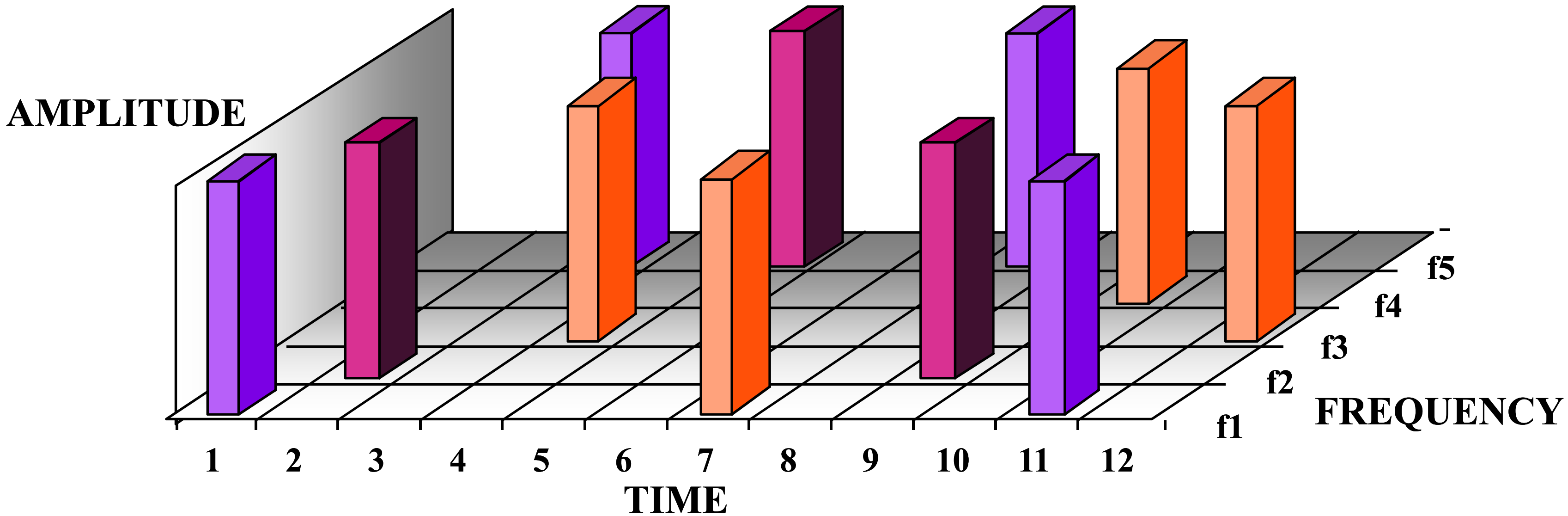
  $G_P\,(dB) = 10LOG\left(\frac{CHIP\ RATE}{DATA\ RATE}\right)$
- PN CORRELATION AT RECEIVER
- PSK DATA MODULATION





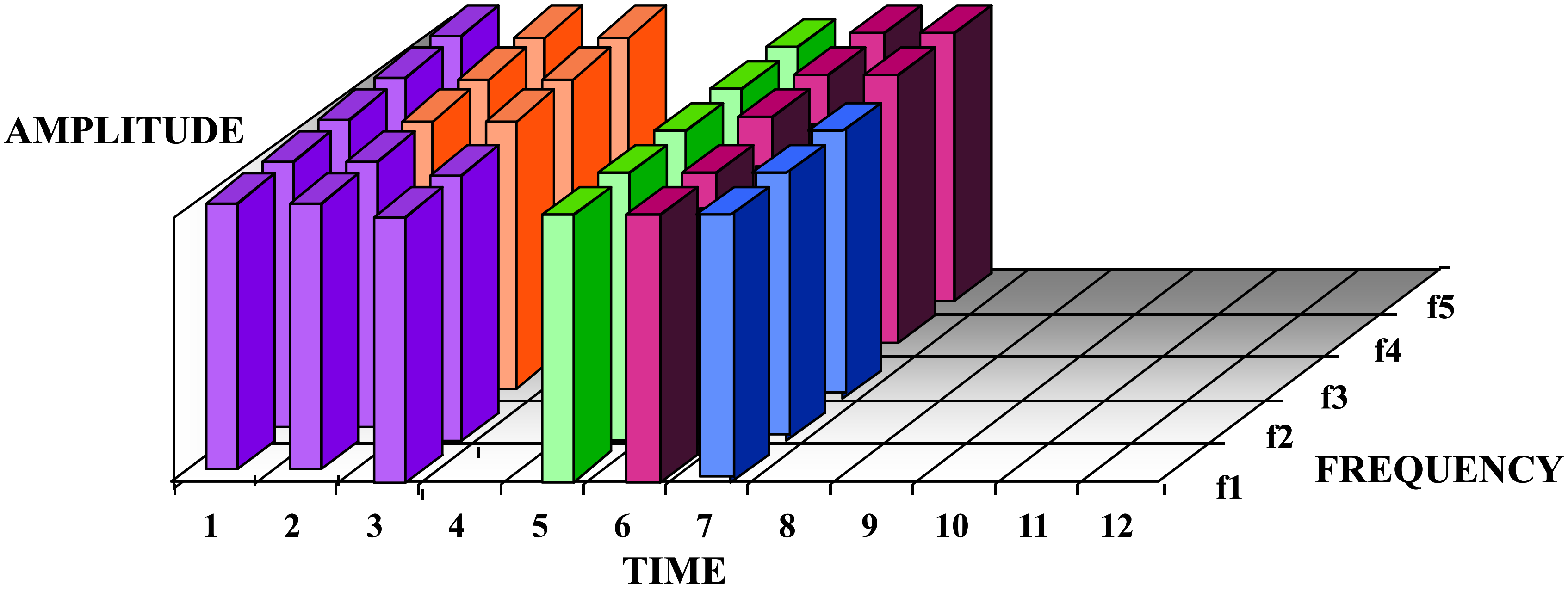
CDMA (Code Division Multiple Access)

FHSS



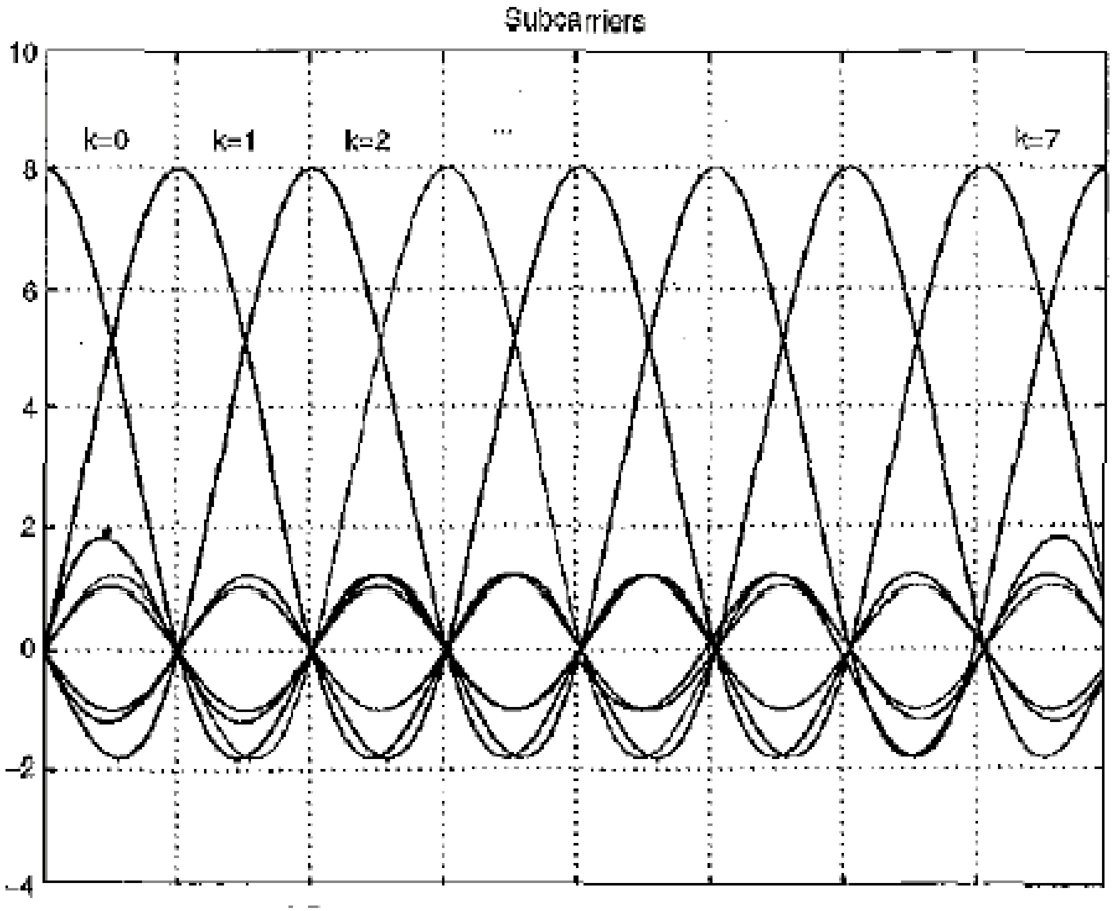
- FSK DATA MODULATION
- PERIODIC CHANGES IN THE CARRIER FREQUENCY SPREADS THE SIGNAL
- CARRIER FREQUENCY CHANGES AT A SPECIFIED HOP RATE
- CARRIER FREQUENCY HOPS AFTER A PRESCRIBED TIME
- TOTAL SYSTEM BANDWIDTH INCLUDES ALL OF THE CHANNEL FREQUENCIES USED IN HOPPING

OFDMA
(Orthogonal Frequency Division Multiple Access)



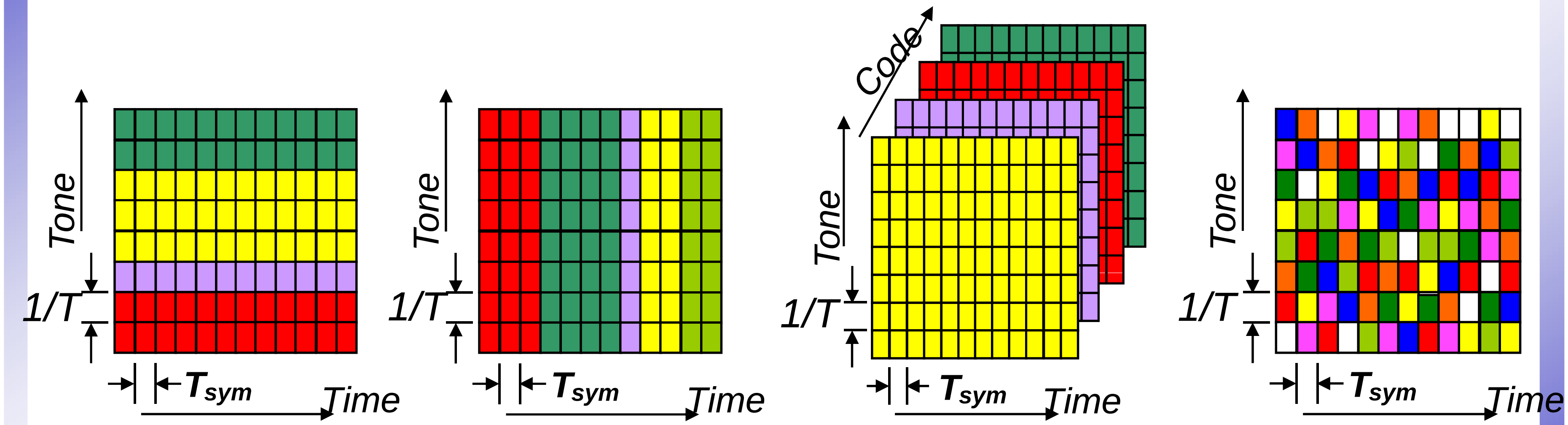
- **TRANSMIT DATA VIA MULTIPLE FREQUENCY**
- **SIMPLE IMPLEMENTATION USING FAST FOURIER TRANSFORM(FFT) AND IFFT**
- **GOOD CAHRATERISTICS FOR HIGHSPEED TRANSMISSION**
- **ROBUSTNESS TO FREQUENCY SLECTIVITY**
- **MINIMUM INTER-CARRIER SPACING**
- **LONGER SYMBOL DURATION : ISI is reduced a lot**

OFDM Frequency



OFDM-Based Multiple Access Techniques

- **Multiple Access Domains**
  - **OFDM-FDMA, OFDM-TDMA, OFDM-CDMA, FH-OFDMA (Subcarrier-level frequency hopping)**



OFDM-FDMA OFDM-TDMA OFDM-CDMA FH-OFDMA

Basic MAC Protocol

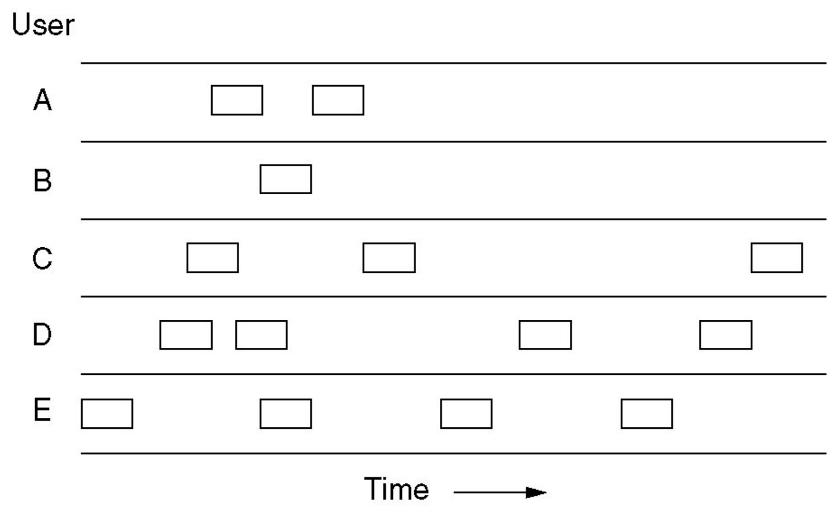
-. ALOHA

-. Carrier Sense Multiple Access

-. Contention Free Protocols

ALOHA(1)

- Uncoordinated users are competing for the use of a single shared channel
- Pure ALOHA and Slotted ALOHA[1]
  - ALOHA system의 basic idea
    - Transmit any time and listen the feedback signal whether it was collided or not
    - 충돌 시 random amount of time을 기다림
  - Contention system
  - Uniform frame size -> maximum throughput



R. Rom and M. Sidi, “Multiple Access Protocols Performance and Analysis”, Springer-Verlag

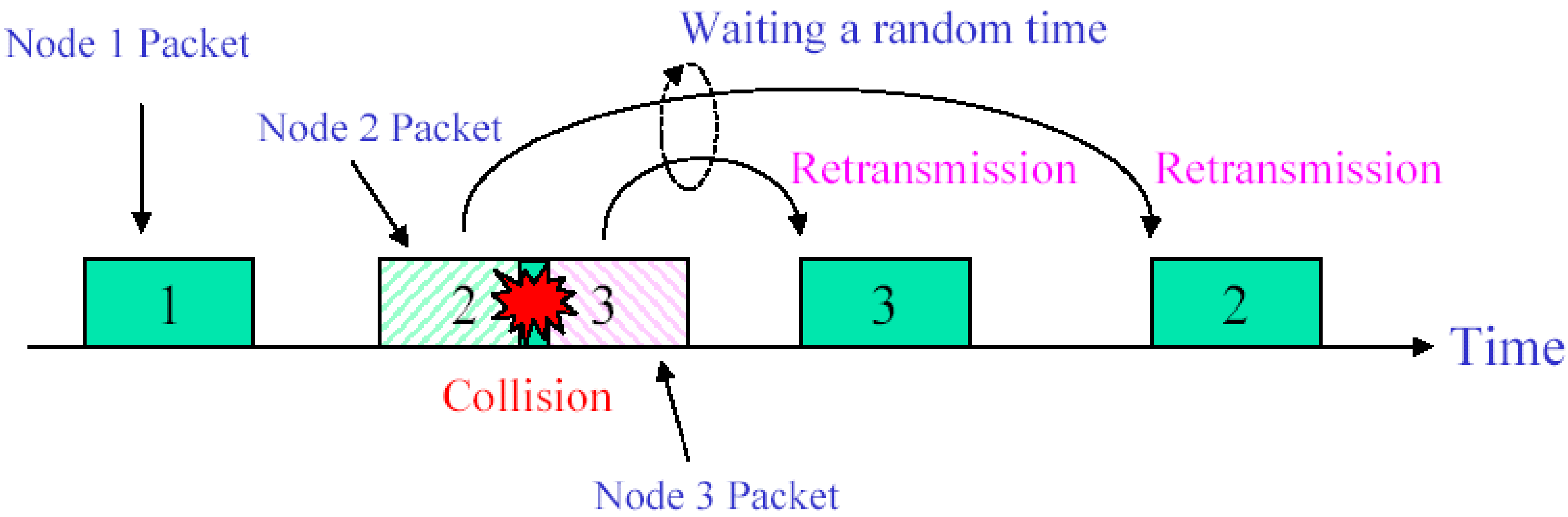
ALOHA(2)

ALOHA channel의 efficiency

- **Infinite population of users**
  - Poisson distribution with mean S frames/frame time
    - $S > 1$: overflow
    - $0 < S < 1$: reasonable throughput
- **Old(retransmission) and new combined transmission**
  - Poisson distribution with mean G frames/frame time
    - At low load : $G \sim S$
    - At high load : $G > S$
- **Throughput**
  - Offered load(G) x P_S(The prob. Of a transmission being successful)

$$S = GP_S$$

ALOHA(3)

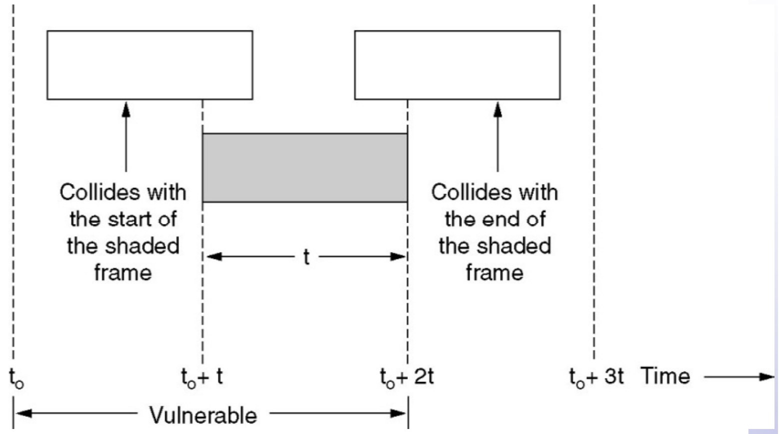


Collision mechanism in ALOHA

ALOHA(4)

- **The prob. that k frames are generated during a given frame time since Poisson distribution**

$$\Pr(k)=\frac{G^k e^{-G}}{k!},\quad \sum_{k=0}^{\infty} k\Pr(k)=G$$



- **The prob. of zero frames is** e^{-G}

- **Vulnerable period**
  - Frame time의 2배 -> the prob. of no other traffic being initiated during the entire vulnerable period is $P_S = e^{-2G}$

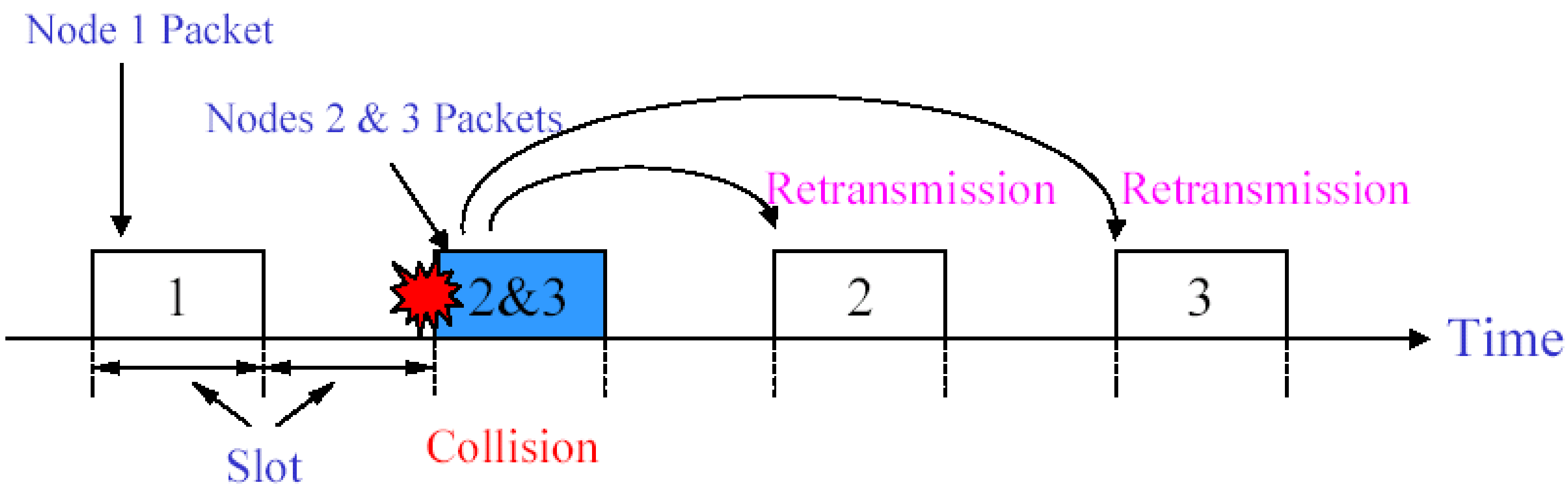
- **Throughput**

$$S = Ge^{-2G}$$

  - Maximum throughput : $S=\frac{1}{2e}$ when $G=0.5$

ALOHA(5)

Slotted ALOHA



Collision mechanism in slotted ALOHA

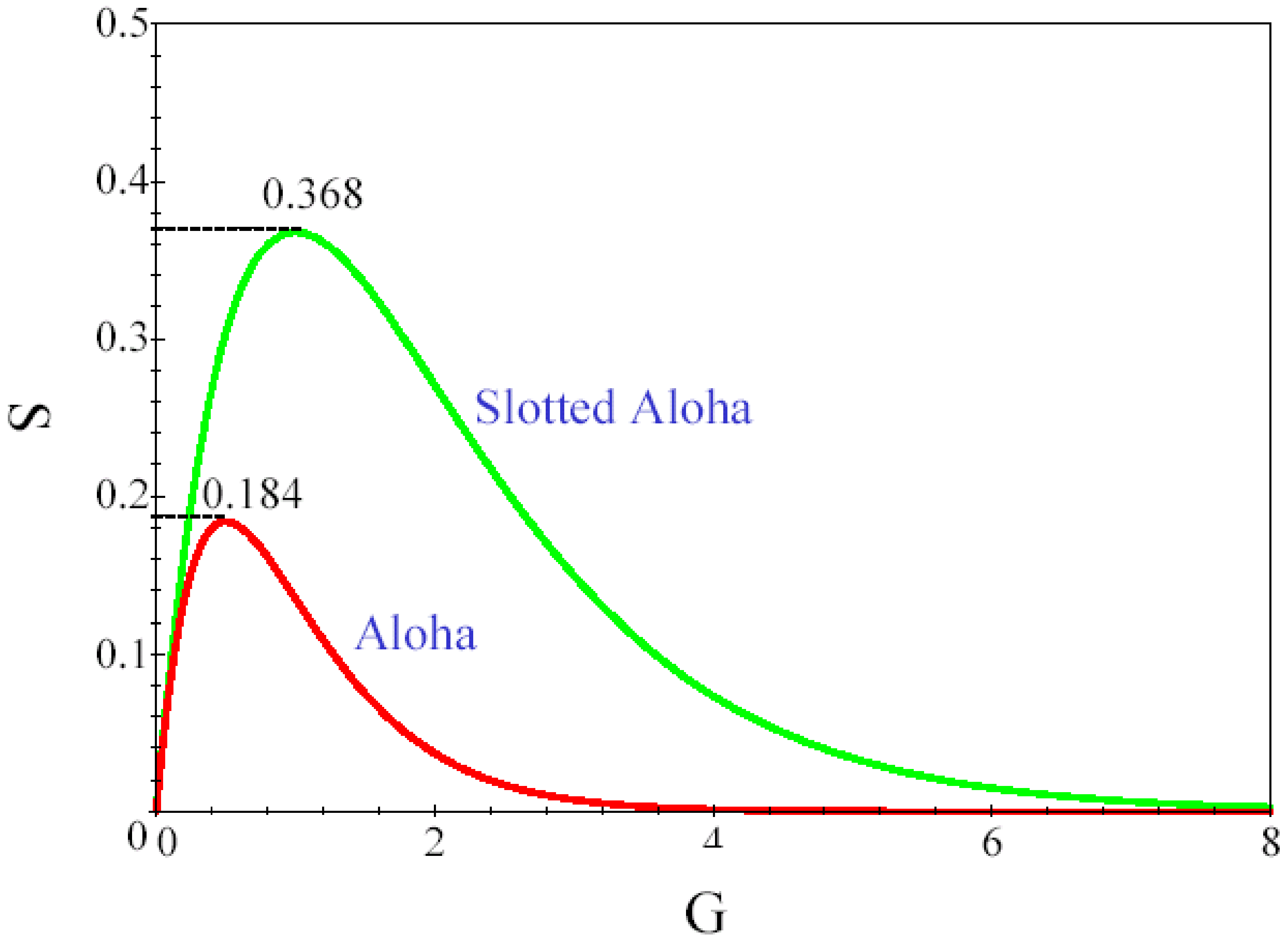
ALOHA(6)

- **Slotted ALOHA**
  - **Continuous -> discrete**
  - **Transmits at the beginning of the slot vulnerable period is reduced to one frame time**
  - **Throughput :** $S = Ge^{-G}$
    - Maximum throughput $S = 1/e$ when $G = 1$
    - G의 증가 -> collision의 증가
    - 임의의 값 G에 대해
      - The prob. It will avoid a collision is e^{-G}
      - Collision이 일어날 확률 $(1- e^{-G})$
    - k시도에 성공할 확률 : $P_k = e^{-G}\left(1-e^{-G}\right)^{k-1}$ (geometric distribution)
  - **Expected number of transmission**

$$E = \sum_{k=1}^{\infty} kP_k = \sum_{k=1}^{\infty} ke^{-G}\left(1-e^{-G}\right)^{k-1} = e^{-G}\sum_{k=1}^{\infty} k\left(1-e^{-G}\right)^{k-1} = e^{-G}\frac{1}{\left\{1-\left(1-e^{-G}\right)\right\}^2} = e^G$$

    - G에 대해 exponentially 증가

ALOHA(7)

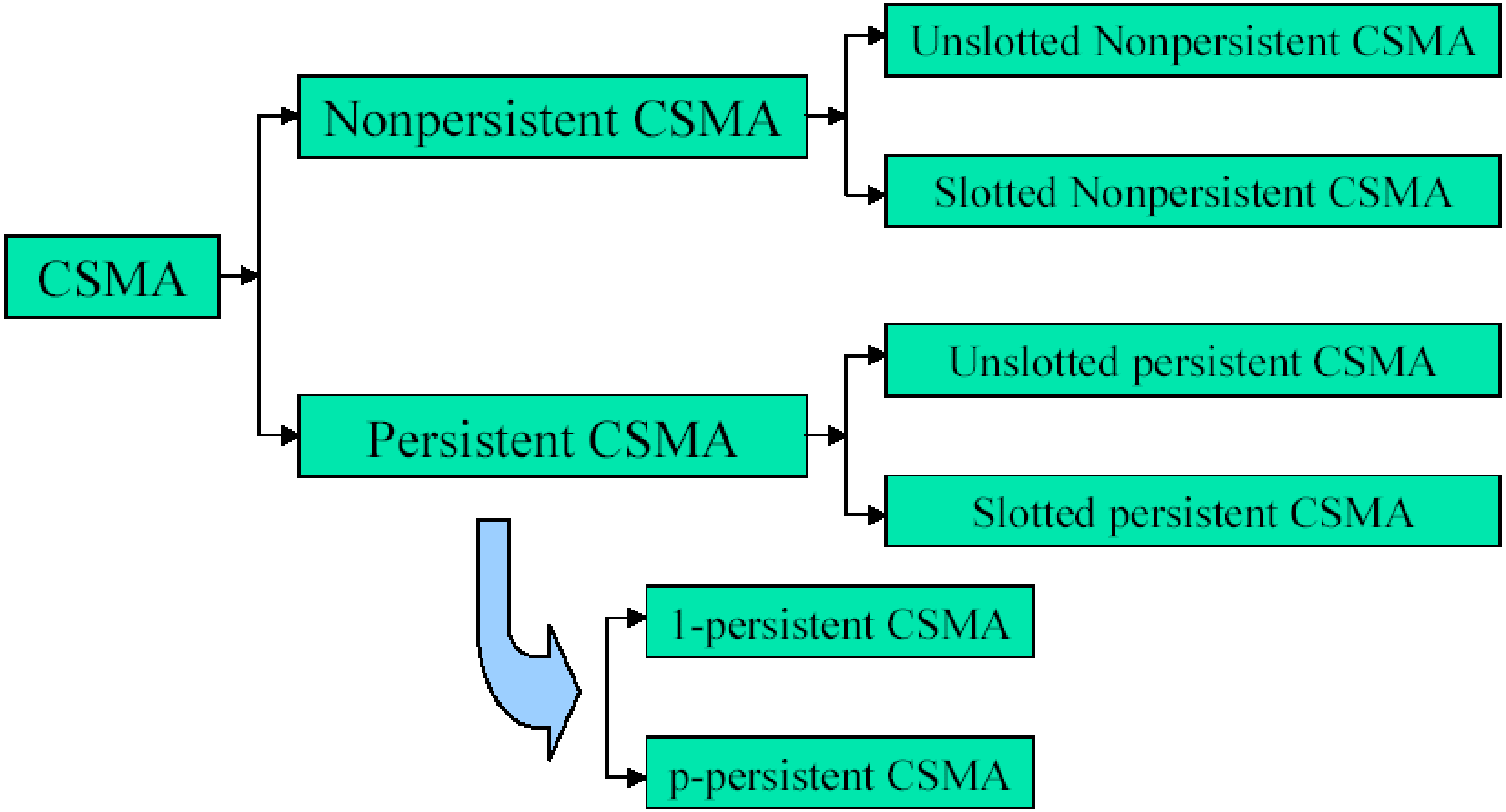


Carrier Sense Multiple Access Protocols(1)

- **Max throughput achievable by slotted ALOHA is 0.368**
- **CSMA gives improved throughput compared to ALOHA protocols**
- **Listens to the channel before transmitting a packet (avoid avoidable collisions)**

Carrier Sense Multiple Access Protocols(2)

- **Types of CSMA protocol**



Carrier Sense Multiple Access Protocols(3)

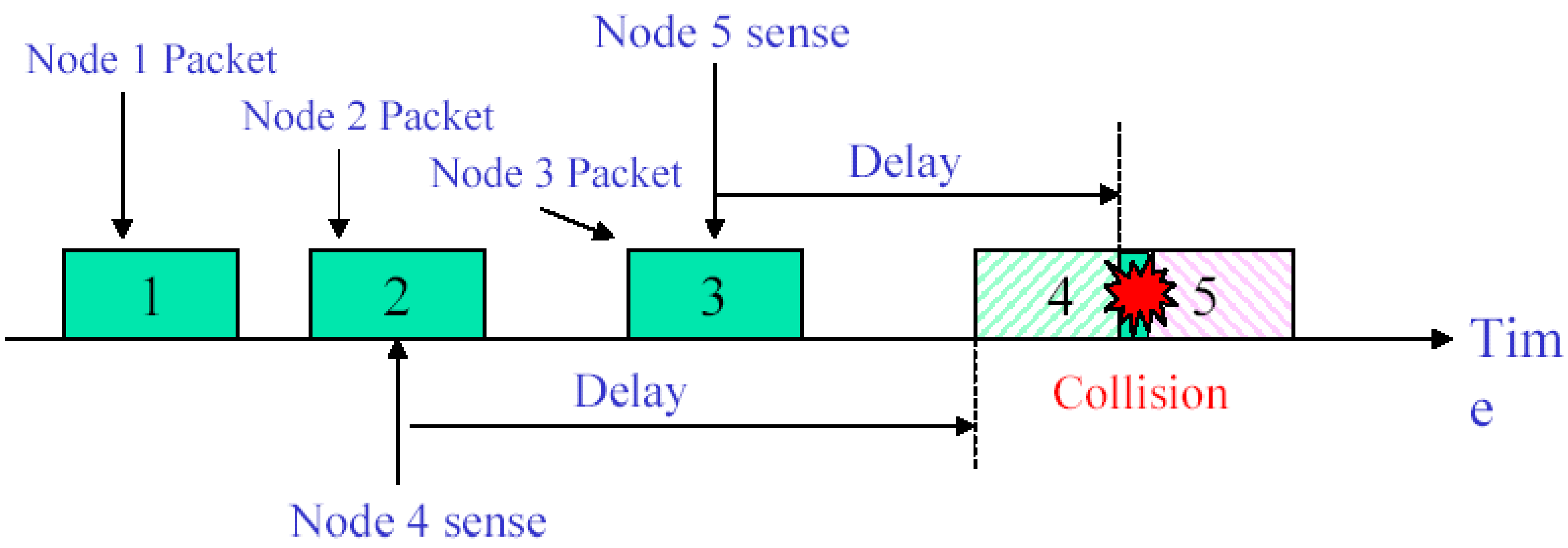
- **1-persistent and non persistent CSMA**
  - **Carrier sense protocol**
    - Stations listen for a carrier
  - **1-persistent CSMA**
    - Step 1: If the medium is idle, transmit immediately
    - Step 2: If the medium is busy, continue to listen until medium becomes idle, and then transmit immediately
      - There will always be a collision if two nodes want to retransmit
  - **Non-persistent CSMA**
    - Step 1: If the medium is idle, transmit immediately
    - Step 2: If the medium is busy, wait a random amount of time and repeat Step 1
      - Random backoff reduces probability of collisions
      - Waste idle time if the backoff time is too long

Carrier Sense Multiple Access Protocols(4)

- **p-persistent CSMA**
  - Apply slotted channel
  - Step 1: If the medium is idle
    - Transmit with probability *p*,
    - Delay for one propagation delay with probability q=1-p
  - Step 2
    - If the medium is busy, continue to listen until medium becomes idle, then go to Step 1
  - Step 3: If transmission is delayed by one time slot, continue with Step 1
  - A good tradeoff between non-persistent and 1-persistent CSMA

Carrier Sense Multiple Access Protocols(6)

Collision Mechanism in CSMA



Carrier Sense Multiple Access Protocols(5)

- **How to Select Probability *p* ?**
  - **Assume that *N* nodes have a packet to send and the medium is busy**
  - ***Np* is the expected number of nodes that will attempt to transmit once the medium becomes idle**
  - **If *Np* > 1, then a collision is expected to occur**
    - Therefore, network must make sure that $Np < 1$, where N is the maximum number of nodes that can be active at a time

Carrier Sense Multiple Access Protocols(6)

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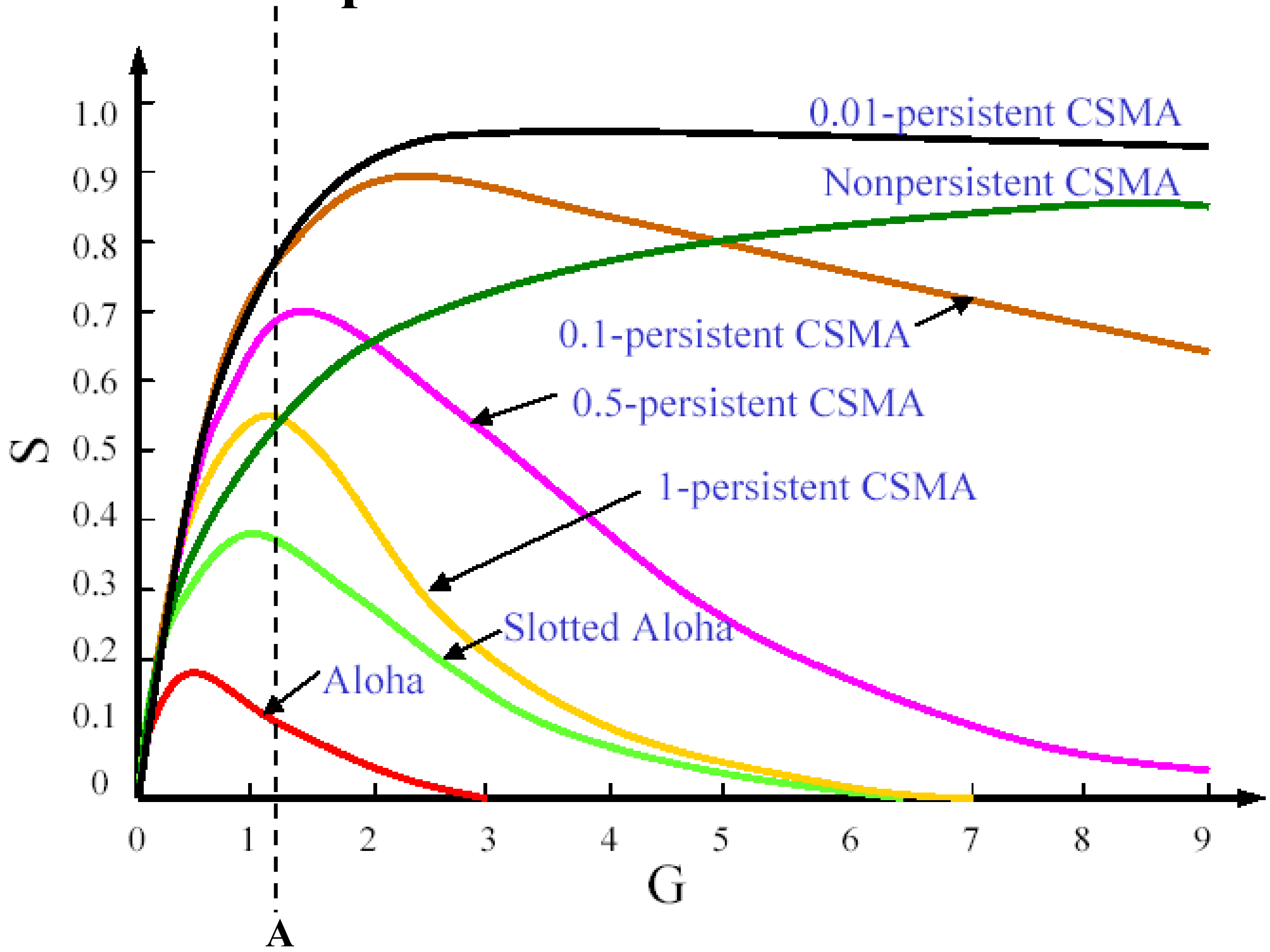
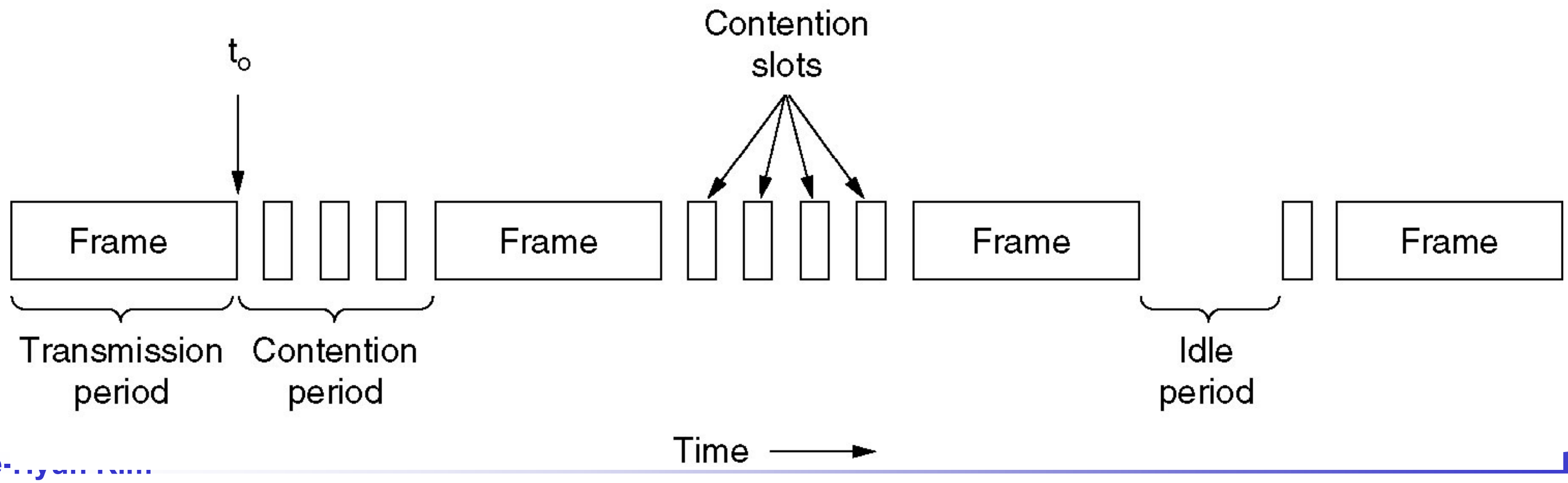
- **Comparison of the channel utilization vs. load for various random access protocols**



Carrier Sense Multiple Access Protocols(7)

- **CSMA/CD**
  - **Station abort their transmission as soon as they detect a collision**
    - Collision : power width
  - **Contention, Transmission, Idle periods가 존재**
  - **각 station은 full cable propagation time(τ)의 2배**
    - Worst case의 경우 2τ동안은 collision 이 발생했는지 들을수 없음
  - **Seized the channel**
    - 다른 모든 station들이 transmission 하는 것을 알고 방해 안 하는 경우
  - **Slotted ALOHA의 경우**
    - Contention interval : 2τ-> slot width
  - **두 개의 0 volt의 충돌을 detect할 수 없으므로 Manchester encoding**



Carrier Sense Multiple Access Protocols(8)

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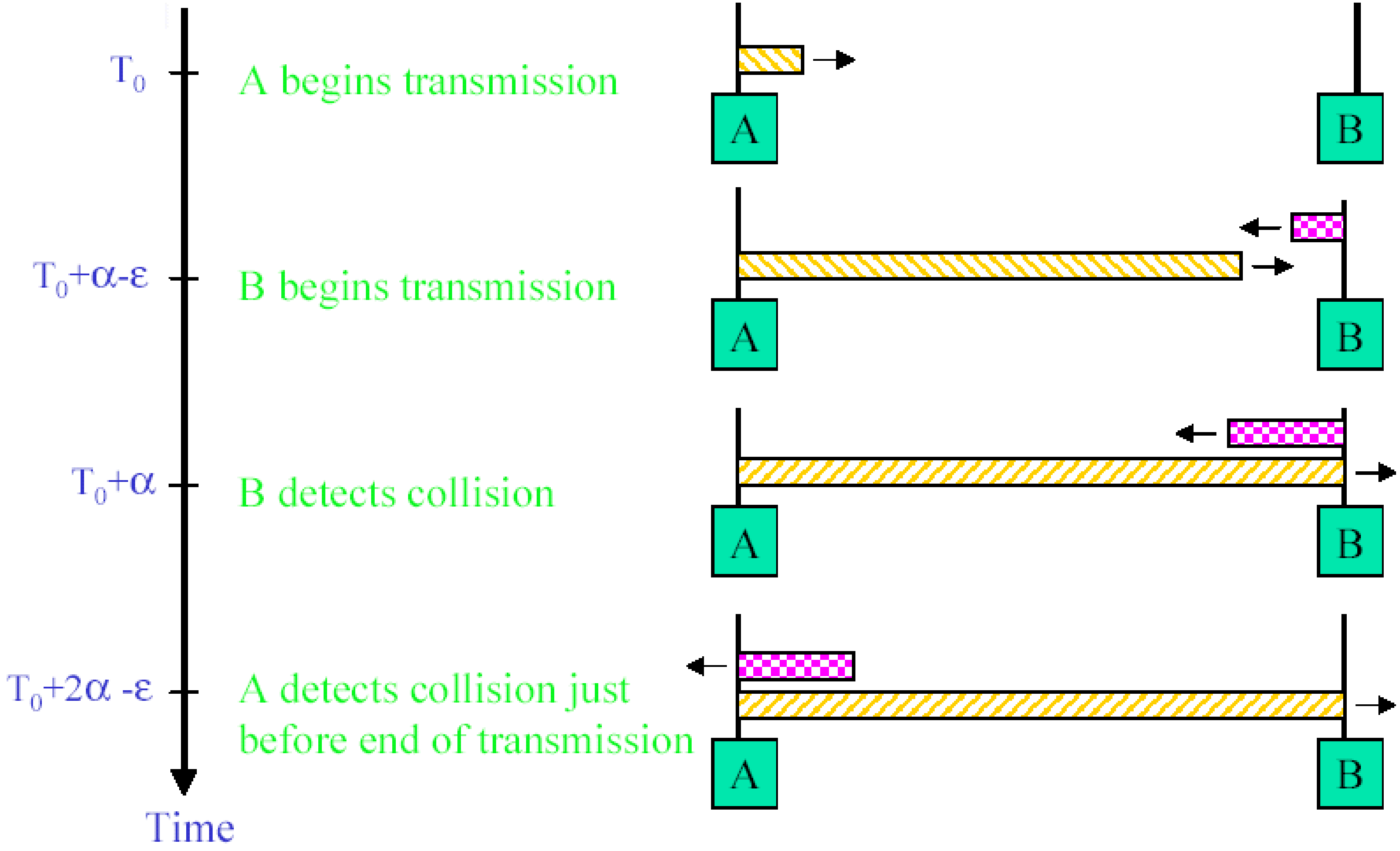
- In CSMA, if 2 terminals begin sending packet at the same time, each will transmit its complete packet (although collision is taking place).
- Wasting medium for an entire packet time.
- CSMA/CD
  - Step 1: If the medium is idle, transmit
  - Step 2: If the medium is busy, continue to listen until the channel is idle then transmit
  - Step 3: If a collision is detected during transmission, cease transmitting
  - Step 4: Wait a random amount of time and repeats the same algorithm

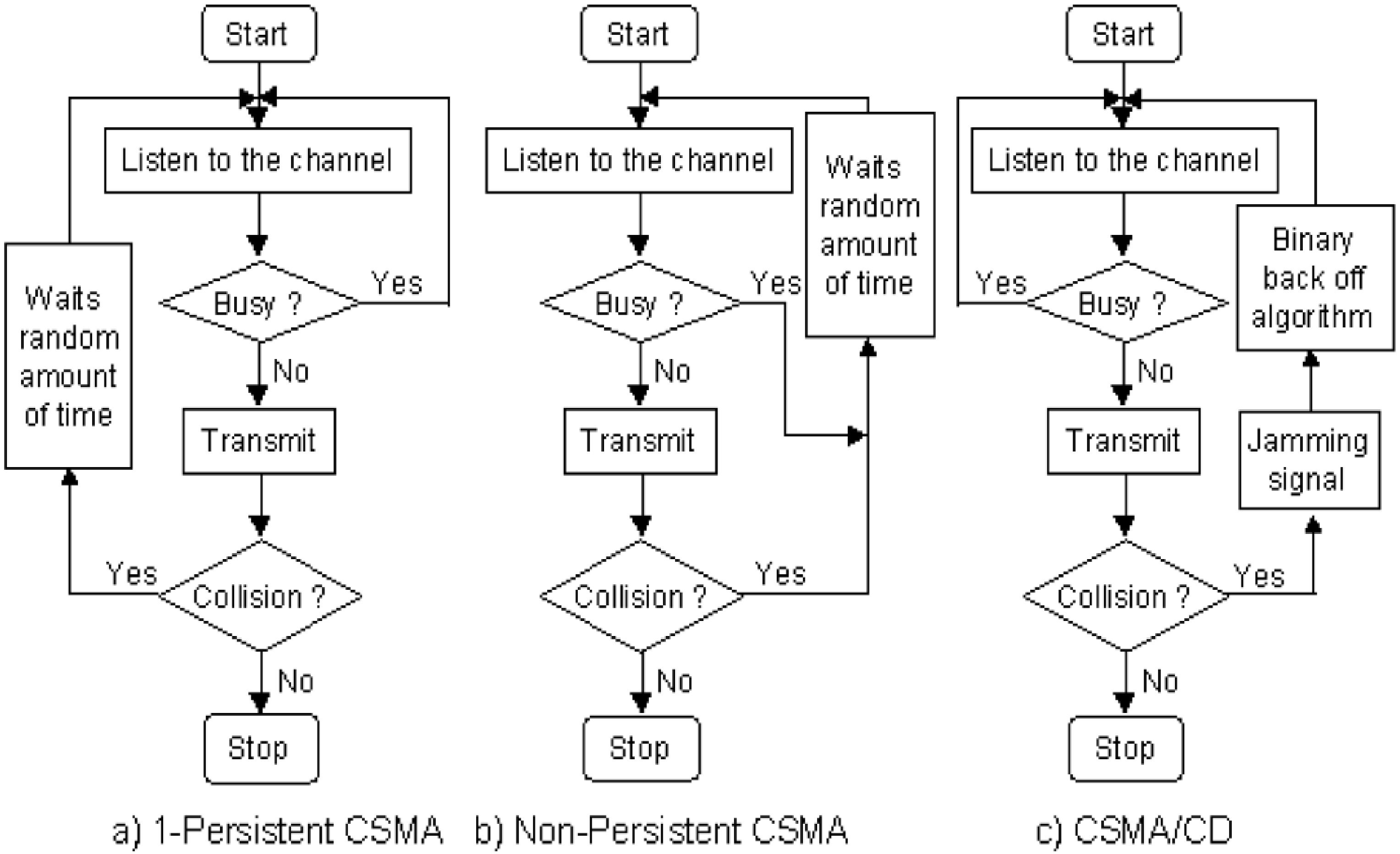
Carrier Sense Multiple Access Protocols(9)



(α is the propagation time)

Carrier Sense Multiple Access Protocols(10)

- **Flow chart for several CSMA protocols**



Carrier Sense Multiple Access Protocols(11)

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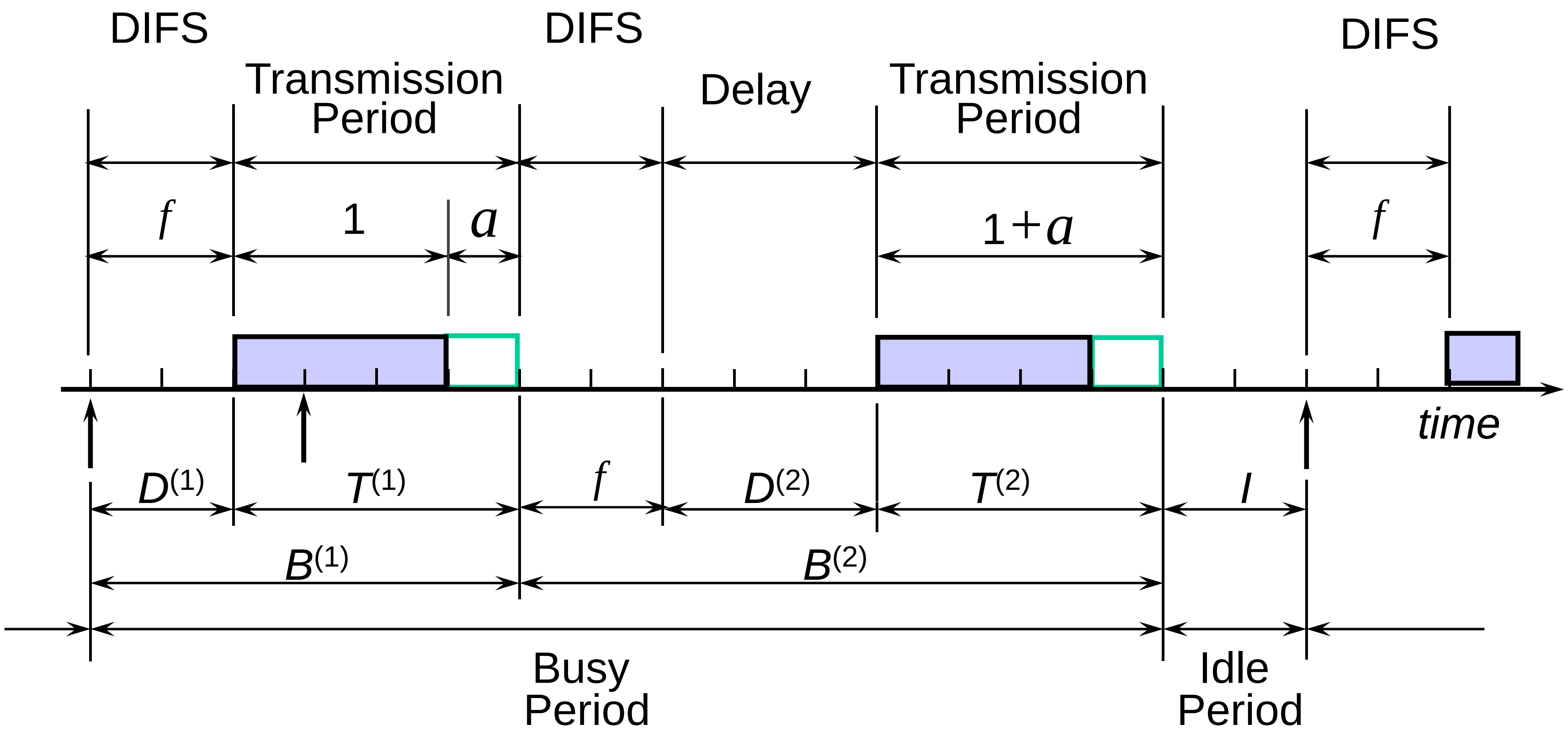
- **CSMA/CA(Collision Avoidance)**
  - **All terminals listen to the medium same as CSMA/CD.**
  - **Terminal ready to transmit senses the medium.**
  - **If medium is busy it waits until the end of current transmission.**
  - **It again waits for an additional predetermined time period DIFS (Distributed inter frame Space).**
  - **Then picks up a random number of slots (the initial value of backoff counter) within a contention window to wait before transmitting its frame.**
  - **If there are transmissions by other terminals during this time period (backoff time), the terminal freezes its counter.**
  - **It resumes count down after other terminals finish transmission + DIFS. The terminal can start its transmission when the counter reaches to zero.**

J. H. Kim and J. K. Lee, "Performance of Carrier Sense Multiple Access with Collision Avoidance Protocols in Wireless LANs," Wireless Personal Communications, Kluwer academic Publishers, Vol. 11 No. 2, pp.161-183, Nov. 1999.

System Model

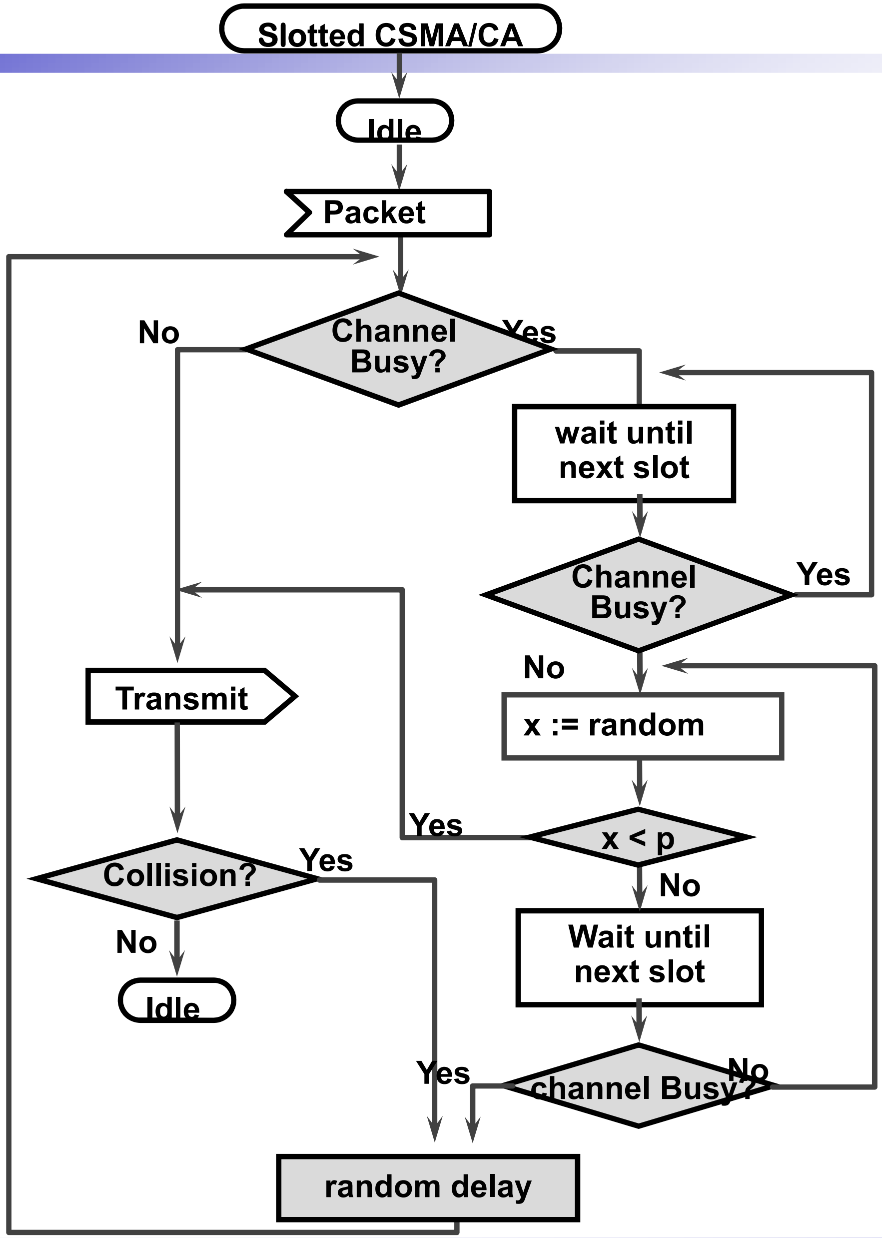
- System Model
  - **Finite population**
  - **Slotted Channel**
  - **CSMA/CA = 1-persistent CSMA + *p*-persistent CSMA**
  - **Cannel (Idle period and Busy period)**
    - Idle Period : no packet is generated
    - Busy period : one or more terminals try to transmit a packet
  - **Renewal Theory**
    - Idle period and Busy period are independent and geometric distribution
  - **The number of users : M**
  - **Slot size (propagation delay) : a**
  - **Packet arrival rate in a slot : g ($0 < g < 1$)**
  - **Packet transmission probability : p ($0 < p \leq 1$)**
  - **All terminals are synchronized.**
  - **Noiseless channel model**
  - **Non-capture effect**
  - **Distance of source and destination pairs is equal**

CSMA/CA Sub-period Model



- DIFS : DCF Inter-Frame Space

Basic CSMA/CA flow chart



CSMA/CA Throughput Analysis

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- **Basic concept**
  - **I : Idle period, B: Busy period, U : Useful transmission period**

$$S = \frac{\overline{U}}{\overline{I} + \overline{B}}$$

- 분석 순서
  - **평균 Busy period**
  - **평균 Useful transmission period**
  - **평균 Idle period**

Throughput of Basic CSMA/CA

$$S = \frac{\overline{U}}{\overline{B} + \overline{I}}$$

$$= \frac{\left[\frac{Mg(1-g)^{M-1}}{1-(1-g)^{M}} + \frac{1}{1-(1-g)^{((1/a)+1)M}} \sum_{N=1}^{M} \left\{ \sum_{k=1}^{\infty} [\, np(1-p)^{(k+1)n-1} \cdot (1-g)^{(k+1)(M-n)} + (M-n)(1-p)^{(k+1)n} g(1-g)^{(k+1)(M-n)-1} \,] + np(1-p)^{n-1} \right\} \cdot \left\{ \binom{M}{n} [\, 1-(1-g)^{((1/a)+1)} \,]^{n} (1-g)^{((1/a)+1)(M-n)} \right\} \right]}{\left[f[\, 1-(1-g)^{M} \,] + 1 + a + \frac{a}{1-(1-g)^{((1/a)+1)M}} \left((f+1+a)[\, 1-(1-g)^{((1/a)+1)M} \,] + a\sum_{k=1}^{\infty} \{(1-p)^{k} - (1-g)^{((1/a)+1)} [\, (1-p)^{k} - (1-g)^{k} \,]\}^{M} - a(1-g)^{((1/a)+a)M} \sum_{k=1}^{\infty} (1-g)^{kM} \right) + \frac{a}{1-(1-g)^{M}} \right]}$$

Analytic Results of Basic CSMA/CA

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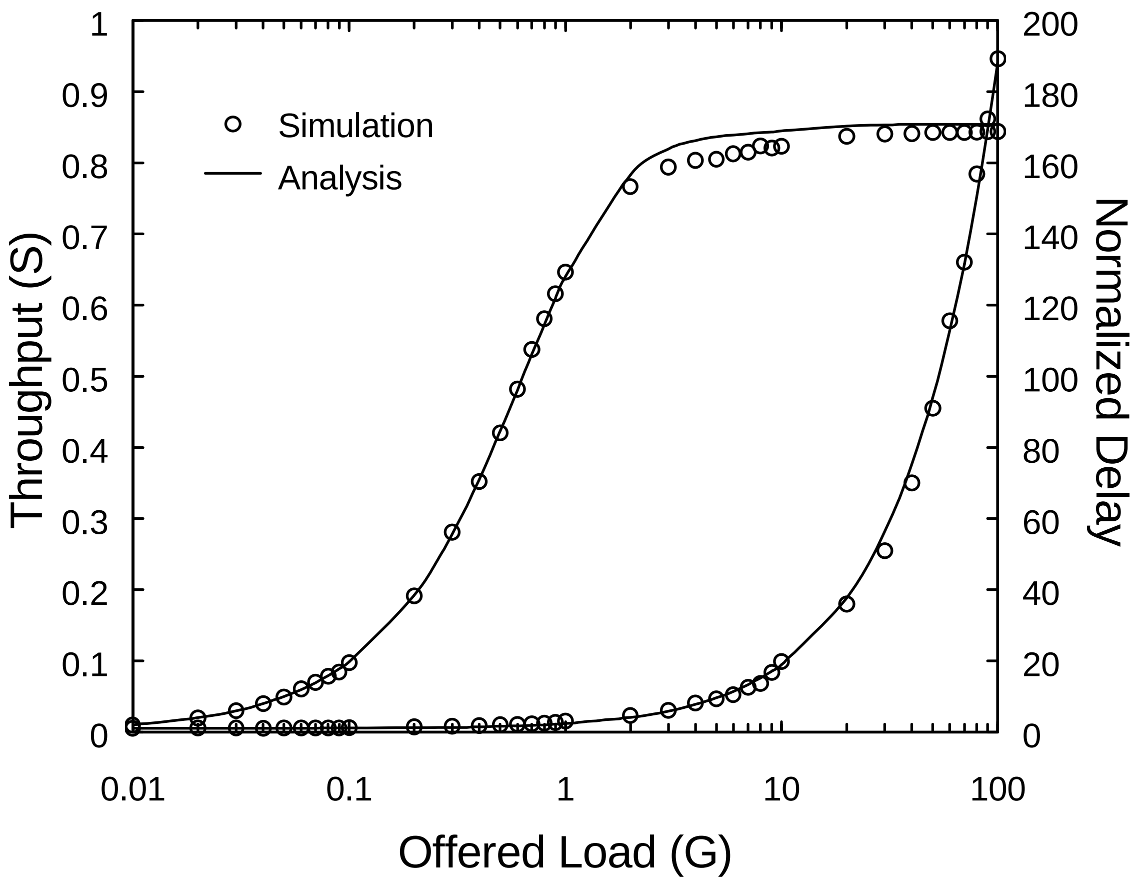
- **Throughput & Delay when the number of user is fixed at 5 (*a* = 0.01 , *p* = 0.03 , *l* = 3)**



CSMA/CA Delay Analysis

- Use channel throughput calculations
- Average number of retransmission for a packet[3]

$$\left(\frac{G}{S}-1\right)$$

- Channel state when the packet is arrived
  - Idle period : $\dfrac{\overline{I}}{\overline{B}+\overline{I}}$
  - Delay period in Busy period : $\dfrac{\overline{D}}{\overline{B}+\overline{I}}$
  - Transmission period in Busy period : $\dfrac{\overline{B}-\overline{D}}{\overline{B}+\overline{I}}$
- Average packet delay for Basic CSMA/CA
  - Y : Random delay

$$L=\left(\frac{G}{S}-1\right)[1+a+\overline{Y}+\overline{R}]+1+a+\overline{R}$$

CSMA/CA Delay Analysis

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- R (delay for a packet)

$$\overline{R} = \frac{\overline{I}}{\overline{B}+\overline{I}} f + \frac{\overline{D}}{\overline{B}+\overline{I}} f + \frac{\overline{B}-\overline{D}}{\overline{B}+\overline{I}}\left[\frac{\overline{(1+a)}^2}{2(1+a)} + E[D^{(2)}]\right]$$

- D (backoff delay)

$$\overline{D} = E[D^{(1)}] + (\overline{J}-1)E[D^{(2)}]$$

$$= f[1-(1-g)^M] + \frac{a}{(1-g)^{((1/a)+1)M}}$$

$$\bullet \left(\sum_{k=1}^{\infty}\{(1-p)^k - (1-g)^{((1/a)+1)}[(1-p)^k - (1-g)^k]\}^M - (1-g)^{((1/a)+a)M}\sum_{k=1}^{\infty}(1-g)^{kM}\right)$$

- E[$D^{(2)}$] calculation

$$E[D^{(2)}] = \frac{a}{1-(1-g)^{((1/a)+1)M}}\left(\sum_{k=1}^{\infty}\{(1-p)^k - (1-g)^{((1/a)+1)}[(1-p)^k - (1-g)^k]\}^M - (1-g)^{((1/a)+a)M}\sum_{k=1}^{\infty}(1-g)^{kM}\right)$$

Expansion to 1-Persistent CSMA in Infinite Population Model

- $p = 1\ , f = 0$ and $M \rightarrow \infty\ , aG = gM$

$$\overline{B} + \overline{I} = \frac{1+a}{e^{-G(1+a)}} + \frac{a}{1-e^{-aG}}$$

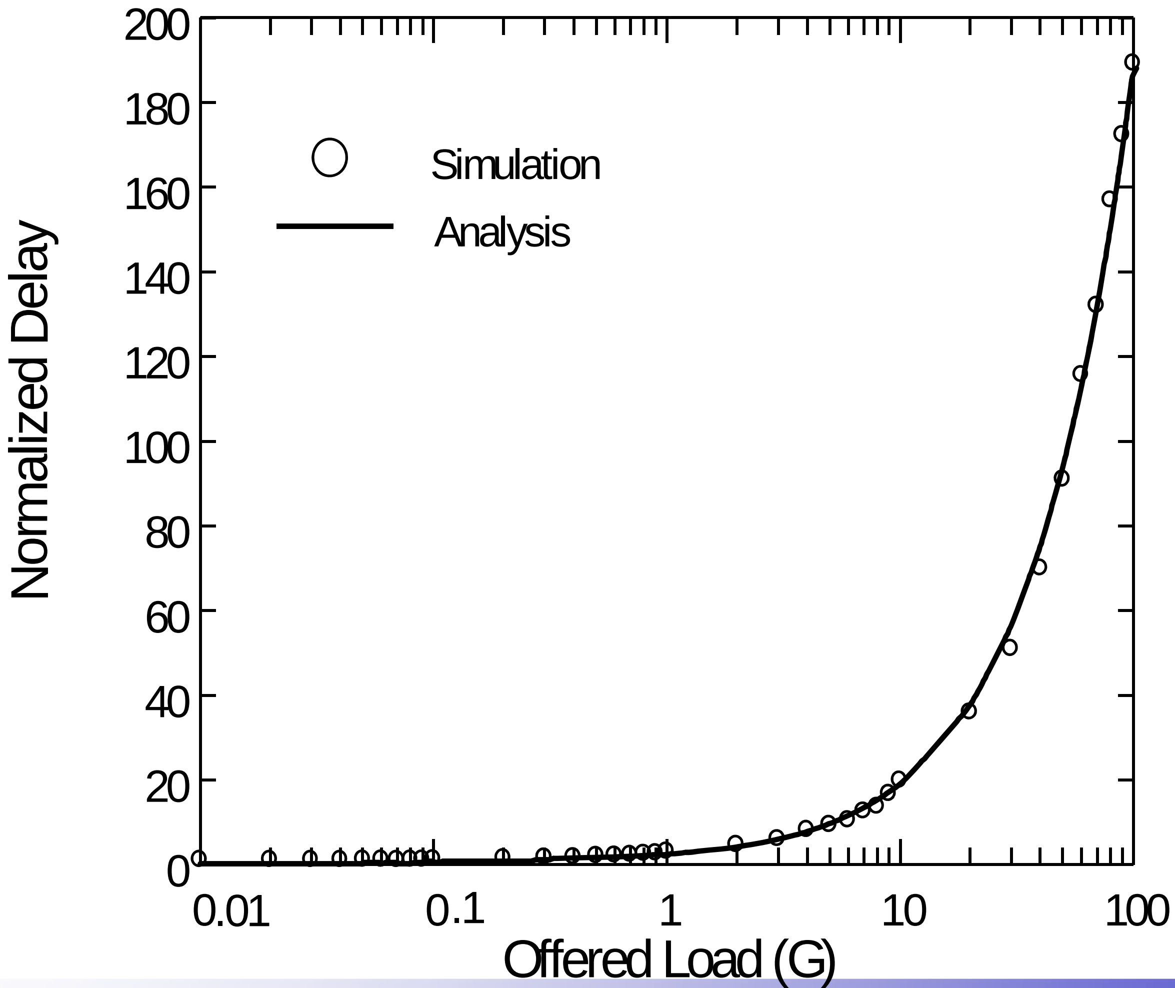
$$\overline{U} = \frac{aGe^{-aG}}{1-e^{-aG}} + \left(\frac{1}{e^{-G(1+a)}} - 1\right)\frac{G(1+a)e^{-G(1+a)}}{1-e^{-G(1+a)}}$$

- Slotted 1-persistent CSMA => In 1975, Kleinrock's result

$$\overline{S} = \frac{Ge^{-G(1+a)}[1+a-e^{-aG}]}{(1(1+a)(1+e^{-aG})+ae^{-G(1+a)}}$$

Analytic Results of Basic CSMA/CA

- **Packet delay of Basic CSMA/CA when the number of users is fixed at 5 (*a* = 0.01 , *p* = 0.03 , *l* = 3)**

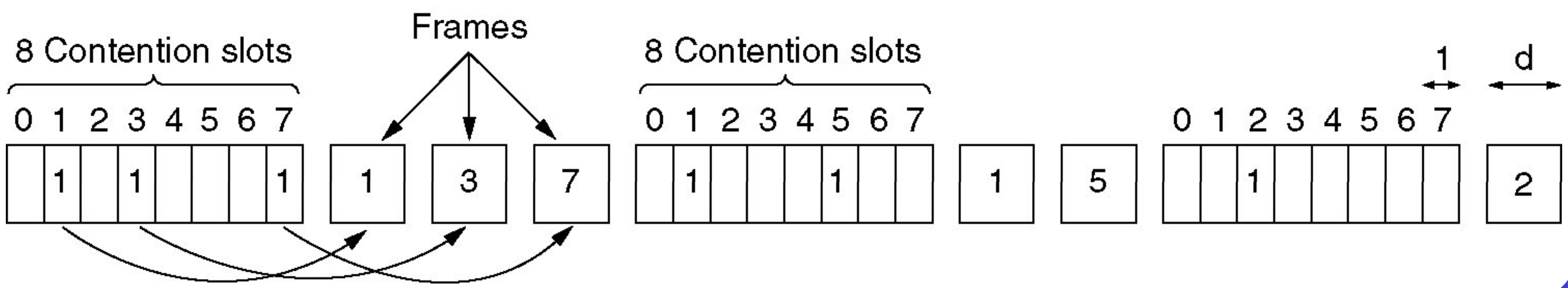


Contention Free Protocols

- A Bit-Map Protocol
  - BRAM
  - MLMA
- Binary Countdown Protocol
- Limited-Contention Protocols
  - Binary Tree Algorithm

Collision-Free Protocols(1)

- **Bit-map protocol**
  - **Each contention period consists of exactly *N* slots**
  - **Station *j* may announce that it has a frame to send by inserting a 1 bit into slot *j***
  - **Ex.) If station 0 has a frame to send**
    - It transmits a 1 bit during the zero the slot
  - **Advantages**
    - Deterministic delay bound
  - **Disadvantages**
    - Higher numbered station has to wait for long data delay, Low number may wait for next reservation slot => unfair
    - System should know # of St
    - Not efficient for low traffic load



Collision-Free Protocols(2)

- **Performance of bit-map protocol**
  - **Measure time in units of the contention bit slot**
  - **Data frames consist of *d* time units**
  - **Low load**
    - Mean waiting time is N slots
      - Low-numbered station : wait on the average $1.5N$ slots
        - $N/2$ slots for the current to scan to finish
        - N slots for the following scan to run to completion before it may begin transmitting
      - High-numbered station : wait on the average $0.5N$ slots
    - Channel efficiency : $d/(d+N)$
  - **High load**
    - All station have something to send all the time (N stations and N slots)
    - Channel efficiency : $d(d+1)$

Collision-Free Protocols(3)

- **BRAM (Broadcasting Recognition Access Method)**
  - **Basic Bit MAP + round robin**
  - **N_1 : index of last transmitted St. , N_2 : index of me, N : total # of ST., G: # of group**
- **Fair BRAM (FB), Parametric Fair BRAM(PFB)**

$$H(n_1, n_2) = \begin{cases} (n_1 - n_2 + N(G)) \text{ modular } N & ; n_1 \neq n_2 \\ N & ; n_1 = n_2 \end{cases}$$

- **Prioritized BRAM (PB), Parametric Prioritized BRAM (PPB)**
  - **Gives priority to the last transmitted ST or Group**

$$H(n_1, n_2) = (n_1 - n_2 + N(G)) \text{ modular } N$$

Collision-Free Protocols(4)

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- **MLMA (Multi-Level Multi-Access) Protocol**
  - **1977 : Rothauser, Wild**
  - **Reserve the bit of digit of address**
  - **Little bit complex**
  - **Ex : 122, 125, 705, 722, 725 ST try to transmit**

bit	9	8	7	6	5	4	3	2	1	0	
0			1						1		(725,722,705,125,122)
1								1		1	(725,722,705)
2					1			1			(725,722) TX
3					1						705 TX
4								1			(125,122)
5					1			1			(125,122) TX

RFID

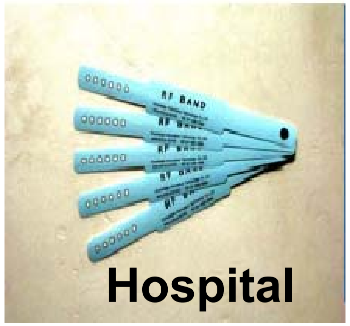
-. RFID Overview

-. Anti-collision Algorithm

-. Performance Evaluation

RFID Overview

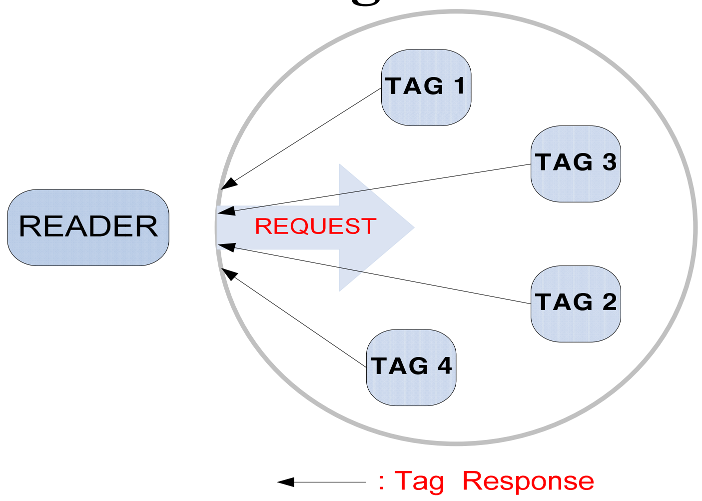
- What is the RFID system?
  - The RFID system is a simple form of ubiquitous sensor networks that are used to identify physical objects
- Application of RFID system
  - Asset tracking(e.g. libraries, animals)
  - Automated inventory
  - Stock-keeping
  - Toll collecting



Anti-Collision Algorithm

- Tag collision problem in RFID system
  - It is impossible to communicate among passive tags
  - The reader broadcasts the request message to the tags
  - If there are more than one tag response for the reader's request, their responses will collide

- We need an anti-collision algorithm to solve collision problem



Tag collision problem

Multi-tag anti-collision algorithm in RFID

	Arbitration	Air Interface (R->T / T->R)	EPC	Data rate (R->T / T->R)	Security
ISO 18000-6 TYPE A	Framed Slotted	Pulse interval ASK / FM0	not defined	33 kbps / 40 kbps	None
ISO 18000-6 TYPE B	Probabilistic Binary tree	Manchester-ASK / FM0	not defined	8/40 kbps / 40 kbps	None
AutoID Class 0	Bit-by-bit Binary Tree	Pulse Width Mod./ FSK	64/96b	40/80 kbps / 40/80 kbps	24-bit kill
AutoID Class 1	Binary tree using 8 bin slots	Pulse Width Mod. / Pulse Interval AM	64/96b	70.18 kbps/ 140.35 kbps	8-bit kill
EPCglobal Gen 2	Probabilistic Slotted	Pulse interval ASK / Miller, FM0	96/496b	40 kbps / 640 kbps	32-bit kill, Access

EPC™, Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz – 960 MHz Version 1.0.9, Jan., 2004.
ISO/IEC 18000-6 : 2005(E), Part 6C : parameters for air interface communications at 860 MHz to 960 MHz, 2005.

RFID 태그 인식 기술

TYPE A

READER	1st REQ	Slot1	Slot2	Slot3	Slot4	2nd REQ
STATE		1011	IDLE	COLL	0101	
TAG1(1011)		1011				
TAG2(1010)				1010		1010
TAG3(0011)				0011		0011
TAG4(0101)					0101	

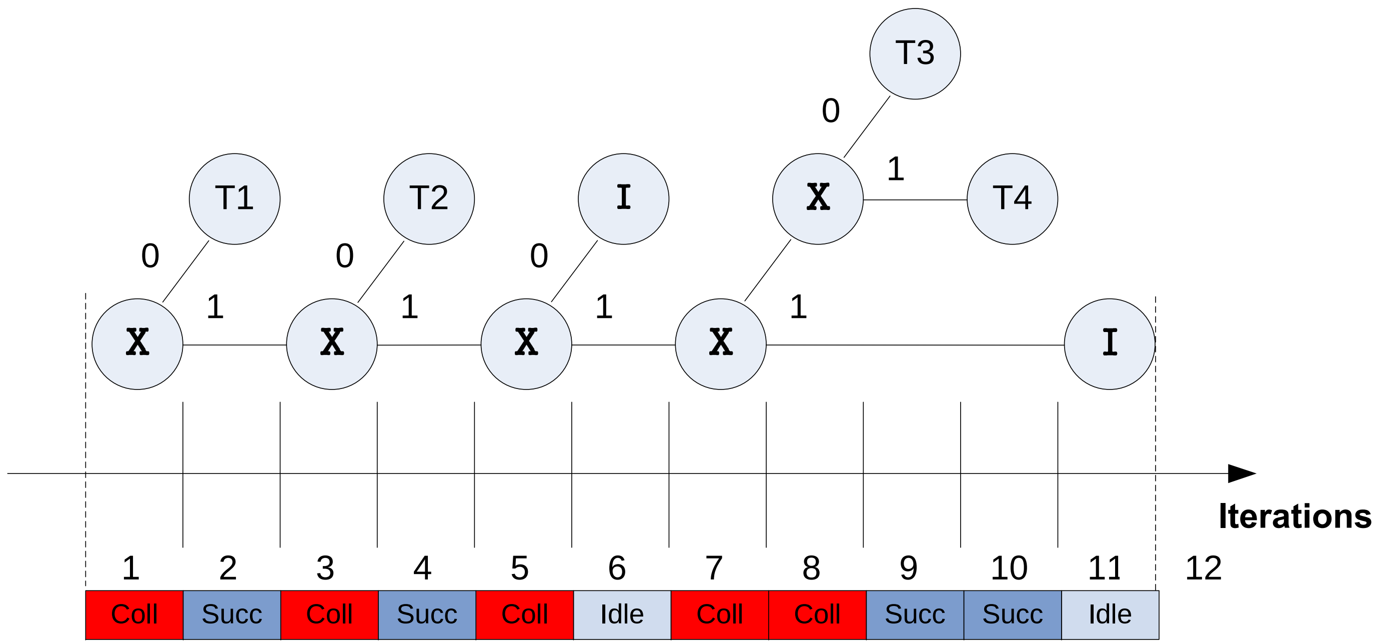
Frame size = 4

Frame size = ?

Need to vary the Frame size for the number of tags

RFID 태그 인식 기술

TYPE B



RFID 태그 인식 기술

Class 0

	READER	TAG	READER	TAG	READER	TAG	READER	TAG	READER
	CMD	REPLY	X(0)	REPLY	X(0)	REPLY	CMD	REPLY	X(0)
STATE		X		X		001		X	
TAG1(001)		0		0		1			
TAG2(011)		0		1				0	
TAG3(100)		1						1	

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RFID 태그 인식 기술

Class 1

Reader			TAG							
COMMAND	PingID	REQ.	Bin 0 (000)	Bin 1 (001)	Bin2 (010)	Bin 3 (011)	Bin 4 (100)	Bin 5 (101)	Bin 6 (110)	Bin 7 (111)
POINTER	0000 0000									
LENGTH	0000 0111									
VALUE	10100001									
STATUS			IDLE	SUCC	COLL	IDLE	IDLE	SUCC	IDLE	IDLE
TAG 1 (1010001110101010)	TAG 1 sends ITM (Full ID)			00111010						
TAG 2 (1010010101001010)					01010100			10100101		
TAG 3 (1010010010011010)					01001101					

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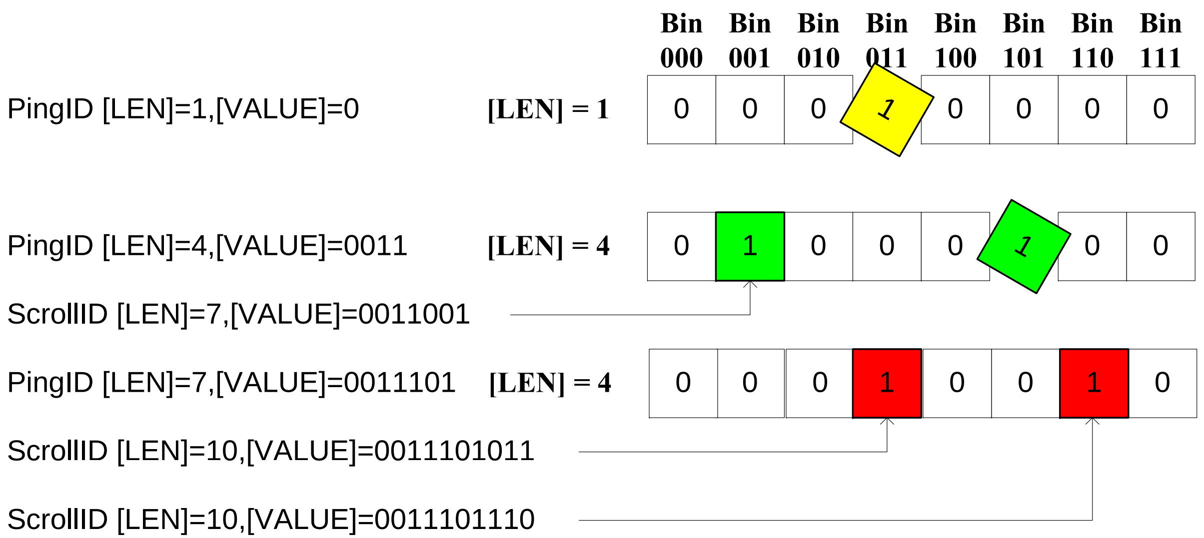
RFID 태그 인식 기술

Class 1

Tag_1	0	0	1	1	0	0	1	1	1	1	0	0	0	0	………………
Tag_2	0	0	1	1	1	0	1	0	1	1	1	0	0	0	………………
Tag_3	0	0	1	1	1	0	1	1	1	0	1	0	0	0	………………



RFID 태그 인식 기술

Class 1 Gen 2

Reader				
Command	Query / ACK / QueryRep		Tag1	Tag2
Session	S0 / n.a.	S.C.	0	0 / 2
Target	A / n.a.	I.F.	A / B	A
Q	2 / n.a.	S	S0	S0
		Act	Send RN16 / Send EPC (ID)	Send RN16 / Wait

where, S.C. : Slot Counter, I.F. : Inventoried Flag, S : Session, Act. : Action

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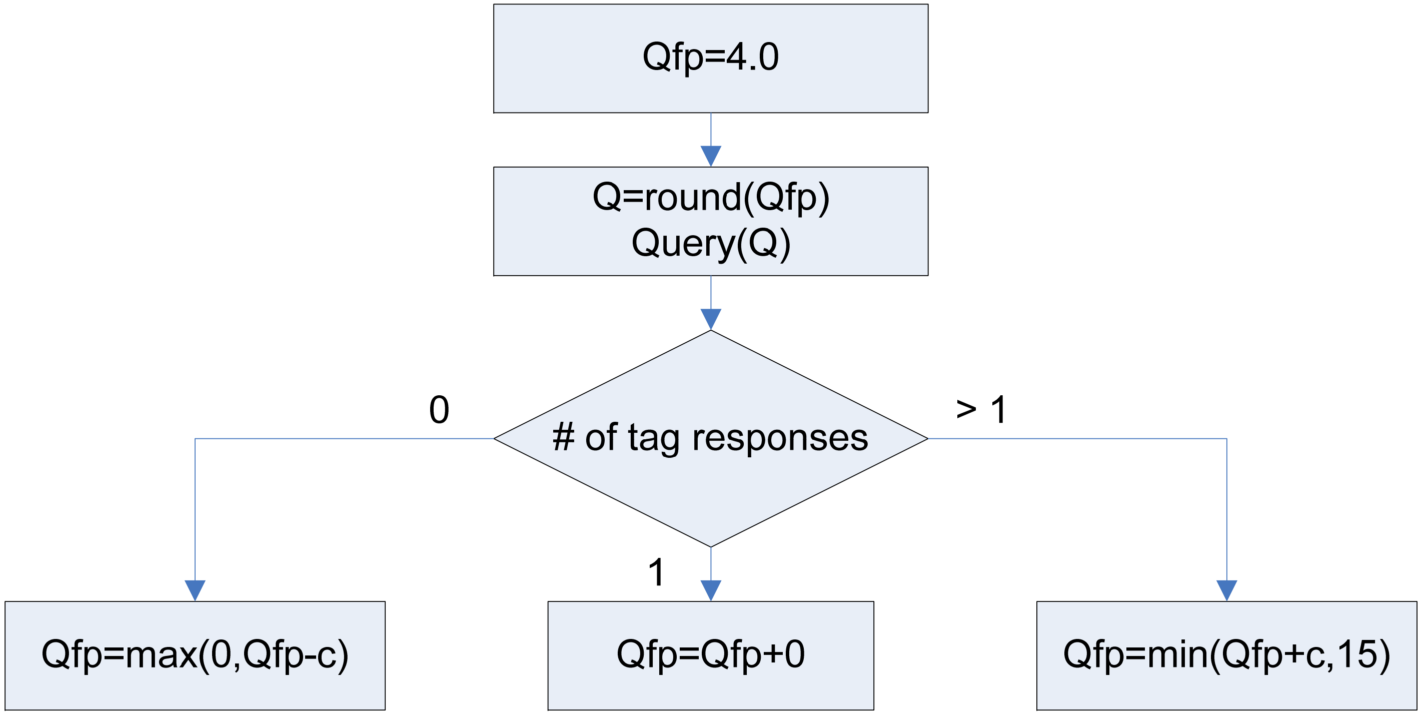
Q-Selection algorithm



※ Typical values for c are 0.1<c<0.5.

Dynamic framed slotted ALOHA I/II algorithms

- **Dynamic framed slotted ALOHA I/II algorithms**
  - **Enhance the performance of the algorithm defined in ISO 18000-6 Type A**
- **Basic concept**
  - **Two Tag Estimation Methods (TEM)**
    - Ratio of the number of collided slots to the frame size

$$C_{ratio} = \frac{\text{Number of collided slots}}{\text{Frame size}} = 1 - \left(1 - \frac{1}{L}\right)^n \left(1 + \frac{n}{L-1}\right).$$

    - Number of tags related with collision in a slot

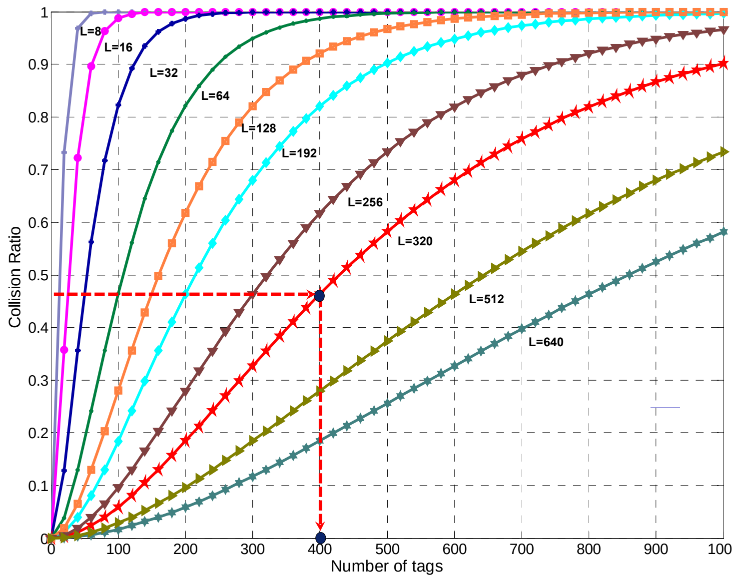
$$C_{rate} = \frac{\text{Prob. that there is the collision in a slot}}{\text{1- Prob. that a tag transfers its ID successfully}} = \frac{P_{coll}}{P_{idle} + P_{coll}}$$

$$C_{tags} = \frac{1}{C_{opt\_rate}} = 2.3922 .$$

$$\text{Number of estimated tags} = 2.3922 \times M_{coll}$$

Where M_{coll} means the number of collided slots in a frame

Process for tag estimation



J. R. Cha and J. H. Kim, "Dynamic Framed Slotted ALOHA Algorithm using Fast Tag Estimation method for RFID System," in *Proc. CCNC2006*, Las Vegas, USA, Jan. 8-10, 2006.

RFID Performance Analysis

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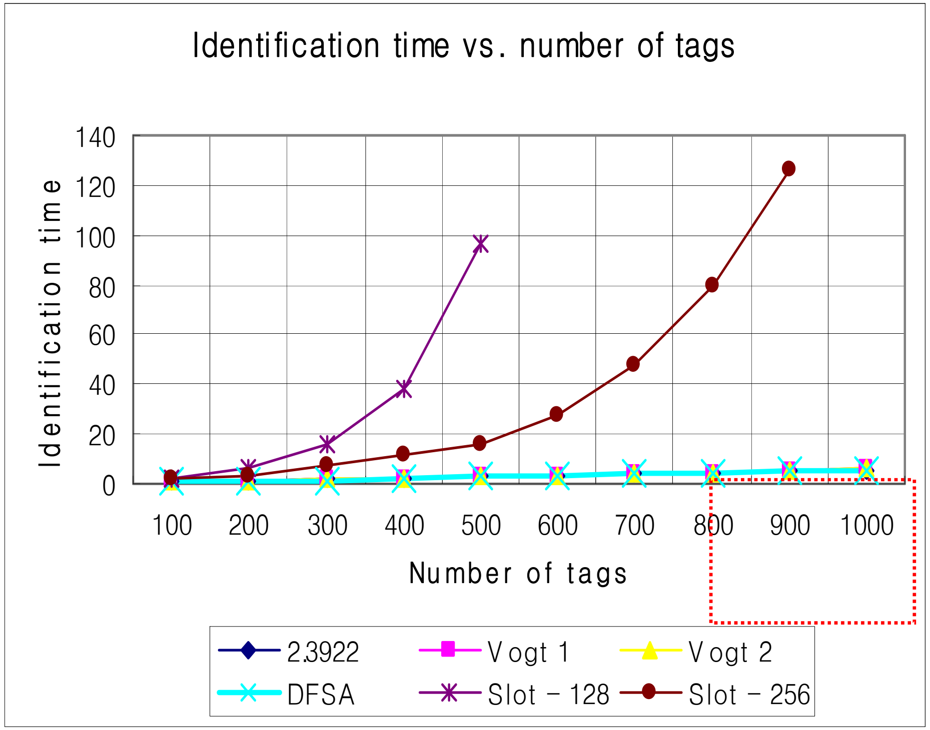
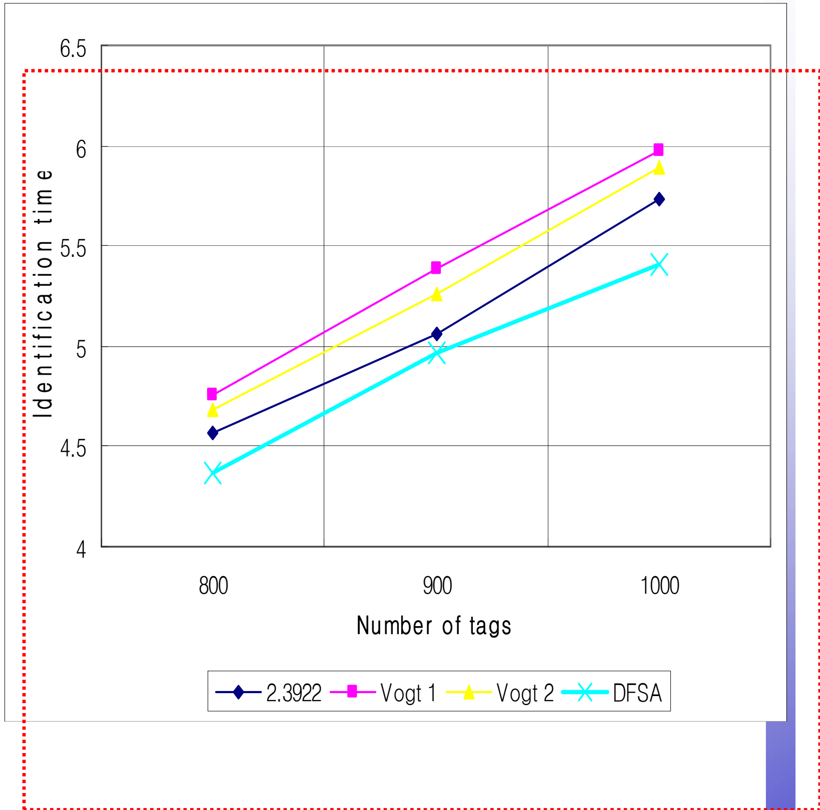
Performance evaluation





J. R. Cha and J. H. Kim, "Dynamic Framed Slotted ALOHA Algorithm using Fast Tag Estimation method for RFID System," in Proc. CCNC2006, Las Vegas, USA, Jan. 8-10, 2006

IEEE 802.11

-. Wireless LAN Architecture

-. QoS Mechanism

-. Channel Access Mechanism

-. Research Issue

Wireless MAC Protocols (IEEE 802.11)

- 무선 LAN관련 MAC 프로토콜 연구 동향
- CSMA 방식
  - L. Kleinrock and F.A. Tobagi : 1975년 CSMA 방식 분석
  - 1-persistent CSMA → Ethernet에서 적용 (CSMA/CD)
- ALOHA 방식 : N. Abramson : 1970 년 하와이 대학에서 개발
- PRMA (Packet Reservation Multiple Access) 방식
  - D.J. Goodman (미국, Rutgers대학) → 1989년 제안
- CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance)
  - CSMA/CD (Carrier Sense Multiple Access/Collision Detection) 방식을 개선 → 무선상에서 패킷충돌 감지가 어려움
  - 패킷간의 충돌 확률을 줄임
  - 다양한 IFS(Inter Frame Space) 를 사용하여 음성 및 데이터의 서비스 가능

Major Task Groups in 802.11 standard

Task Group	Objectives
802.11 a	PHY & MAC for 5 GHz
802.11 b	PHY & MAC for 2.4 GHz
802.11 e	MAC Enhancements for Quality of Service
802.11 f	Inter Access Point Protocol
802.11 g	Higher Rate (20+ Mbps) in the 2.4GHz
802.11 h	Spectrum Managed 802.11a
802.11 i	MAC Enhancements for Enhanced Security
802.11 k	Radio Resource Measurement Enhancements
802.11 n	High Throughput

IEEE 802.11 Overview (PHY & Data Rates)

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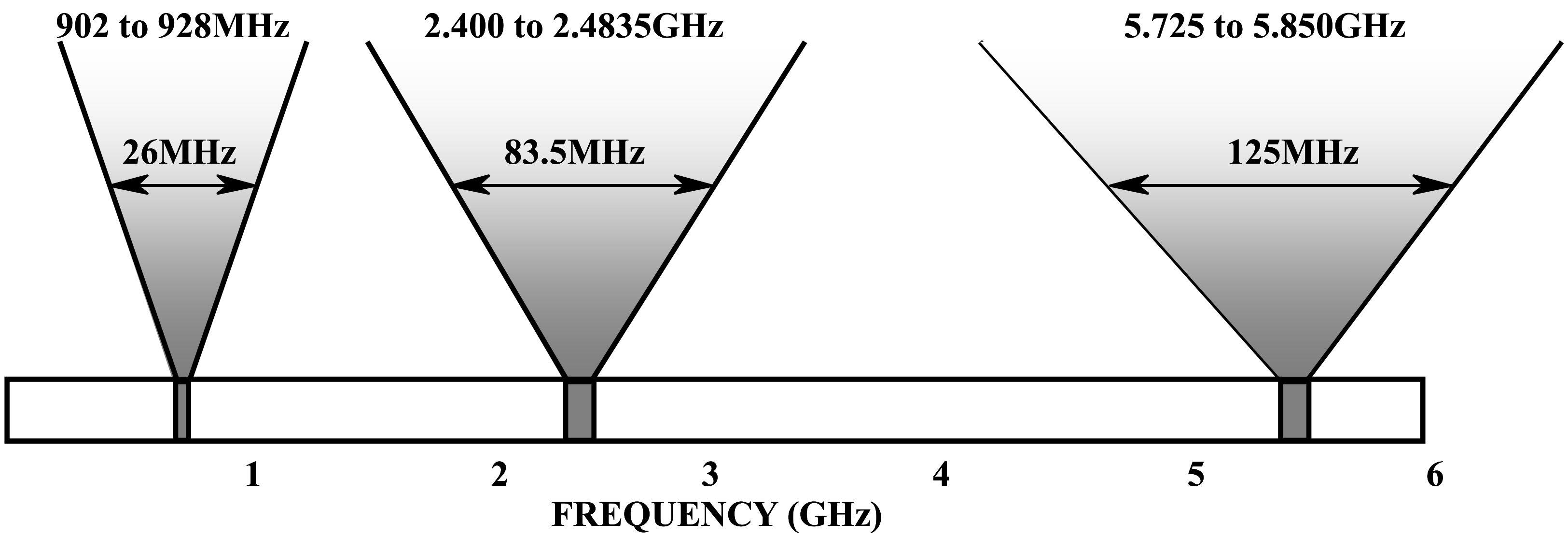
		802.11a		802.11b		802.11g	
Frequency		5.2 GHz		2.4GHz			
Data Rate (Mbps)	Carrier	PHY Modulation Scheme					
		Mandatory	Optional	Mandatory	Optional	Mandatory	Optional
1	Single			DS/SS		DS/SS	
2	Single			DS/SS		DS/SS	
5.5	Single			CCK	PBCC	CCK	PBCC
6	Multi	OFDM				OFDM	CC-OFDM
9	Multi		OFDM				OFDM, CCK-OFDM
11	Single			CCK	PBCC	CCK	PBCC
12	Multi	OFDM				OFDM	CC-OFDM
18	Multi		OFDM				OFDM, CCK-OFDM
22	Single						PBCC
24	Multi	OFDM				OFDM	CC-OFDM
33	Multi						PBCC
36	Multi		OFDM				OFDM, CCK-OFDM
48	Multi		OFDM				OFDM, CCK-OFDM
54	Multi		OFDM				OFDM, CCK-OFDM

Wireless LAN Frequency Bands

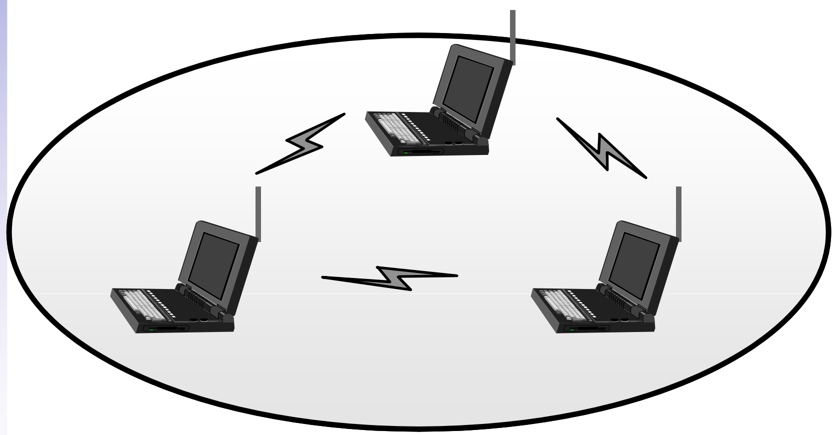
Industrial, Scientific and Medical (ISM) Bands



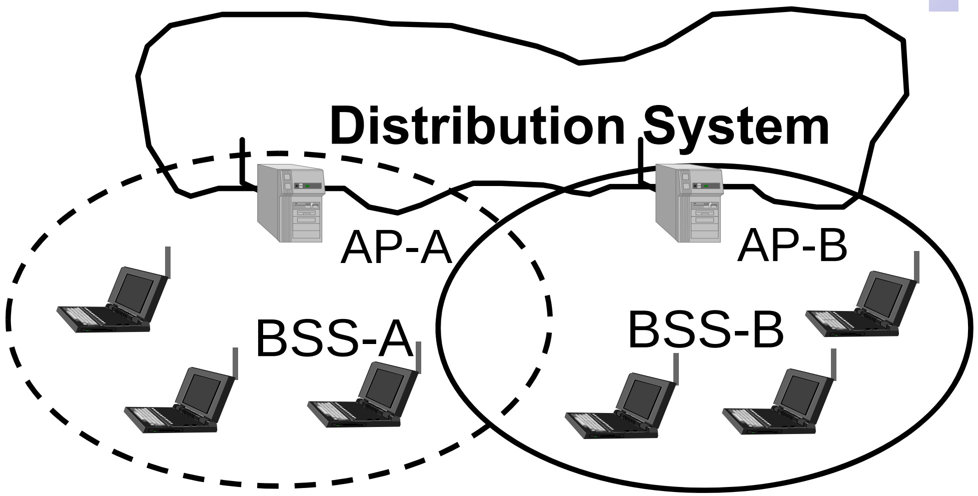
- UNLICENSED OPERATION GOVERNED BY FCC DOCUMENT 15.247, PART 15
- SPREAD SPECTRUM ALLOWED TO MINIMIZE INTERFERENCE
- 2.4GHz ISM BAND
  - More Bandwidth to Support Higher Data Rates and Number of Channels
  - Available Worldwide
  - Good Balance of Equipment Performance and Cost Compared with 5.725GHz Band
  - IEEE 802.11 Global WLAN Standard

Wireless LAN Architecture

- **Ad hoc WLAN Mode**
  - **Peer-to-peer communication only**
  - **Independent Basic Service Set → IBSS**
- **Infrastructure WLAN Mode**
  - **No peer to peer communication, always through AP**
  - **Distribution system : Connect two or more BSS**



Ad hoc network



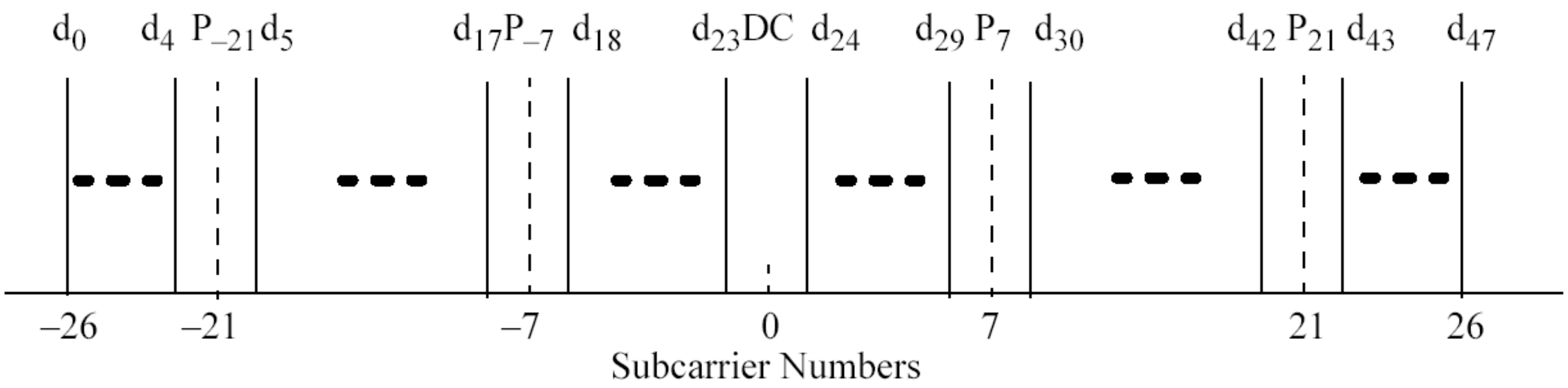
Infrastructure network

IEEE 802.11 PHY

- FHSS
  - 2.4GHz band, 1 and 2 Mbps transmission
  - 2GFSK, 4GFSK
  - hop over 79 channels (North America)
- DSSS
  - 2.4GHz band, 1, 2, 5.5 or 11 Mbps transmission
  - DBPSK, DQPSK
  - 11 chip Barker sequence
- OFDM
  - 2.4GHz & 5GHz, 6 to 54 Mbps
  - No Spread Spectrum
- Baseband IR
  - Diffuse infrared
  - 1 and 2 Mbps transmission, 16-PPM and 4-PPM

IEEE 802.11a/g PHY

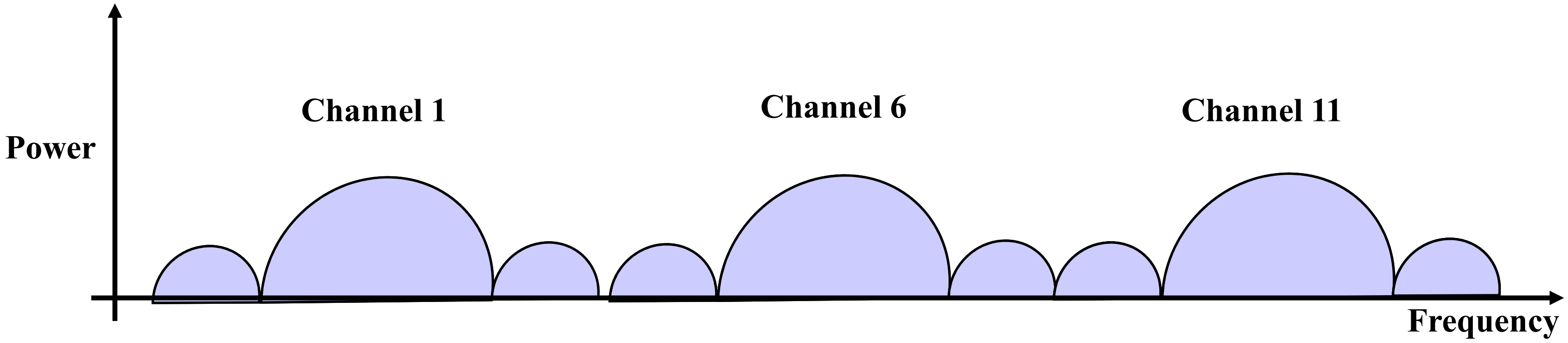
- **OFDM Subcarrier Frequency Allocation**



- **Total 52 subcarriers (-26 ~ 26) using 64 FFT**
  - **48 subcarriers for data**
  - **4 subcarriers for pilot (-21, -7, 7, 21)**
  - **20MHz channel**
- **Runs in 5GHz U-NII bands (in case of US)**
  - **300MHz from 5.15-5.35(8 Ch.) & 5.725-5.825GHz (4 Ch.)**
  - **Total 12 channels available**

IEEE 802.11b PHY

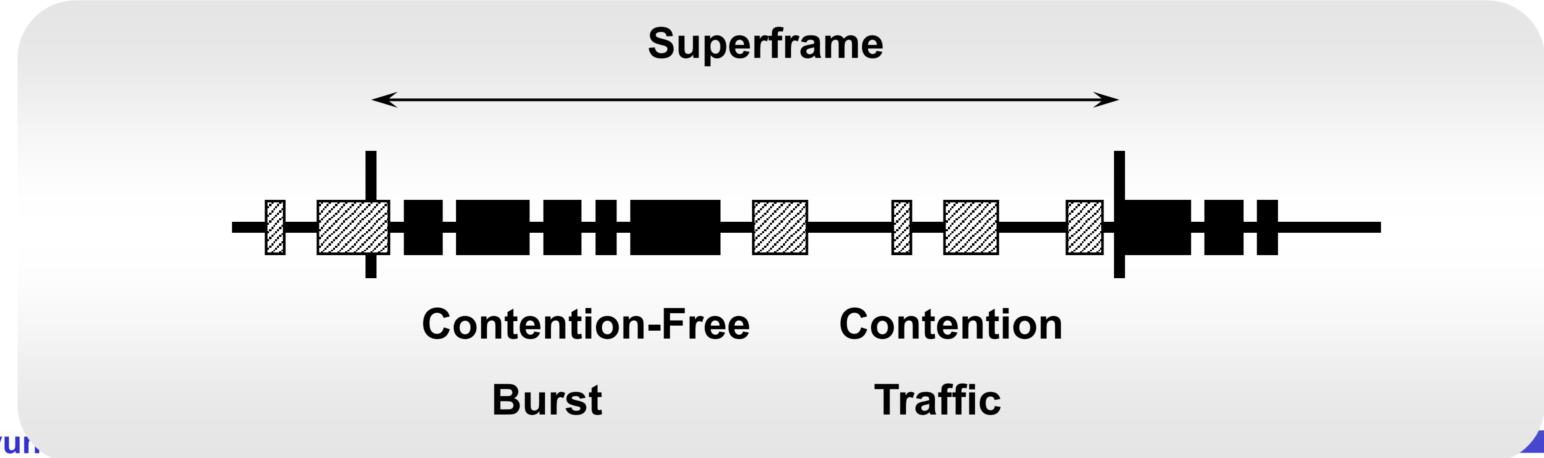
- Runs in 2.4GHz ISM bands (US : 2.412 – 2.462 GHz)
  - 11 22MHz channel



- 4 different transmission rates:
  - Complementary Code Keying (CCK) for 5.5 & 11 Mbps
  - Direct-Sequence Spread Spectrum (DSSS) for 1 & 2 Mbps

Service Types and Coordination Functions

- Asynchronous Service : Data service, FTP, Web, etc.
  - Contention Traffic
  - DCF (Distributed Coordination Function)
  - Distributed controlled by STA (Station)
- Isochronous Service : Delay sensitive traffic, voice, etc
  - Contention-Free Traffic
  - PCF (Point Coordination Function)
  - Centralized controlled by AP (Access Point)
- Super Frame Concept



DCF

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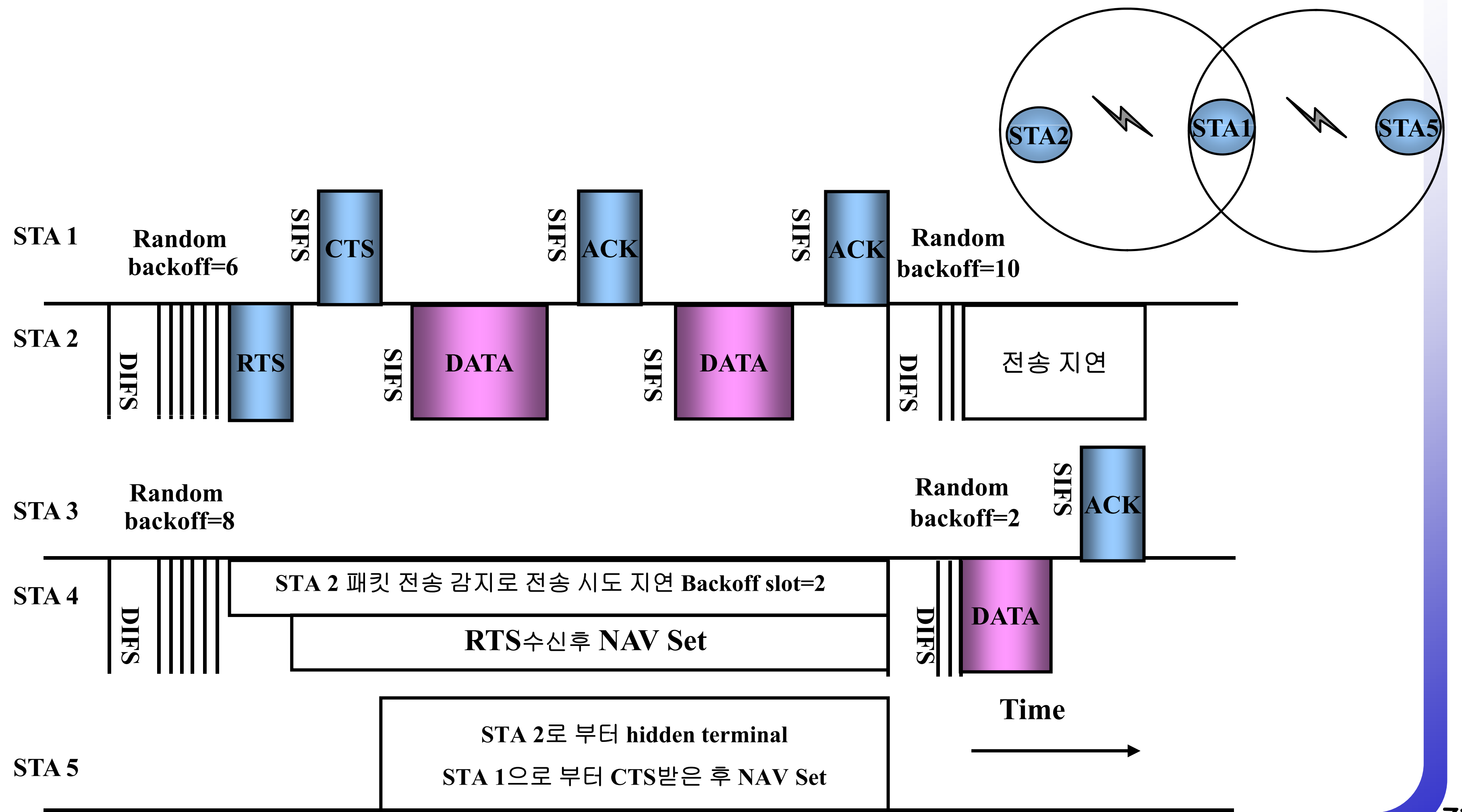
- **Baseline 802.11 MAC includes a virtual carrier sensing scheme to address the Hidden Terminal Problem**

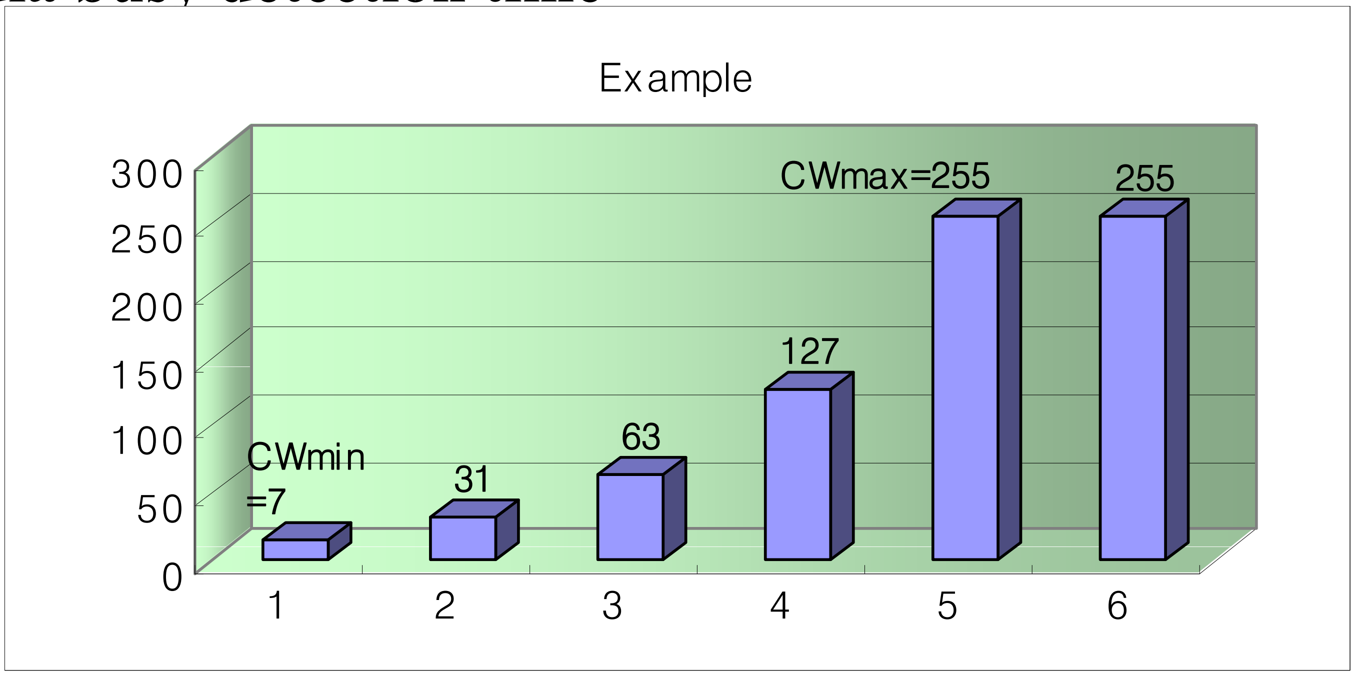


Exponential Backoff Algorithm

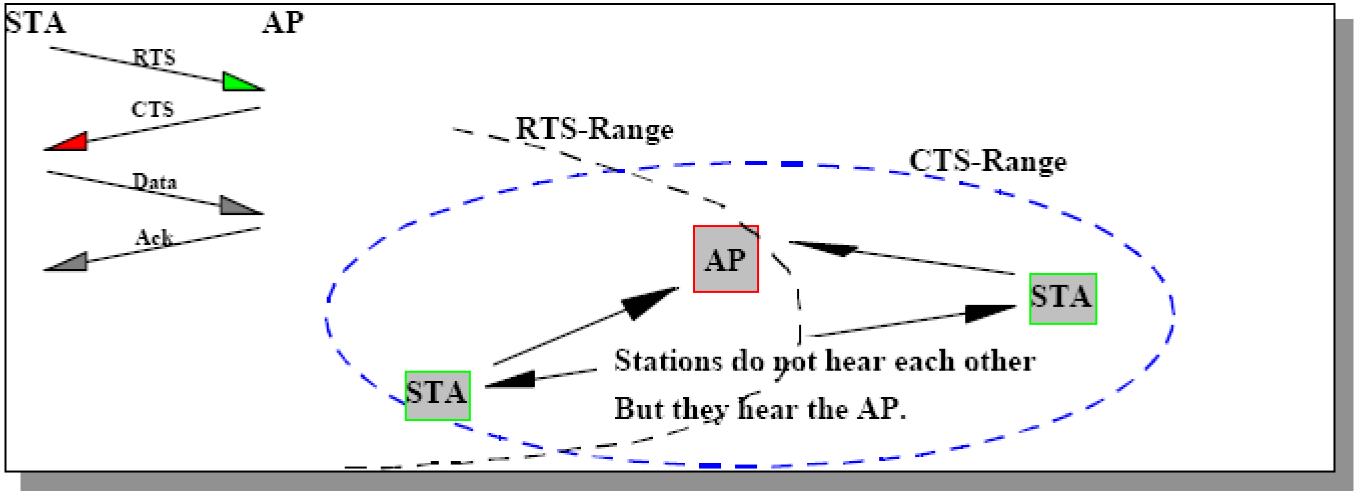
- **CW : Contention Window (0 to CW_{min} ~ CW_{max}) :**

  Backoff delay = INT(CW × Random()) × Slot Time

  - **CW is doubled when transmission is failed**
  - **CW_{min} : 11.a = 15, 11.b = 7, 11.b HR = 31, CW_{max} = 1023**
- **Slot time : Receiver turn on time + propagation delay + media busy detection time**

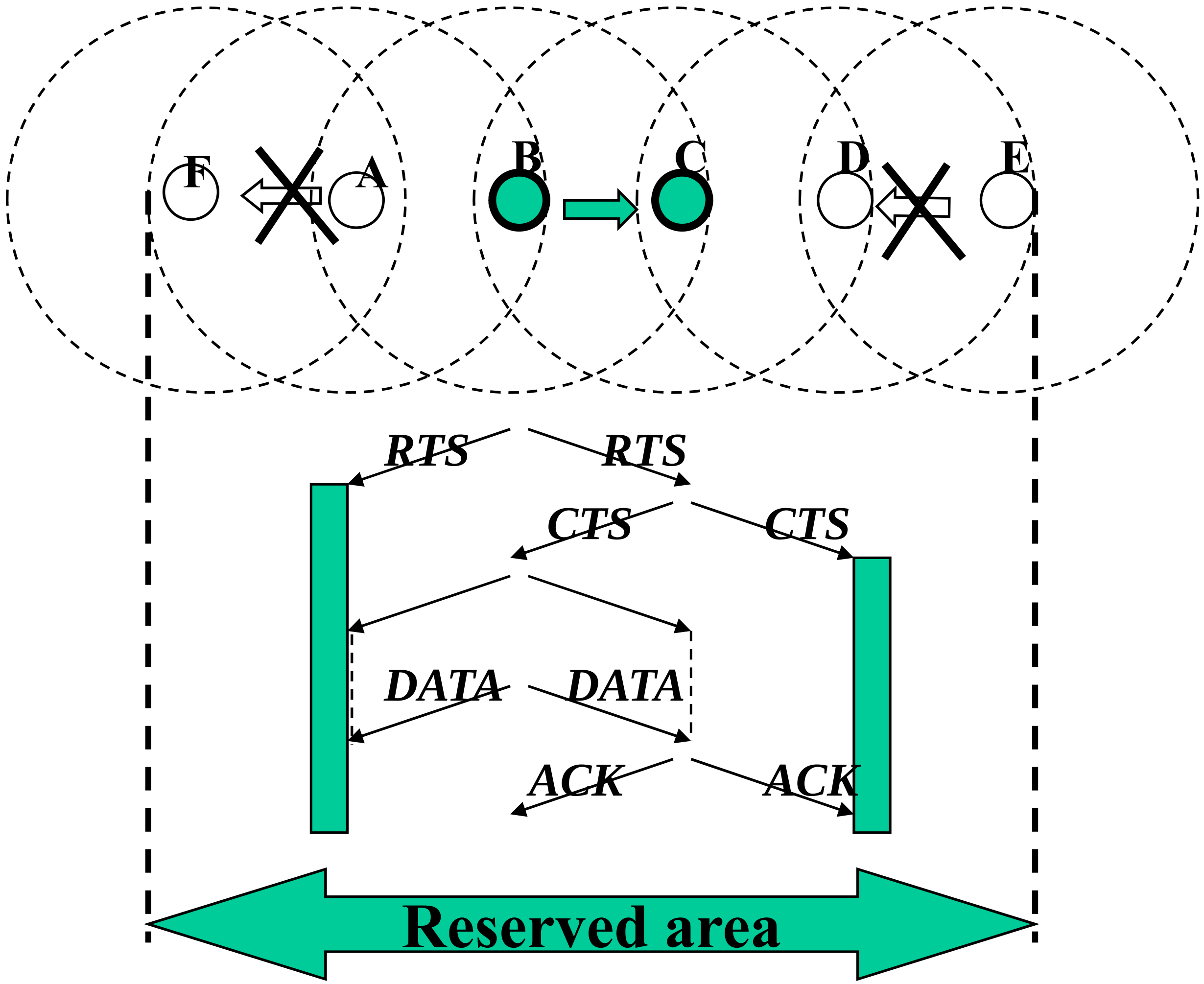


“Hidden Node” Problem



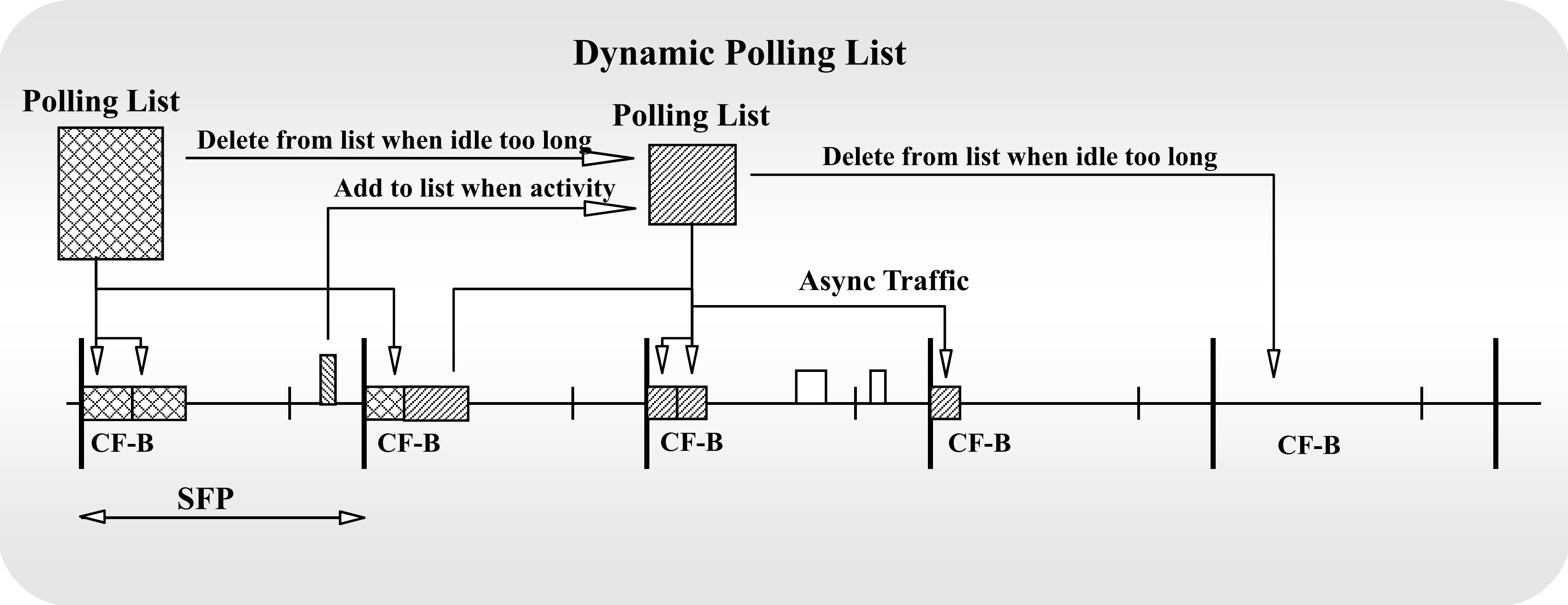
- Separate control frame exchange (RTS/CTS)
- Distribute duration around both Tx and Rx station

"Exposed Node" Problem



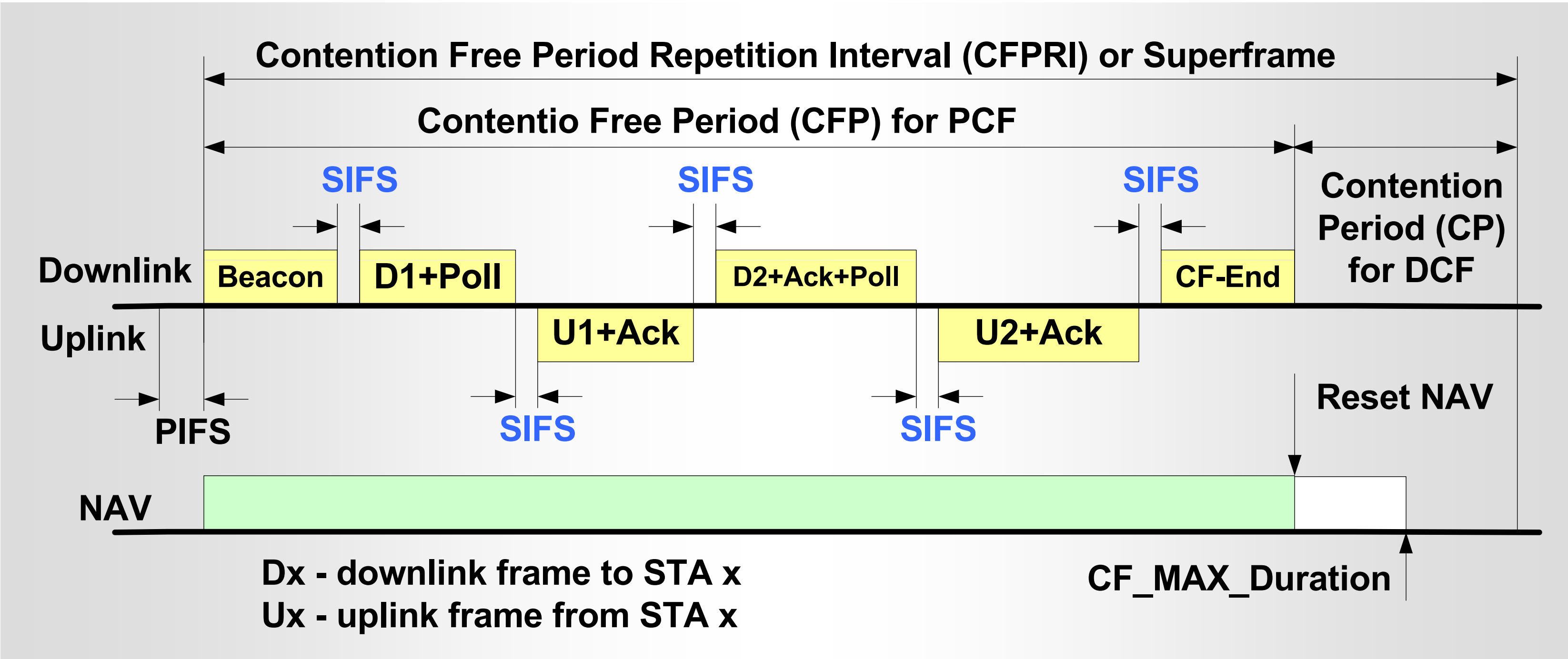
PCF

- Send Request in Contention Period
- AP poll STA by the polling list



Contention Free Operation

- Two consecutive frames are separated by SIFS
- CFP lengths depend on traffic amount
  - Maximum length announced by AP; used for NAV set

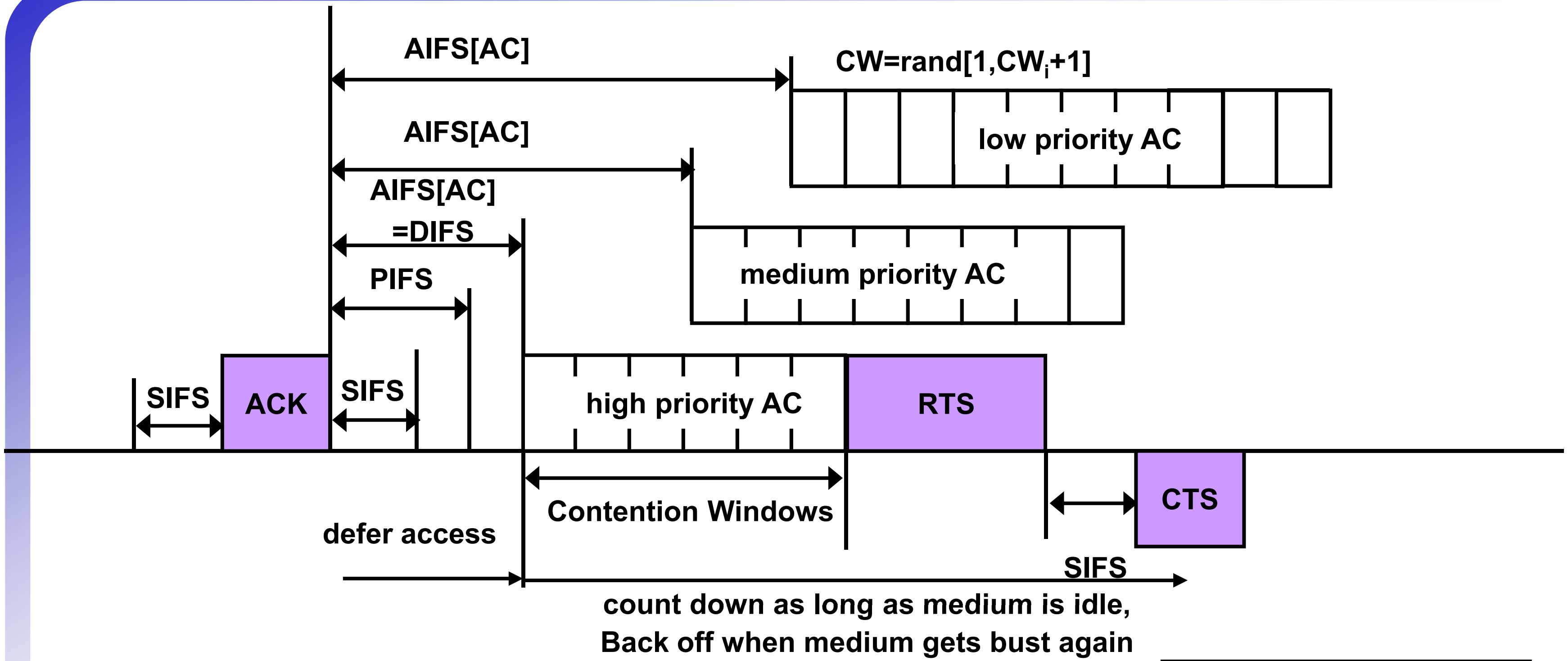


Channel Access Mechanism for QoS

- **HCF (Hybrid Coordination Function)**
  - **EDCA (Enhanced Distributed Channel Access)**
    - Contention based channel access
    - Basic 4 AC (Access Category)
    - Probabilistic channel access according to priority
      - AIFS (Arbitrary Inter Frame Space), CW_{min}, CW_{max}, TXOP limit
  - **HCCA (HCF Controlled Channel Access)**
    - Reservation based channel access
    - Negotiate with HC (Hybrid Coordinator) using TSPEC (Traffic Specification)
    - HC grant TXOP (Transmission Opportunity) in CF-Poll frame

IEEE 802.11 WG, IEEE P802.11e/D13.0, ***Draft Amendment to Standard for Information Technology - Telecommunications and Information Exchange between Systems - LAN/MAN Specific Requirements - Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Medium Access Control (MAC) Quality of Service (QoS) Enhancements*****, Nov. 2003**

EDCA



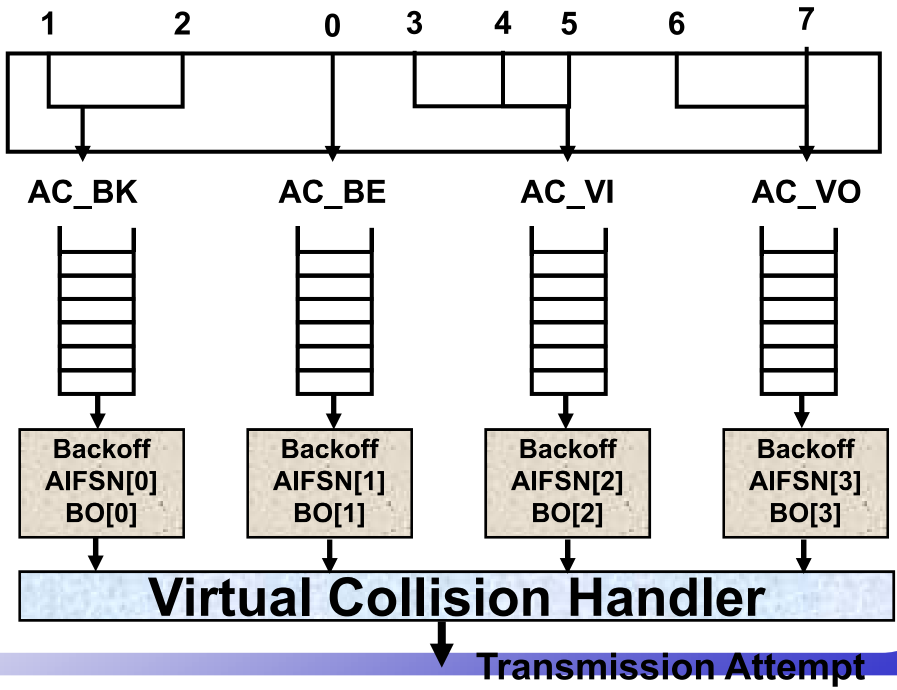
AC	CWmin	CWmax	AIFSN
AC_BK	CWmin	CWmax	3
AC_BE	CWmin	CWmax	7
AC_VO	(CWmin+1)/2-1	CWmin	2
AC_VI	(CWmin+1)/4-1	(CWmin+1)/2-1	2

With 802.11a
- aSlotTime: 9us
- SIFS: 16us
- PIFS: 25us
- DIFS: 34us
- AIFS: >=34 us

$$CW_{i+1}[AC] = \min\{(CW_i[AC]+1) \cdot PF[AC] - 1, CW_{MAX}\}$$

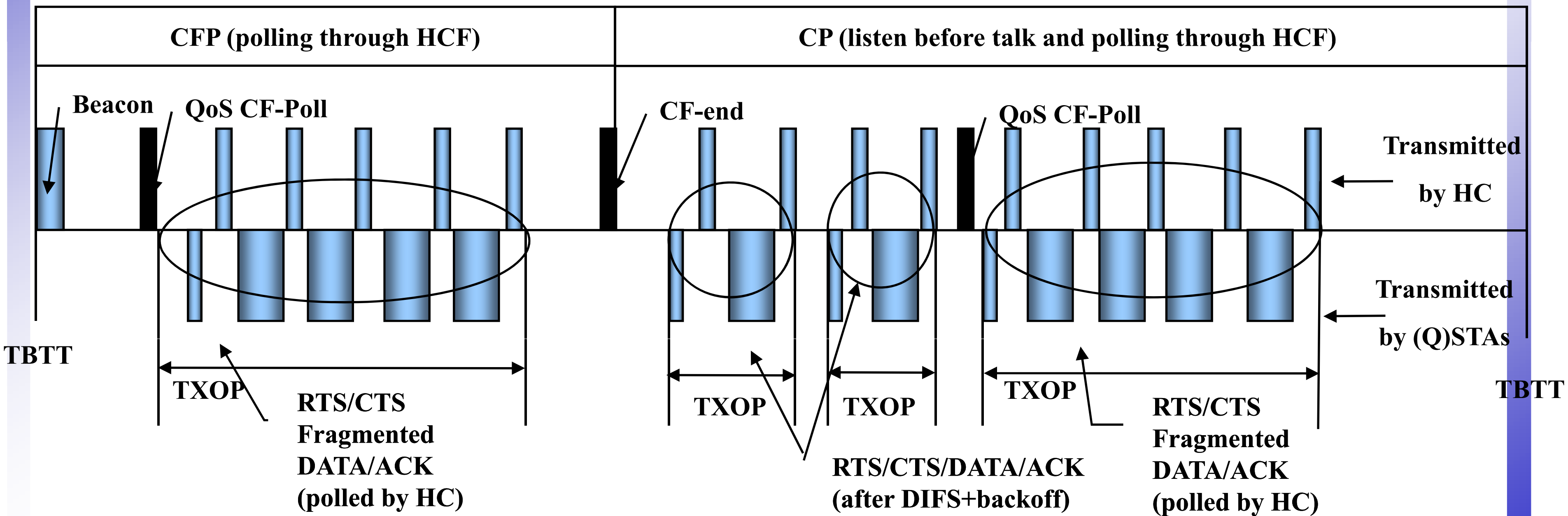
Prioritized QoS

- **AC as a virtual DCF**
  - **4 ACs implemented to support 8 user priorities**
- **EDCA Parameters**
  - **AIFS**
    - Minimum time interval between wireless medium becoming idle and the start of transmission of frame
    - AIFS[AC]=SIFS+AIFSN[AC]*aSlotTime
  - **Contention window parameters**
    - Random number for backoff mechanism
  - **TXOP Limit**
    - Max. TXOP duration
  - **PF (Persistent Factor)**



HCCA

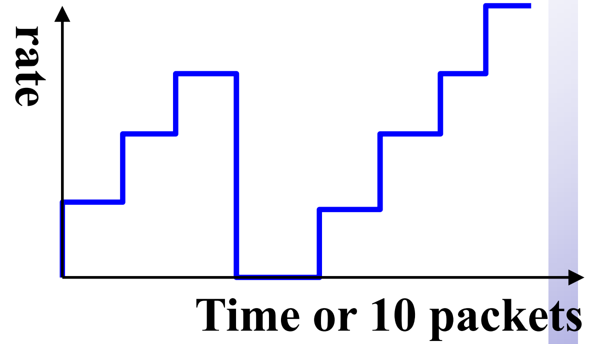
- Used both CFP (Contention Free Period) and CP (Contention Period)
- Overcome the weaknesses of PCF



<HCCA procedure>

Rate Control Algorithm

- ARF (Automatic Rate Fall-back)
  - **Different modulation using the temporary fallback mechanism**
  - **Two more consecutive channel error**
    - Decrease to the lowest transmission rate
    - Timer is activated
  - **10 more successive ACKs or Timer is expired**
    - Increase the transmission rate one time
  - **Slowly adapt to channel quality**



- RBAR (Receiver Based Auto Rate)
  - **Acquire the channel quality information using RTS/CTS packet**
  - **Need to modify RTS/CTS packet**
  - **Fast adapt to channel quality**

A. Kamerman and L. Montean, "WaveLan-II: A High-Performance Wireless LAN for the Unlicensed Band," ***Bell Labs Technical Journal*****, pp. 118-133, Summer, 1997.**

G. Holland, N. Vaidya, and P. Bahl, "A Rate-Adaptive MAC Protocol for Multi-hop Wireless Networks," in ***Proc. MOBICOM 2001*****, Rome, Italy, Jul., 2001, pp. 236-251.**

Traffic Stream

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- **Packet scheduler**
  - **Use the mandatory set of TSPEC parameters**
  - **Procedure**
    - Calculate SI (Service Interval)
    - Calculation of TXOP
      - Number of MSDUs during the SI (*N*) $N_i = \left\lceil \frac{SI \times \rho_i}{L_i} \right\rceil$
      - TXOP duration (*T*) $T_i = \max\left(\frac{N_i \times L_i}{R_i} + O, \frac{M}{R_i} + O \right)$
- **ACU (Admission Control Unit)**
  - **Assume CBR (Constant Bit Rate)**
  - **TS (Traffic Stream) is admitted by simple time constraint**

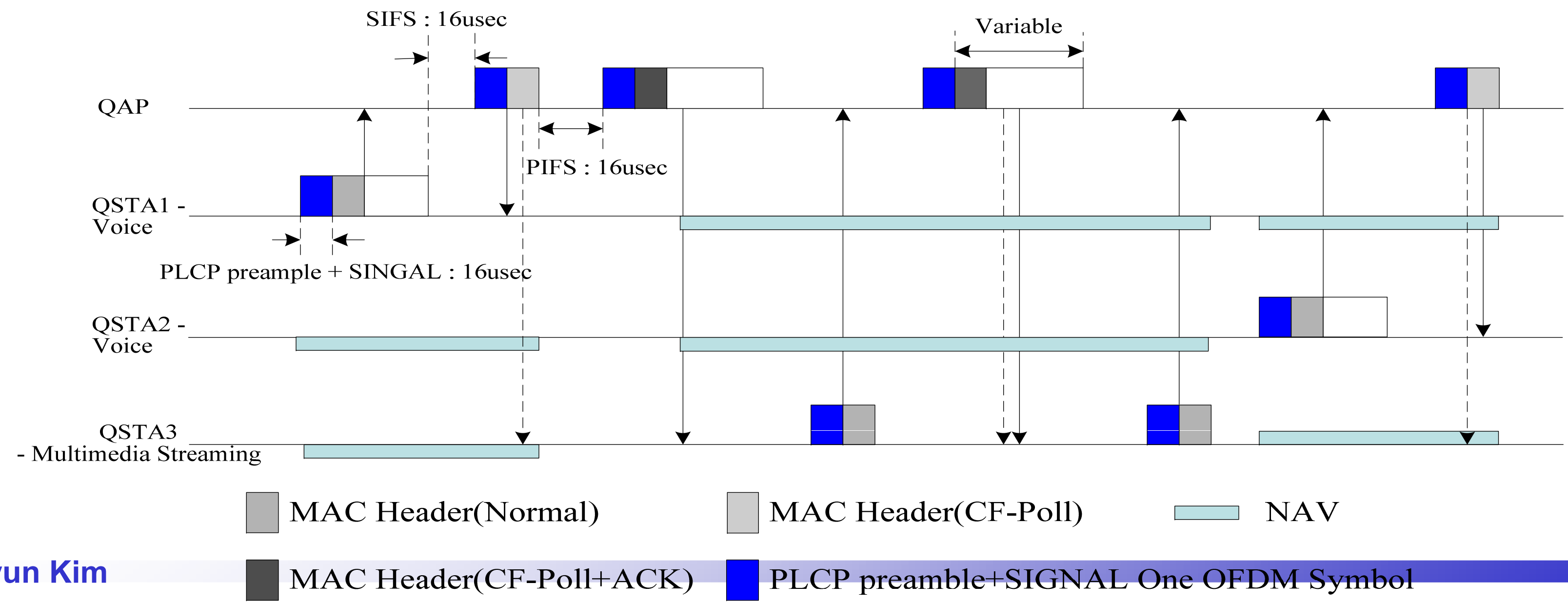
$$\frac{TXOP_{k+1}}{SI} + \sum_{i=1}^{k} \frac{TXOP_i}{SI} \le \frac{T - T_{CP}}{T}$$

R_i : physical transmission rate
M : maximum allowable size of MSDU
O : overhead time includes IFSs, ACKs and CF-polls
ρ_i : mean data rate of service flow

L : nominal MSDU size
k : number of existing streams
$k+1$: index for the newly arriving stream
T : beacon interval
T_{CP} : time used for EDCA traffic

Piggyback Problem in WLAN

- **Piggyback Problem at low transmission rate[4]**
  - **CF-Poll frame**
    - Used to grant TXOP to TS
    - Can be piggybacked in a normal QoS-Data frame
  - **NAV (Network Allocation Vector) rule**
    - CF-Poll frame is transmitted by the allowable low transmission rate to set NAV
  - **If any QSTA has low physical transmission rate, piggyback cause the decrease of the channel efficiency and the increase of the frame transmission delay**
- **Solution**
  - **CF-Poll piggyback is activated according to the channel efficiency**



Delay Efficiency based piggyback algorithm

- **Assumption**
  - **Each QSTAs using HCCA has just one TS**
  - **Service packets for TS are just arrived at queue for HCCA when SI is started**
  - **The characteristic of TS for HCCA has CBR**
- **Delay Efficiency of piggyback (Δ)**
  - **The maximum delay difference between CF-Poll piggyback and no CF-Poll piggyback**

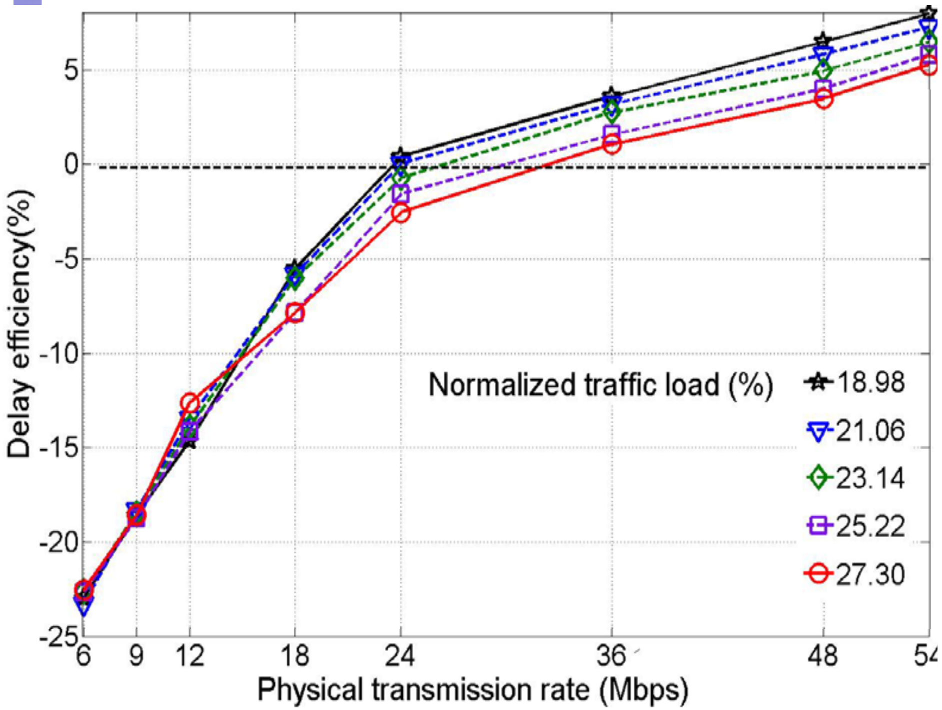
$$\Delta = \delta_{pb} - \delta_{npb} = \left(\frac{1}{R_j} - \frac{1}{R_{CF-Poll}} \right) L_{MSDU,1} - \frac{L_{CF-Poll}}{R_{CF-Poll}}$$

- R_i : physical transmission rate of i^{th} QSTA
- LCF-Poll : CF-Poll frame size
- $R_{CF-Poll}$: physical transmission to send the CF-Poll frame
- $L_{MSDU,l}$: l^{th} MSDU size

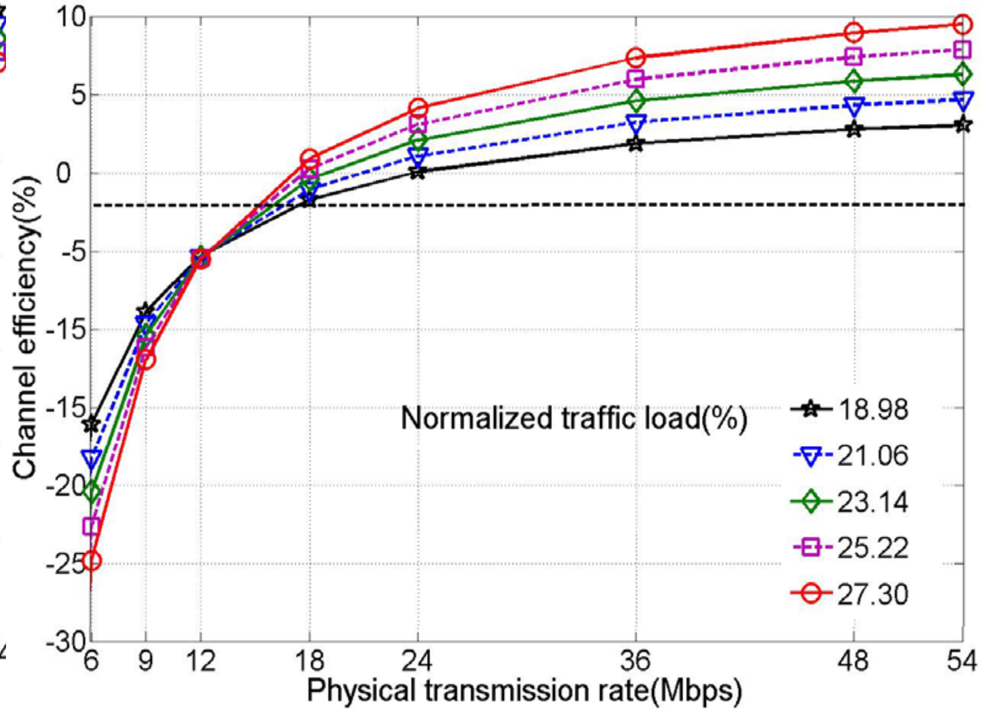
H. J. Lee, J. H. Kim and S. H. Cho, " An Optimal CF-Poll Piggyback Scheme in IEEE 802.11e HCCA, " in *Proc. ICACT'06*, Vol. 3, Pyong Chang, Korea, Feb. 20-22, 2006, pp. 1954-1959.

Simulation Results

- Number of QSTAs : 35~115
- The average delay
  - **Much influenced by the minimum transmission rate of QSTA and CF-Poll piggyback**
    - Data rate(6 Mbps), Traffic load (27%)
      - CF-Poll piggyback -> 16.5msec
      - No CF-Poll piggyback -> 12.3msec
  - **Less influenced by the traffic load**



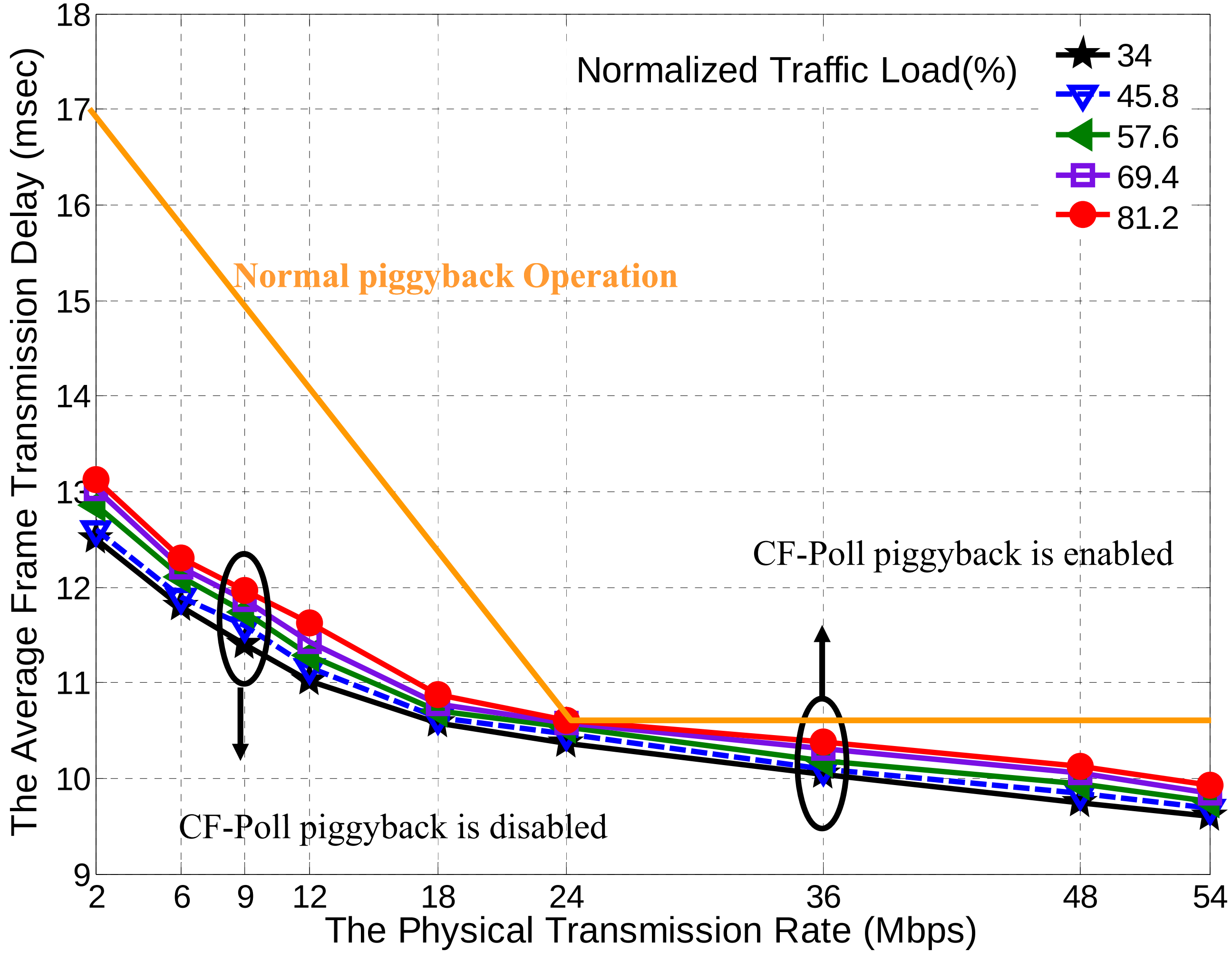
<Delay efficiency>



<Channel efficiency>

Simulation Results

- **Delay Efficiency based piggyback algorithm**
  - **Minimize the effect of piggyback problem**



IEEE 802.15

-. IEEE 802.15.1

-. IEEE 802.15.3

-. IEEE 802.15.4

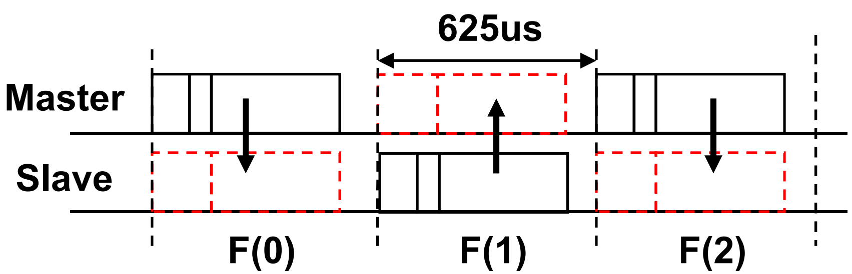
IEEE 802.15.1 Overview

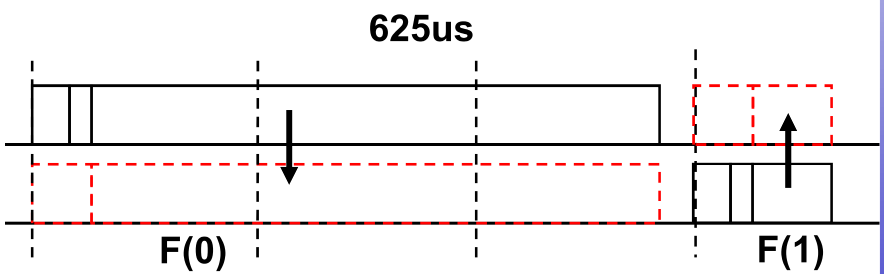
- Concept
  - Short Range : 0.01m - 10m (100m)
  - Low Power : 1mW, 2.5 mW, 100 mW
  - Low Cost : < $5
- Can be used for
  - Appliance Cable replacement
  - Personal Ad-Hoc Connectivity
- Standard (Bluetooth SIG and IEEE802.15.1)
  - 1999 : Version 1.0b
  - 2003 : Version 1.2 (1Mbps)
  - 2004 : Version 2.0 + EDR (Enhanced Data Rate) (3Mbps)
- Topology
  - Piconet, Scatternet

IEEE 802.15 WG, IEEE P802.15.1/D1.0.1, *Draft Standard for Information Technology – Telecommunications and information exchange between system – Local and metropolitan area network – Specific requirements – Part 15.1: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Wireless Personal Area Networks (WPANs)*, Sep. 2001

Channel Allocation

- Full duplex TDD
- No direct connection between slaves
- Synchronized frequency hopping
- Transmission
  - Master : even number slot
  - Slave : odd number slot
- TDD/Single slot
- Multi-slot allocation

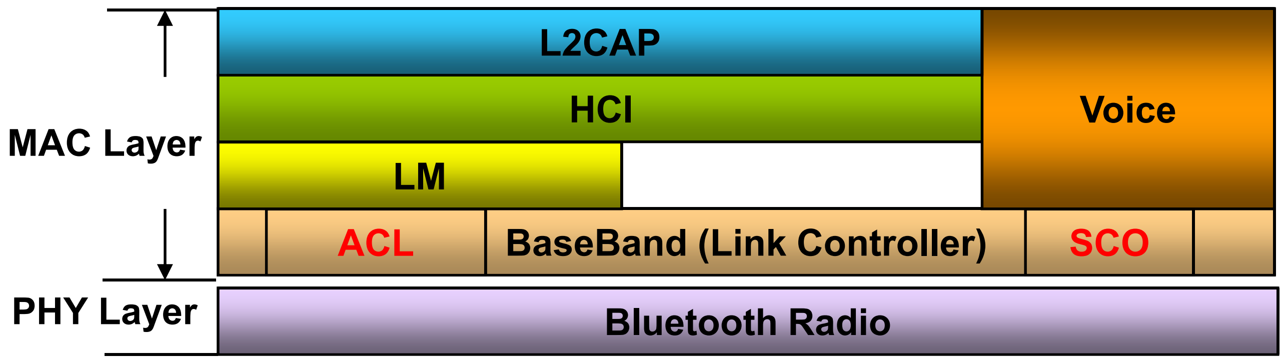




Type of Service

- Support both circuit and packet switching service

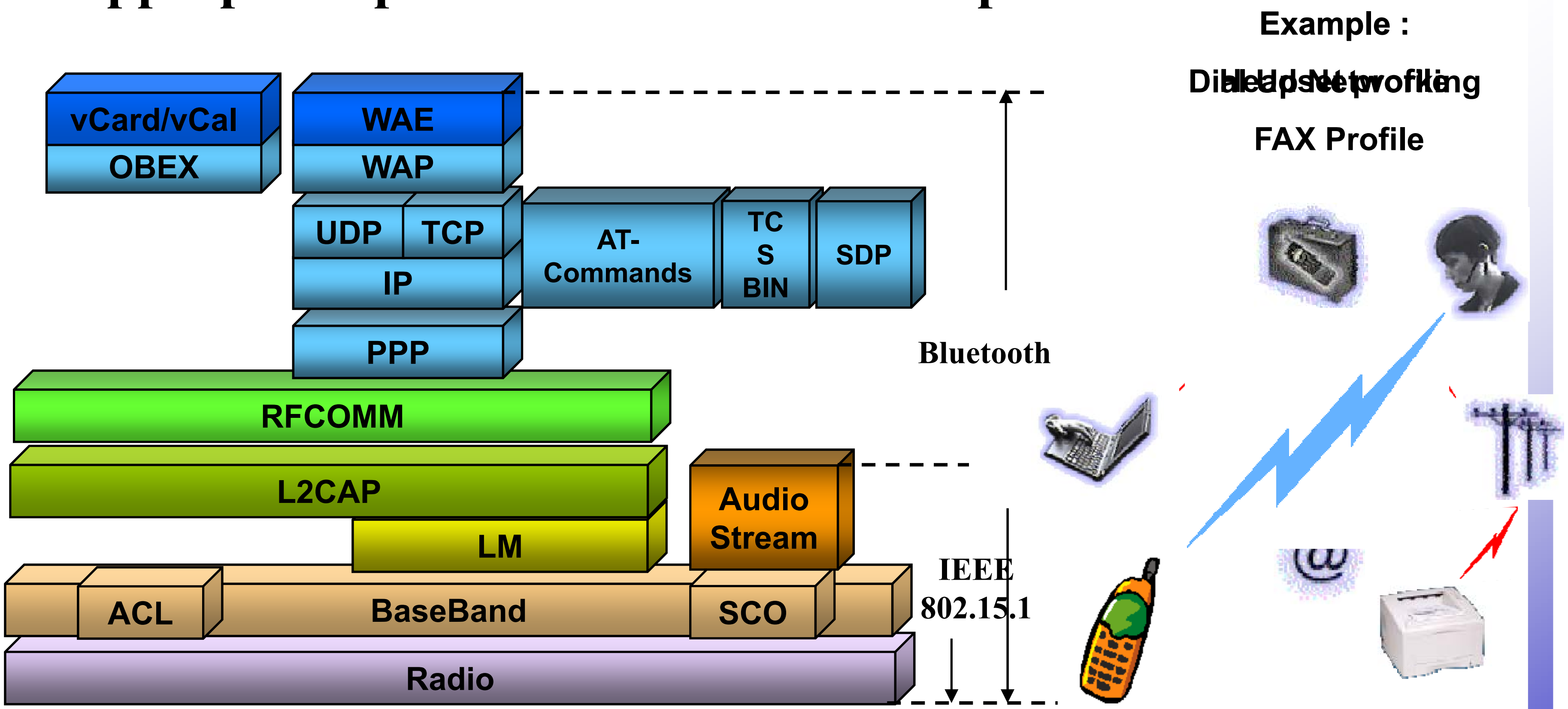
Name	SCO	ACL
Link type	Symmetric Point-to-point	Asynchronous & isochronous Point-to-multipoint
Channel access	Reservation	Polling
Connection	3 connection	1 connection (aggregated traffic)
Retransmission	No retransmission (use FEC)	Retransmission



- SCO : Synchronous Connection-Oriented – ACL :Asynchronous Connectionless
- LM : Link Manager - HCI :Host Control Interface - L2CAP : Logical Link Control and Adaptation Protocol

Service Profile and Protocol Stack

Appropriate protocol stack for service profiles



- SDP : Service Discovery Protocol
- OBEX Object Exchange protocol
- TCS : Telephony Control protocol Spec.
- WAE : WAP Application Environment

Function of Layer

- LM
  - Link setup, security, authentication, link configuration, timer setup
  - Use DM1(Data Medium rate) or DV (Data Voice)
  - Self-contained or user input
- HCI
  - Provide a standard interface to bluetooth
- L2CAP
  - Provide connection-oriented and connectionless data services
  - Only use ACL
  - Label each connection by CID (Channel Identification)

Link Control

- **Link control state**
  - **Standby state**
    - Default state
    - Low power consumption mode
    - Not associated in any piconet
  - **Connection state**

Mode	Description
Active	– Actively communicate on the wireless channel – Master schedules the transmission based on traffic requirements to and from slaves
Sniff	– Can change to a power-saving mode – Need to listen to the master traffic every ACL slot when slave participates on an ACL link
Hold	– Can change to a power-saving mode – Temporarily do not support ACL packet while support SCO packet – Need to agree on the time duration
Park	– Synchronized to the piconet – Do not communicate

IEEE 802.15.3 Overview

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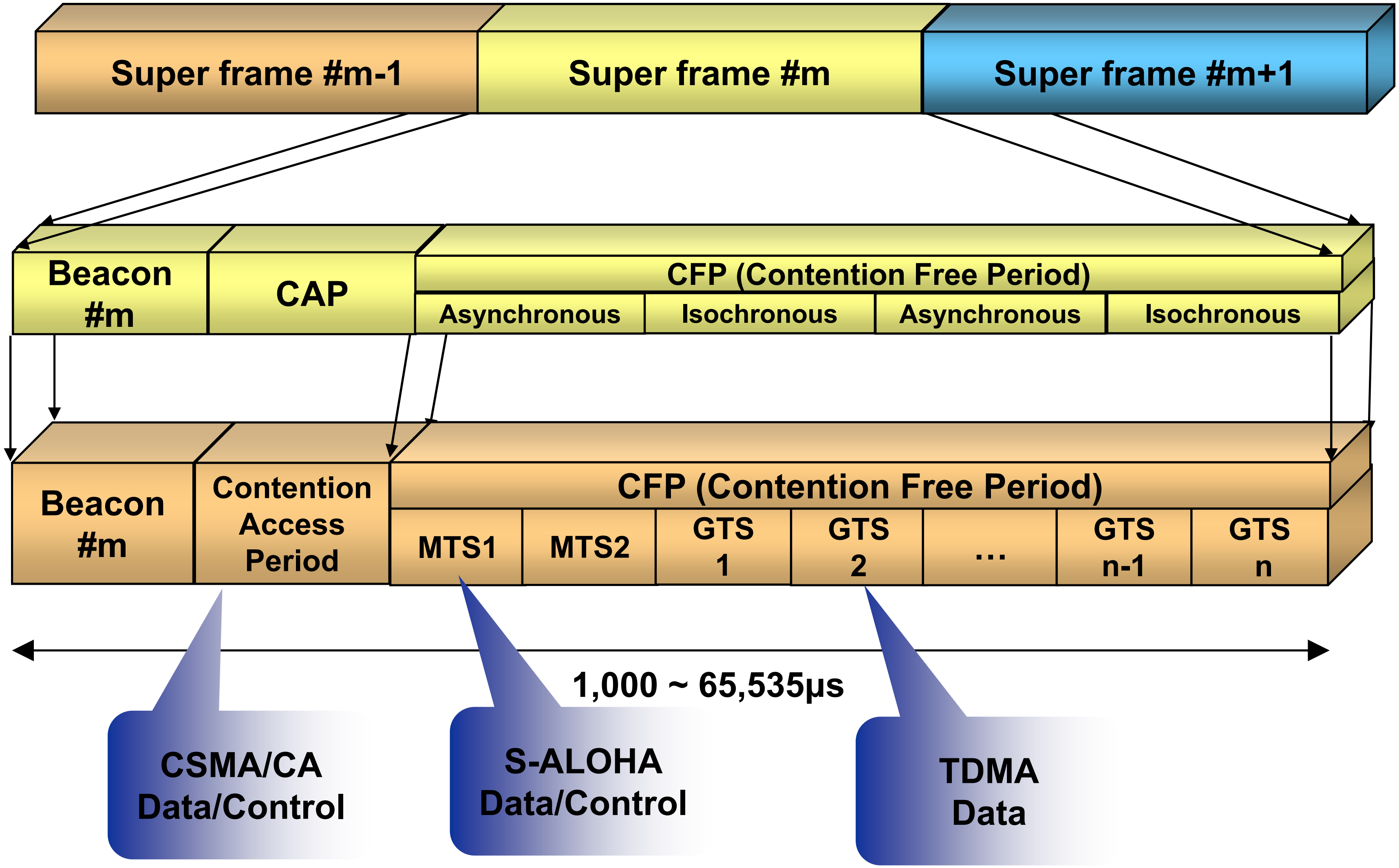
- **Concept**
  - Low complexity, Low cost, Low power, Short Range, QoS Capable, Peer to peer communication, High data rate (> 20Mbps)
- **PHY**
  - 2.4GHz 5 Channel
- **MAC Functionality**
  - Fast Connection Time
  - Ad hoc Network
  - QoS support
  - Security
  - Dynamic Membership
  - Efficient data transfer

Channel ID	Center frequency	High-density	802.11b coexistence
1	2.412GHz	X	X
2	2.428GHz	X	
3	2.437GHz		X
4	2.445GHz	X	
5	2.462Hz	X	X

- **Topology**
  - Piconet, Child piconet, Neighbor piconet
  - Piconet Coordinator (PNC), Device (DEV)

IEEE 802.15 WG, IEEE P802.15.3™2003, *IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs)*, Sep. 2003

Superframe Structure (1)



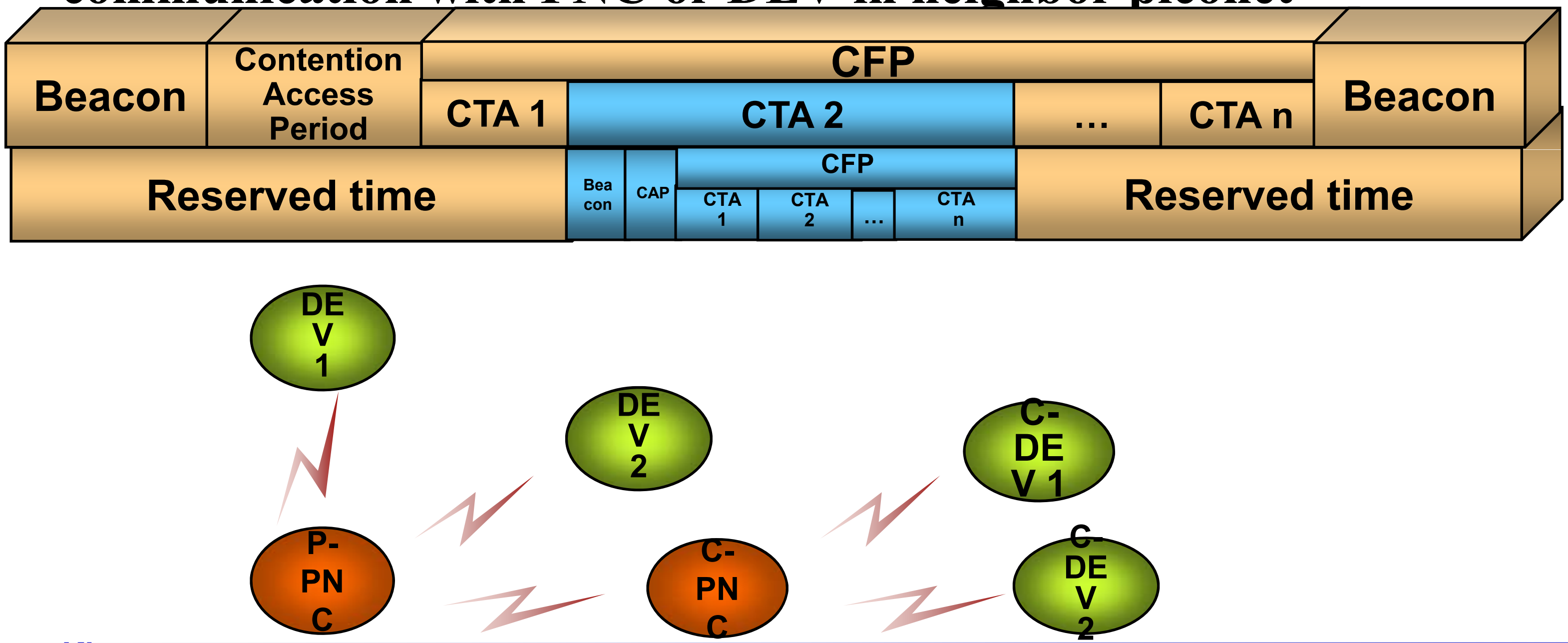
- MCTA : Management Channel Time Allocation

Superframe Structure (2)

- Beacon
  - Provide the piconet synchronization information
  - Provide CAP end time
  - Provide CTA (Channel Time Allocation) for CFP
- CAP
  - Contention based channel access
  - Two different interframe space
    - SIFS, RIFS (Retransmission IFS)
- CFP
  - Assigned by CTA
  - Two type of slot :
    - MTS (Management Time Slot) : control traffic and data traffic
    - GTS
      - Pseudo Static GTS : dynamically change the location of the reserved slot
      - Dynamic GTS : fixed location

Piconet

- **Independent piconet**
  - **PNC (Piconet Coordinator) and DEV (Device)**
- **Dependent piconet**
  - **Child piconet : # DEV > 255, extended area, Communication with PNC or DEV in parent piconet**
  - **Neighbor piconet : when no available channel in parent piconet, communication with PNC or DEV in neighbor piconet**



IEEE 802.15.4 Overview

- **Concept**
  - **Low Rate : 20, 40, 250kbps**
  - **Low Cost**
  - **Low Power Short Range : ~ 10m**
  - **Dynamic device addressing**
  - **Low power consumption**
- **Apply to**
  - **u-Smart Network : Energy save, Consumer Electronics, Toy, Security**
  - **Health care check and monitoring System**
- **Topology**
  - **Star or peer-to-peer topology**

IEEE 802.15.4 MAC features

- Features of the MAC sub-layer
  - Beacon management
  - Channel access
  - Guaranteed time slot management
  - Frame validation
  - Acknowledged frame delivery
  - Association and disassociation
  - Security mechanism
- FFD (Full Function Device)
  - A device capable of operating as a coordinator or device, implementing the complete protocol set.
- RFD (Reduced Function Device)
  - A device operating with a minimal implementation of the IEEE 802.15.4 protocol.

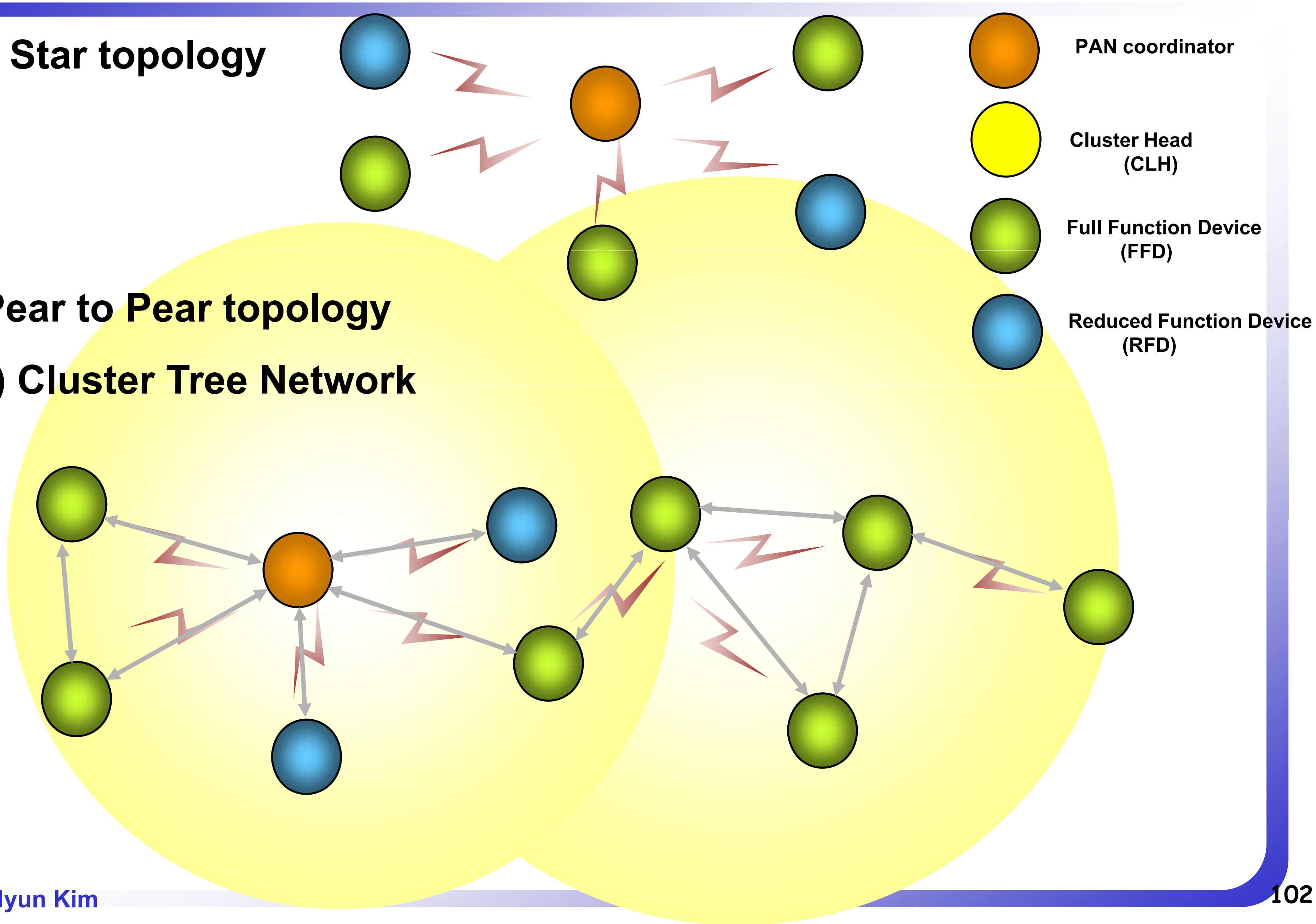
IEEE 802.15 WG, IEEE P802.15.4/D18, *Standard for Information technology -Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks Specific Requirements - Draft Standard for Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low Rate Wireless Personal Area Networks (LR-WPANs)*, Feb. 2003

Star / Pear-to-Pear Topology

- Star topology

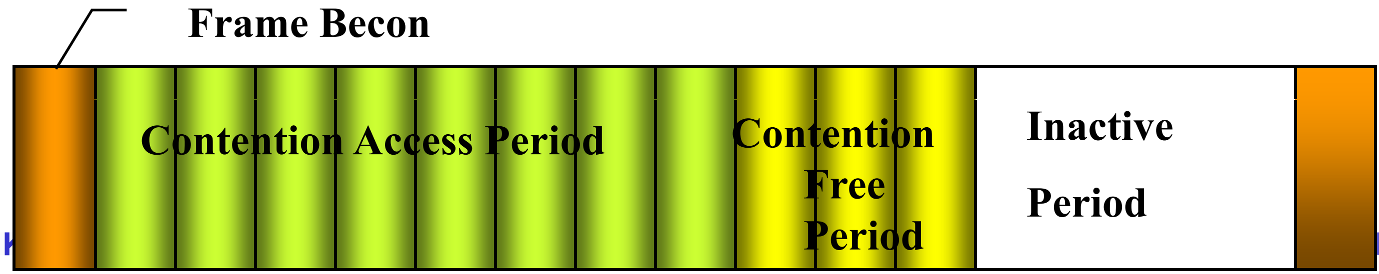
- Pear to Pear topology

ex) Cluster Tree Network



Superframe Structure

- **Optional use of superframe structure**
- **Divided into 16 equally sized slots**
- **CAP**
  - **Slotted CSMA-CA**
  - **Transactions shall be completed by the time of the next network beacon.**
- **CFP**
  - **Included GTS (Guaranteed Time Slot)**
  - **PNC (PAN Coordinator) allocate up to seven of these GTSs**
- **Channel access mechanism**
  - **Beacon enabled network**
    - slotted CSMA-CA
  - **A non beacon enabled network**
    - Unslotted CSMA-CA, TDD



Traffic Type

- Periodic data
  - Data size is defined by the application and mostly low data rate
  - Typical example is sensor traffic
- Intermittent data
  - Data generation is activated by external stimulus
  - Typical example is light switch traffic
- Repetitive low-latency data
  - Traffic is generated continuously
  - Require low latency data transfer
  - Example is mouse device traffic

Typically CAP

Typically GTS

IEEE 802.16

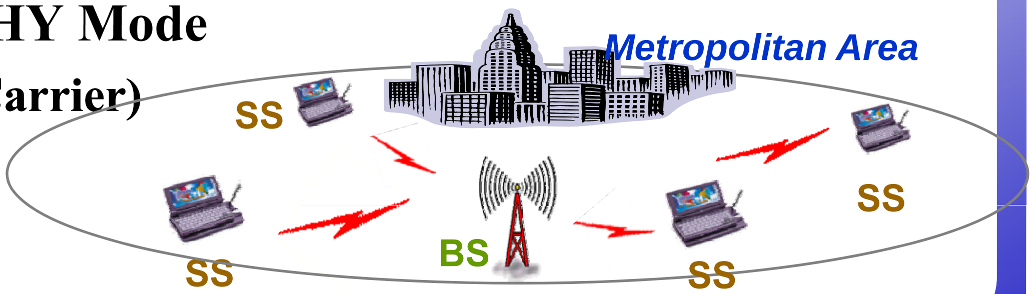
-. Frame Structure

-. IEEE 802.15.3

-. IEEE 802.15.4

IEEE 802.16 Overview

- Wireless Metropolitan Area Network
  - Broadband Wireless Access
  - Coverage area : 1 Km
  - Max Data Rate : 120Mbps~
- IEEE 802.16 Air Interface Standard
  - IEEE 802.16 : Air Interface (MAC and 10 ~ 66 GHz PHY)
    - WiMAX forum coordinating interoperability testing
    - Interoperability documentation in development
  - P802.16a : amendment, 2 ~ 11 GHz
    - Licensed
    - Licensed-exempt
- 802.16 Standard defines 4 PHY Mode
  - WirelessMAN-SC (Single Carrier)
  - WirelessMAN-SCa
  - WirelessMAN-OFDM
  - WirelessMAN-OFDMA



IEEE 802.16 TGs

- **TG1 – Air Interface (MAC and 10 ~ 60 GHz PHY)**
  - **TGa : Amendment 2, PHY spec. for 2 ~ 11 GHz**
  - **TGc : Amendment 1, Detailed System Profiles for 10–66 GHz**
  - **TGd : Amendment 3: Detailed System Profiles for 2-11 GHz**
  - **TGC :**
    - TGC/C1 : Protocol Implementation Conformance Statements for 10-66 GHz WirelessMAN-SC Air Interface
    - TGC/C2 : Test Suite Structure and Test Purposes (TSS&TP) for 10-66 GHz WirelessMAN-SC Air Interface
    - TGC/C3 : Radio Conformance Tests (RCT) for 10-66 GHz WirelessMAN-SC Air Interface 10-66 GHz WirelessMAN-SC Air Interface
  - **TGe : Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands (Mobile Wireless MAN)**
- **TG2 : Coexistence of Fixed Broadband Wireless Access Systems**
  - **TGa : amendment to IEEE Std 802.16.2**

IEEE 802.16 Structure

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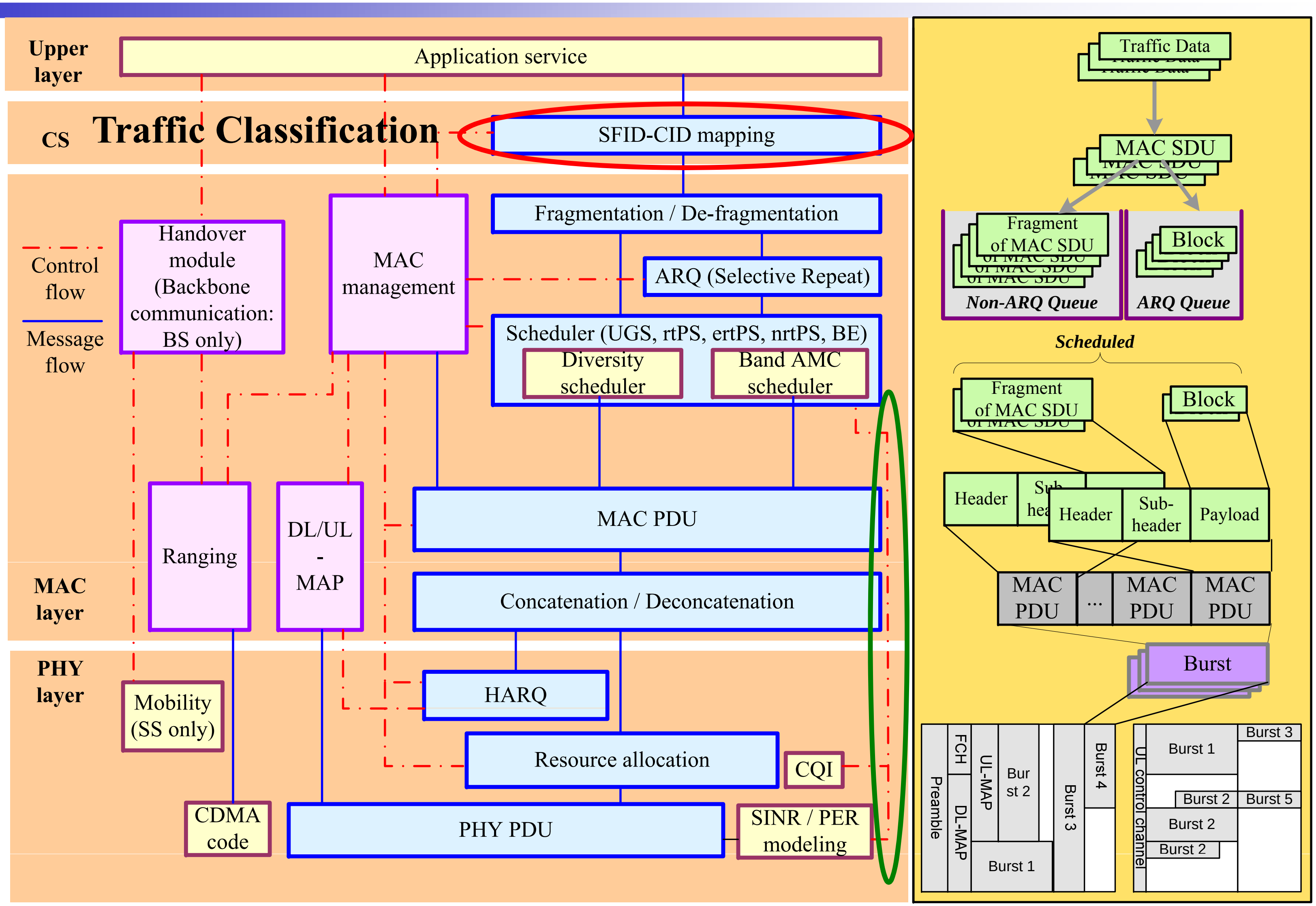

Use to channel information

PHY specification

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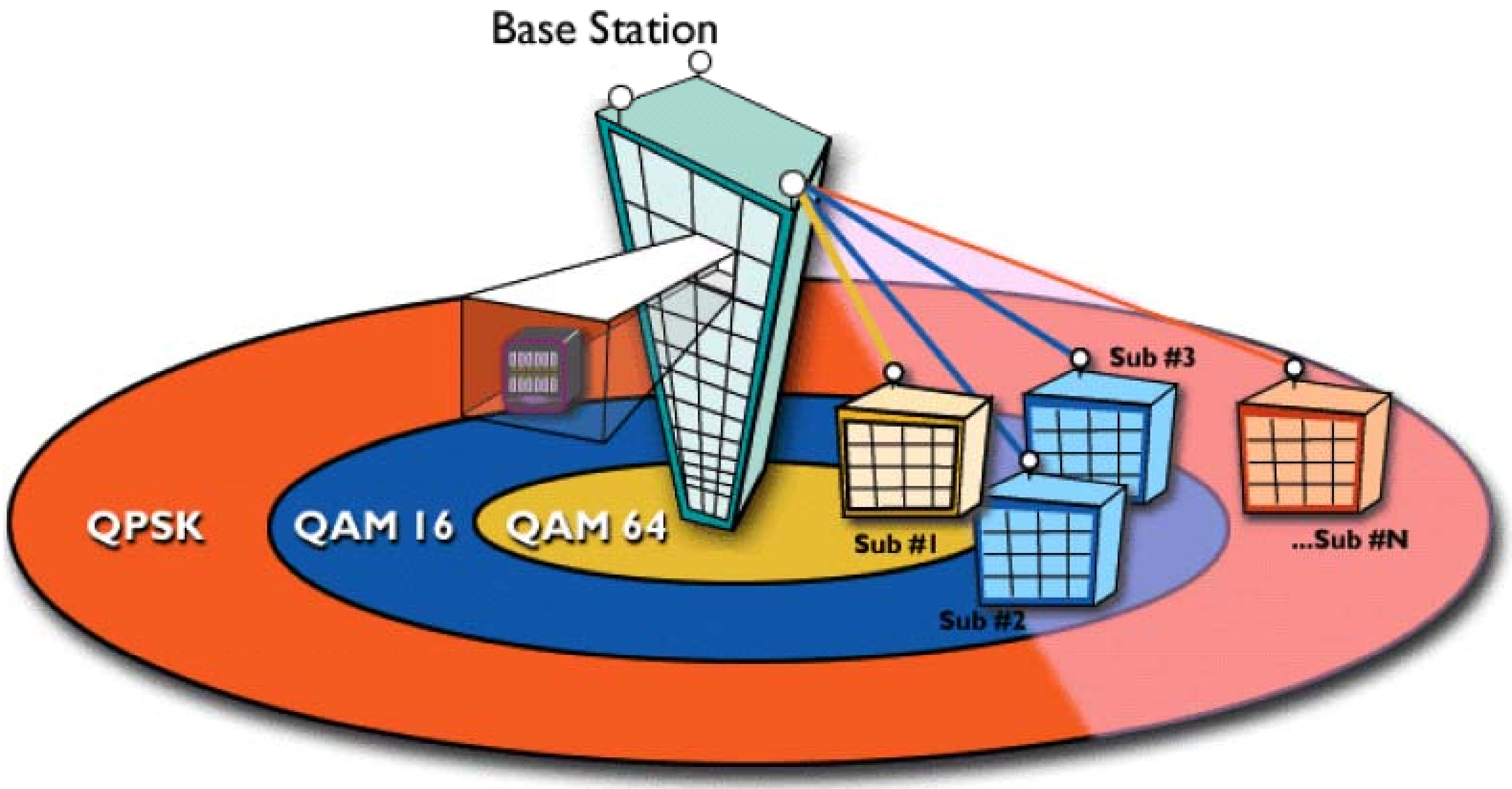
- PHY Specification Overview
  - 5~6 GHz unlicensed frequency bands
  - Orthogonal Frequency Division Multiplexing
  - channelization of 20, 10 and optional 5 MHz
    - to allow different deployment scenarios
      from dense populated areas to sparse populated areas
  - FFT size: mandatory 64, 256 and optional 2048
  - multiple access: TDMA / OFDMA, TDD duplexing

Mode	A	B	C
Access method	TDMA	OFDM	OFDMA
FFT size	64	256	2048
Status	Mandatory	Mandatory	Optional
Carrier Allocation	4 pilots at –21, -7, 7, 21 / dc / 48 data carriers	8 pilots at –84,-60,-36,-12,12,36,60,84 / dc / 192 data carriers	constant/variable location pilots, different pilot allocation in up- and down-stream

IEEE 802.16WG, IEEE Std 802.16e™-2005 *and* IEEE Std 802.16™-2004/Cor 1-2005, *Standard for Local and metropolitan area networks Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems Amendment 2:Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1*, Dec. 2005

Adaptive PHY



Adaptive Burst Profiles

- Burst profile
  - Modulation and FEC
- Dynamically assigned according to link conditions
  - Burst by burst, per subscriber station
  - Trade-off capacity vs. robustness in real time
- Roughly doubled capacity for the same cell area
- Burst profile for downlink broadcast channel is well-known
  - All other burst profiles could be configured "on the fly"
  - Subscriber station capabilities recognized at registration

IEEE 802.16 Frame Structure

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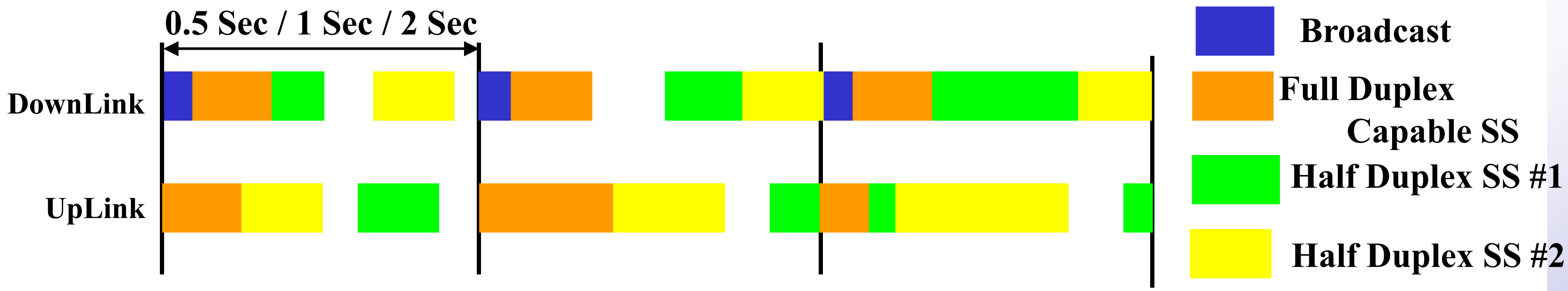
- The frame structure
  - Preamble
  - FCH (Frame Control Header)
  - DL_MAP & UL_MAP
  - DL/UL data bursts
  - UL control channel for ranging
- 2 types of subcarrier permutation mode in 802.16 OFDMA
  - The distributed subcarrier permutation mode
    - PUSC, OPUSC, FUSC or OFUSC mode
  - The adjacent subcarrier permutation mode
    - AMC mode

-OxUSC : Optional x Usage Sub-Channel

FDD vs. TDD

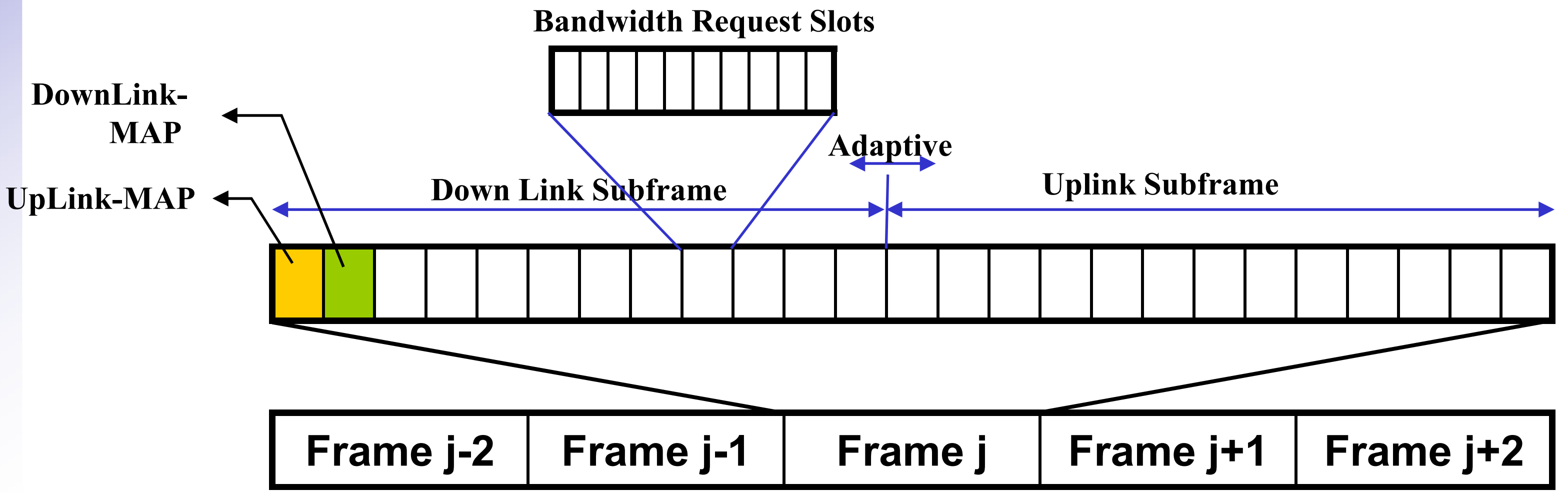
FDD

- the uplink and downlink channels are on separate frequencies.

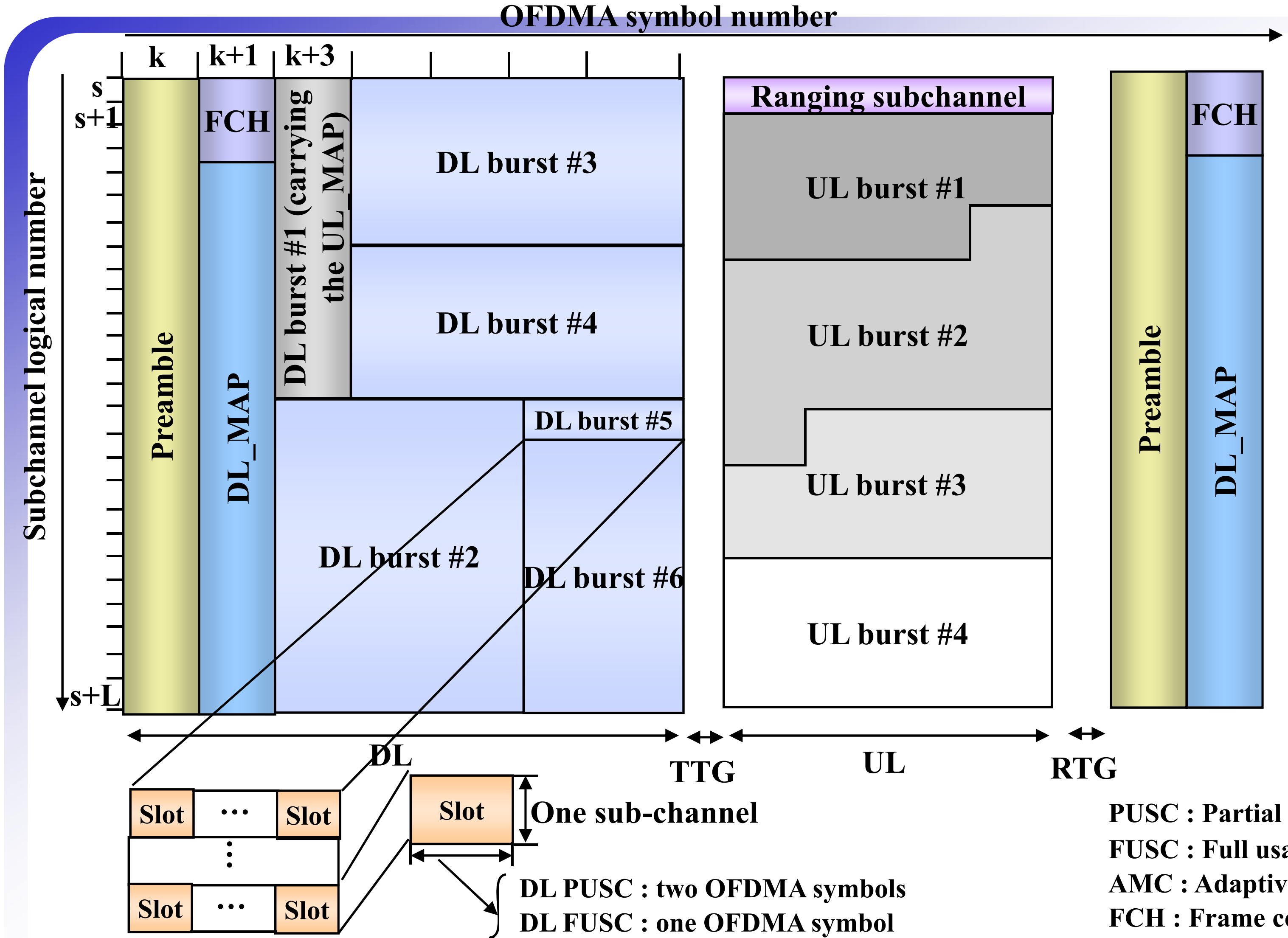


TDD

- the uplink and downlink transmissions share the same frequency but are separated in time



Frame Structure of IEEE 802.16 OFDMA



DL PUSC : two OFDMA symbols
DL FUSC : one OFDMA symbol
UL PUSC : three OFDMA symbols
DL/UL AMC : two, three or six OFDMA symbols

PUSC : Partial usage of subchannels
FUSC : Full usage of subchannels
AMC : Adaptive modulation and coding
FCH : Frame control header
TTG : Transmit/receive transition gap
RTG : Receive/transmit transition gap

Refer to IEEE 802.16e std 2005

IEEE 802.16 MAC Overview

- Point-to-Multipoint
- Metropolitan Area Network
- Connection-oriented
- Supports different user environments
  - High bandwidth, hundreds of users per channel
  - Continuous and burst traffic
  - Very efficient use of spectrum
- Protocol-Independent core
  - ATM / IPv4/ IP v6 / Ethernet
- Balances between stability of contention-less and efficiency of contention-based operation
- Flexible QoS offerings
  - CBR, rt-VBR, nrt-VBR, BE, with granularity within classes
- Supports multiple 802.16 PHYs

IEEE 802.16 MAC layer function

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- Transmission scheduling :
  - Controls up and downlink transmissions so that different QoS can be provided to each user
- Admission control :
  - Ensures that resources to support QoS requirements of a new flow are available
- Link initialization
  - Scans for a channel, synchronizes the SS with the BS, performs registration, and various security issues.
- Support for integrated voice/data connections
  - Provide various levels of bandwidth allocation, error rates, delay and jitter
- Fragmentation :
  - Sequence number in the MAC header is used to reassemble at the receiver
- Retransmission :
  - Implement an ARQ(Automatic Repeat Request

Basic of the MAC Protocol

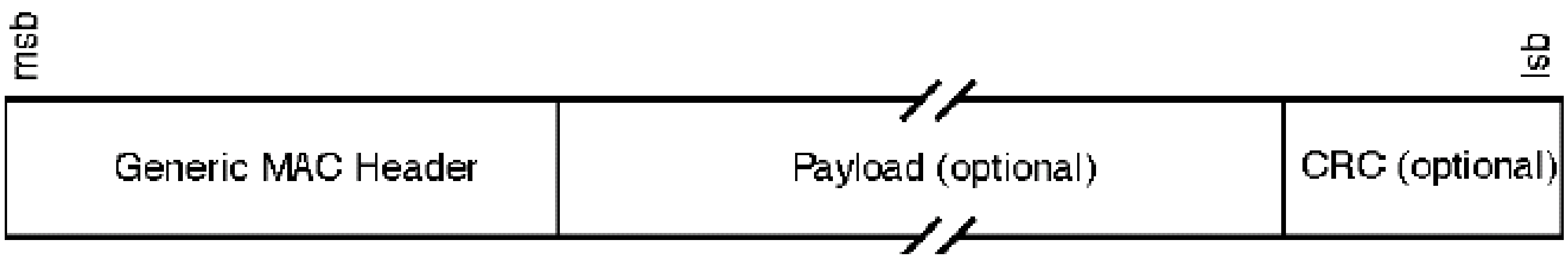
- **Downlink**
  - **Broadcast phase : The information about uplink and downlink structure is announced.**
  - **DL-MAP(Downlink Map)**
    - DL-MAP defines the access to the downlink information
  - **UL-MAP(Uplink Map)**
    - UL-MAP message allocates access to the uplink channel
- **Uplink**
  - **Random access area is primarily used for the initial access but also for the signaling when the terminal has no resources allocated within the uplink phase.**

Definitions

- Service Data Unit (SDU)
  - Data units exchanged between adjacent layers
- Protocol Data Unit (PDU)
  - Data units exchanged between peer entities
- Connection and Connection ID
  - a unidirectional mapping between MAC peers over the airlink (uniquely identified by a CID)
- Service Flow and Service Flow ID
  - a unidirectional flow of MAC PDUs on a on a connection that provides a particular QoS (uniquely identified by a SFID)

MAC PDU format

- The Generic MAC header has fixed format
- One or more MAC sub-headers may be part of the payload
- The presence of sub-headers is indicated by a Type
- field in the Generic MAC header



Generic MAC Header

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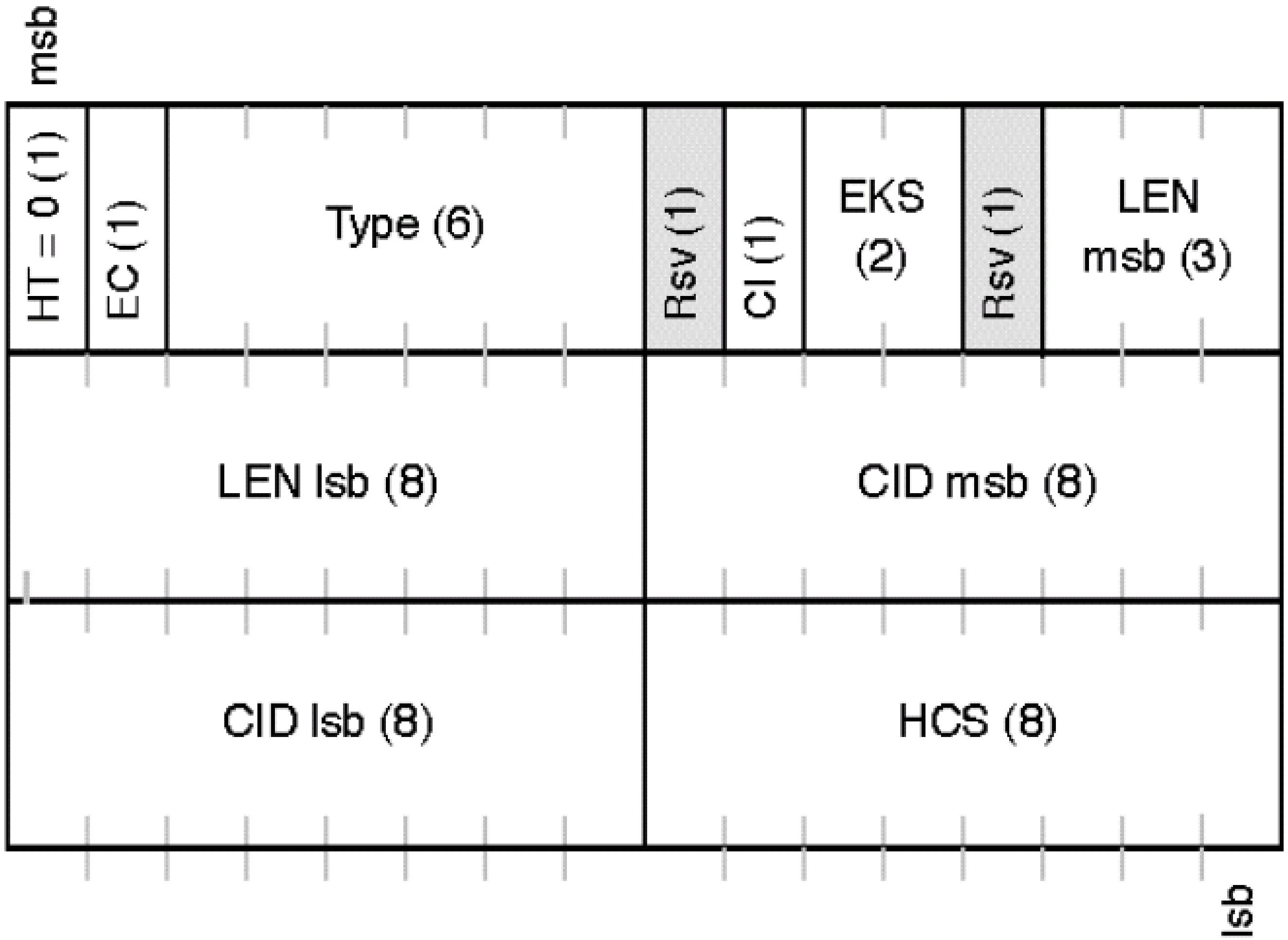
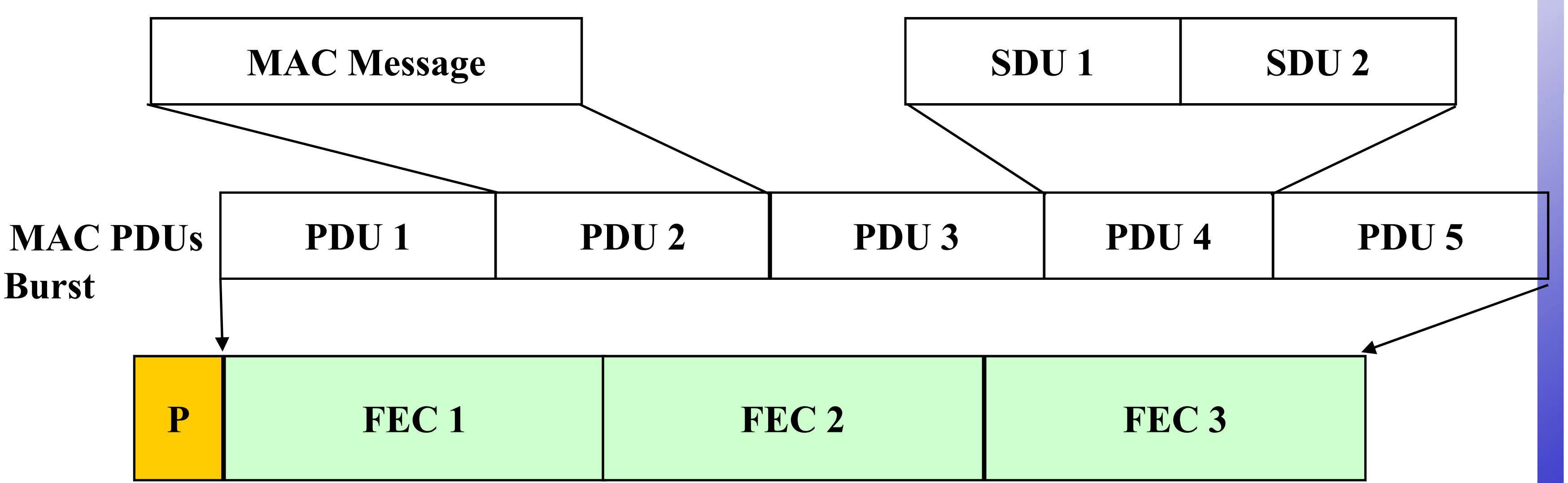


MAC PDU Transmission

- MAC PDUs are transmitted in PHY bursts
- A single PHY burst can contain multiple
- *Concatenated* MAC PDUs
- The PHY burst can contain multiple FEC blocks
- MAC PDUs may span FEC block boundaries
- The TC layer between the MAC and the PHY allows for capturing the start of the next MAC PDU in case of erroneous FEC blocks



- P : Preamble

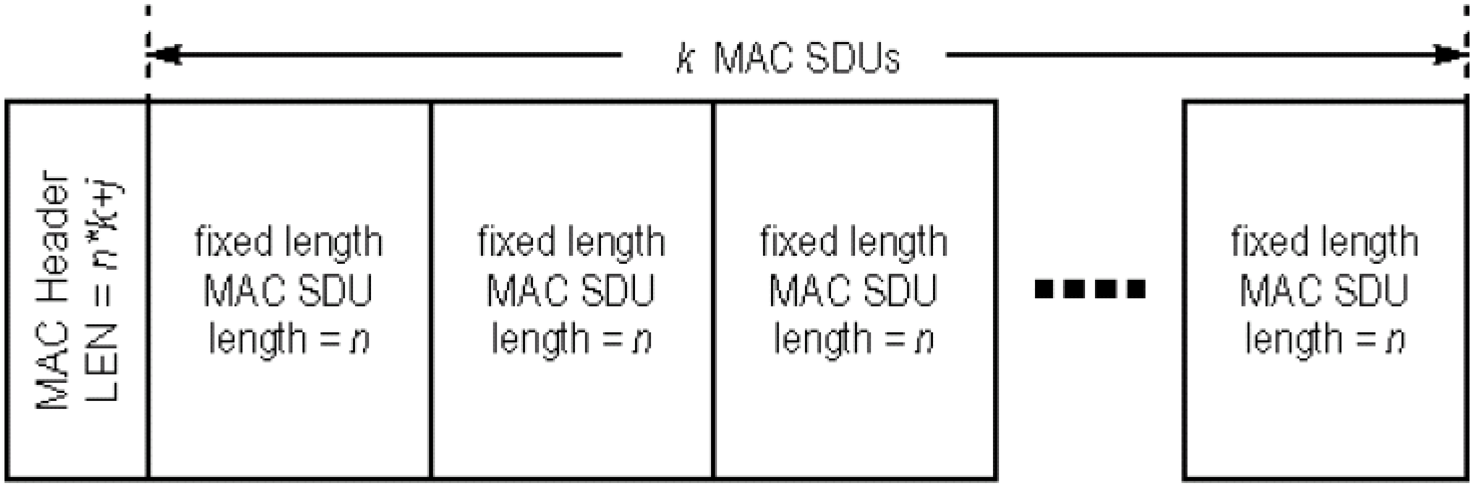
Fragmentation

- **Partitioning a MAC SDU into fragments transported in multiple MAC PDUs**
- **Each connection can be in only a single fragmentation state at any time**
- **Contents of the fragmentation sub-header:**
  - **2-bit Fragmentation Control (FC)**
    - Unfragmented, Last fragment, First fragment, Continuing fragment
  - **3-bit Fragmentation Sequence Number (FSN)**
    - required to detect missing continuing fragments
    - continuous counter across SDUs

Packing

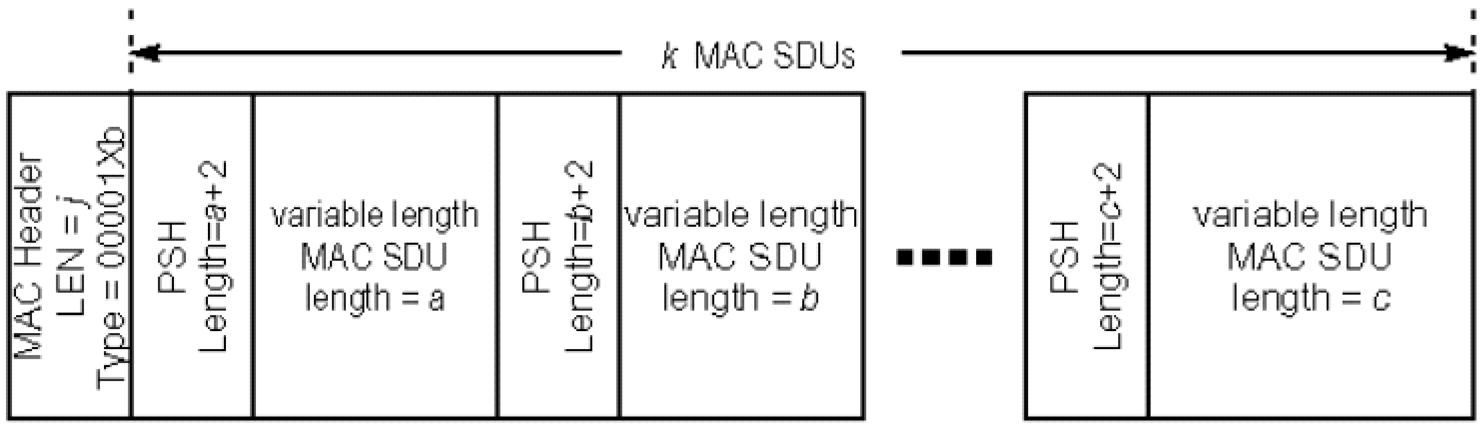
- **The process of combining multiple MAC SDUs (or fragments thereof) into a single MAC PDU**
- **On connections with variable length MAC SDUs**
  - **Packed PDU contains a sub-header for each packed SDU (or fragment thereof)**
- **On connections with fixed length MAC SDUs**
  - **No packing sub-header needed**
- **Packing and fragmentation can be combined**
- **Can, in certain situations, save up to 10% of system bandwidth**

Packing Fixed-Length SDUs



Packing Variable-Length SDUs

- 2 Byte Packing Sub-Header before each SDU
  - Length of the SDU: 11 bits
  - fragmentation control (FC): 2 bits
  - fragmentation sequence number (FS): 3 bits

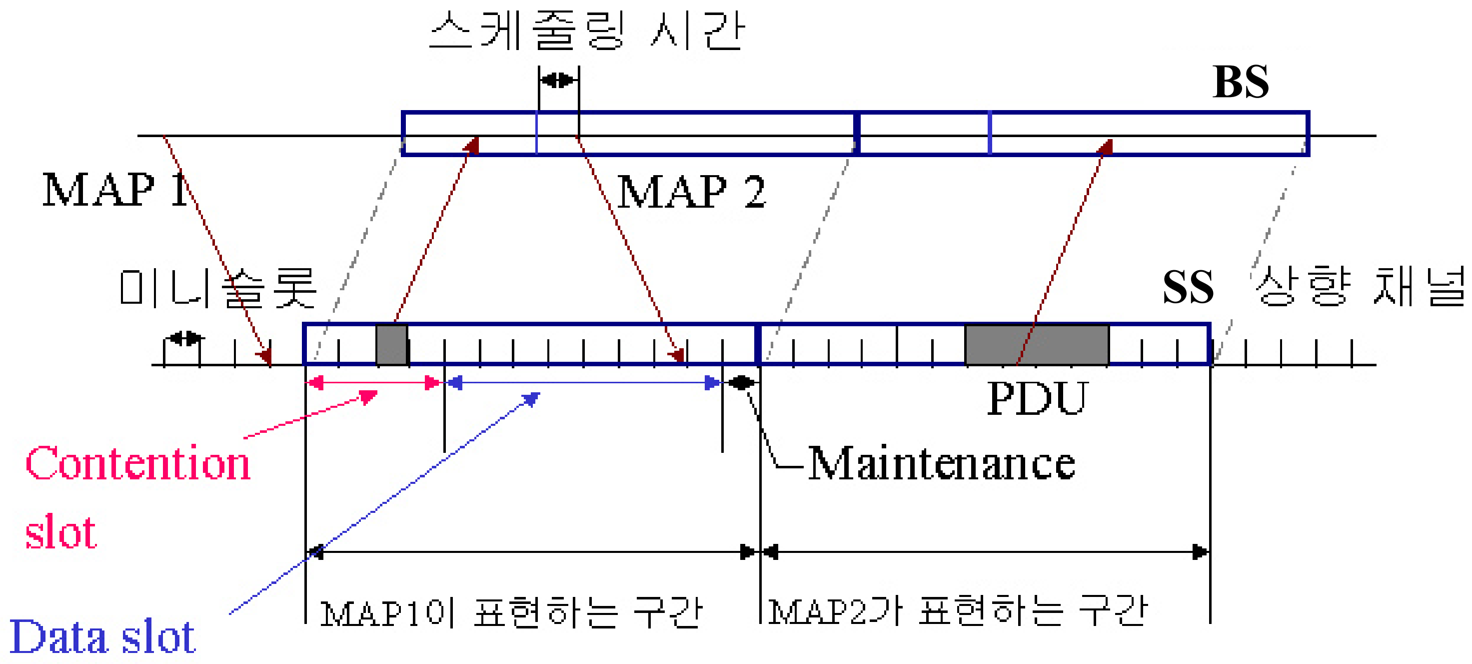


Bandwidth Request

- **Come from the Connection**
- **Several kinds of requests:**
  - **Implicit requests (UGS)**
    - No actual messages, negotiated at connection setup
  - **BW request messages**
    - Uses the special BW request header
    - Requests up to 32 KB with a single message
    - Incremental or aggregate, as indicated by MAC header
  - **Piggybacked request (for non-UGS services only)**
    - Presented in GM sub-header and always incremental
    - Up to 32 KB per request for the CID
  - **Poll-Me bit (for UGS services only)**
    - Used by the SS to request a bandwidth poll for non-UGS services

Uplink Channel Allocation

- **Uplink Channel Allocation**
  - **Transmits the bandwidth request message in contention slot**
  - **BS schedules the data transmission time**
  - **BS allocates the data transmission time using bandwidth allocation MAP message**
  - **SS transmits the data in data transmission slot allocated by BS**



Ranging

- For uplink transmissions, times are measured at BS
- At startup, SS sends a RNG-REQ in a ranging window
- BS measures arrival time and signal power; calculates required advance and power adjustment
- BS sends adjustment in RNG-RSP
- SS adjusts advance and power; sends new RNG-REQ
- Loop is continued until power and timing is ok

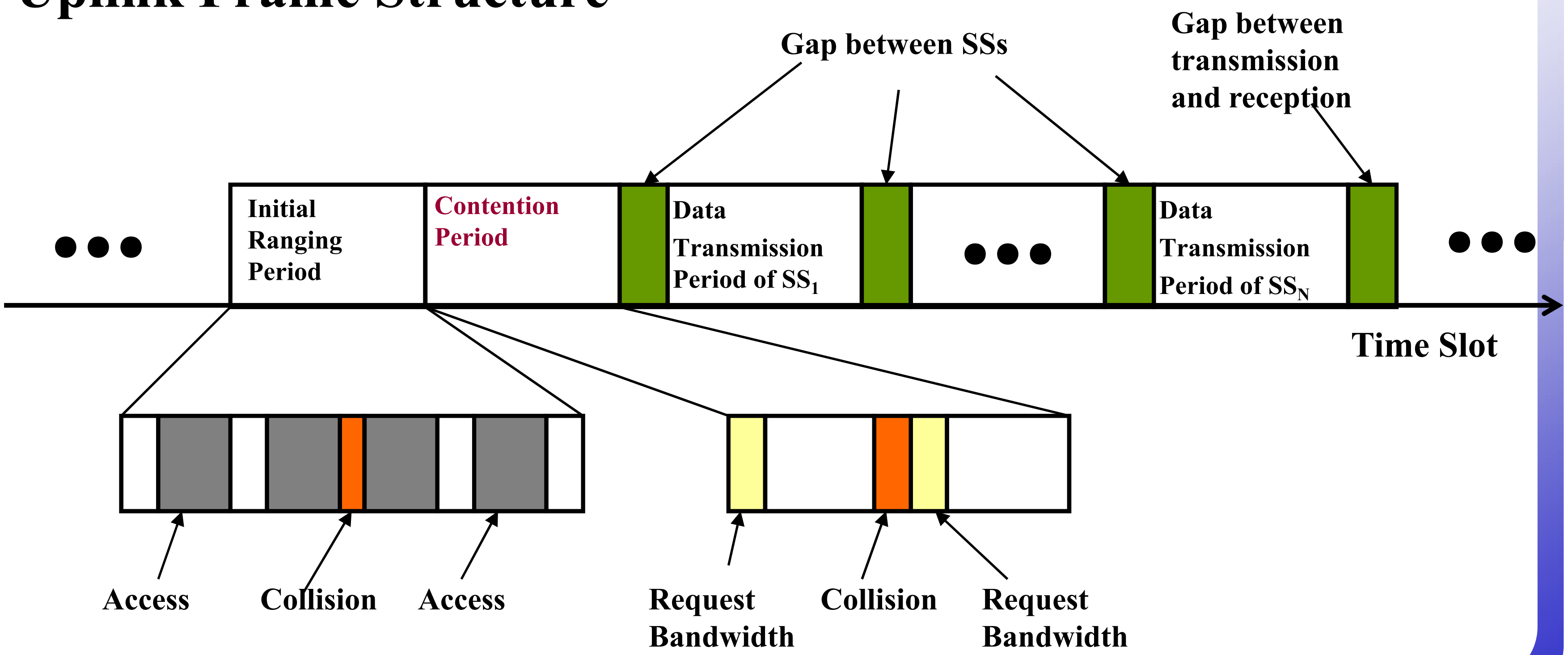
Service Classes

Service	Definition	Application	QoS Parameter
UGS	– Support fixed size real-time service at periodic interval	– VoIP without silence suppression	– Maximum Sustained Traffic Rate – Maximum Latency – Tolerated Jitter
ert-PS	– Support variable size real-time service at periodic interval	– VoIP with silence suppression – Variable size vocodec	– Maximum Sustained Traffic Rate – Minimum Reserved Traffic Rate – Maximum Latency
Rt-PS	– Support variable size real-time service based on polling access	– MPEG video	– Minimum Reserved Traffic Rate – Maximum Sustained Traffic Rate – Maximum Latency
Nrt-PS	– Support non real-time service flows based on polling basis	– FTP	– Minimum Reserved Traffic Rate – Traffic Priority
BE	– Best-effort	– HTTP	– Traffic Priority

- UGS :Unsolicited Grant Service
- ertPS : extended real-time Polling services
- rtPS : real-time Polling Service
- nrt-PS : non-real-time Polling Service
- BE : Best Effort

IEEE 802.16 SC (Single Carrier) MAC Protocol

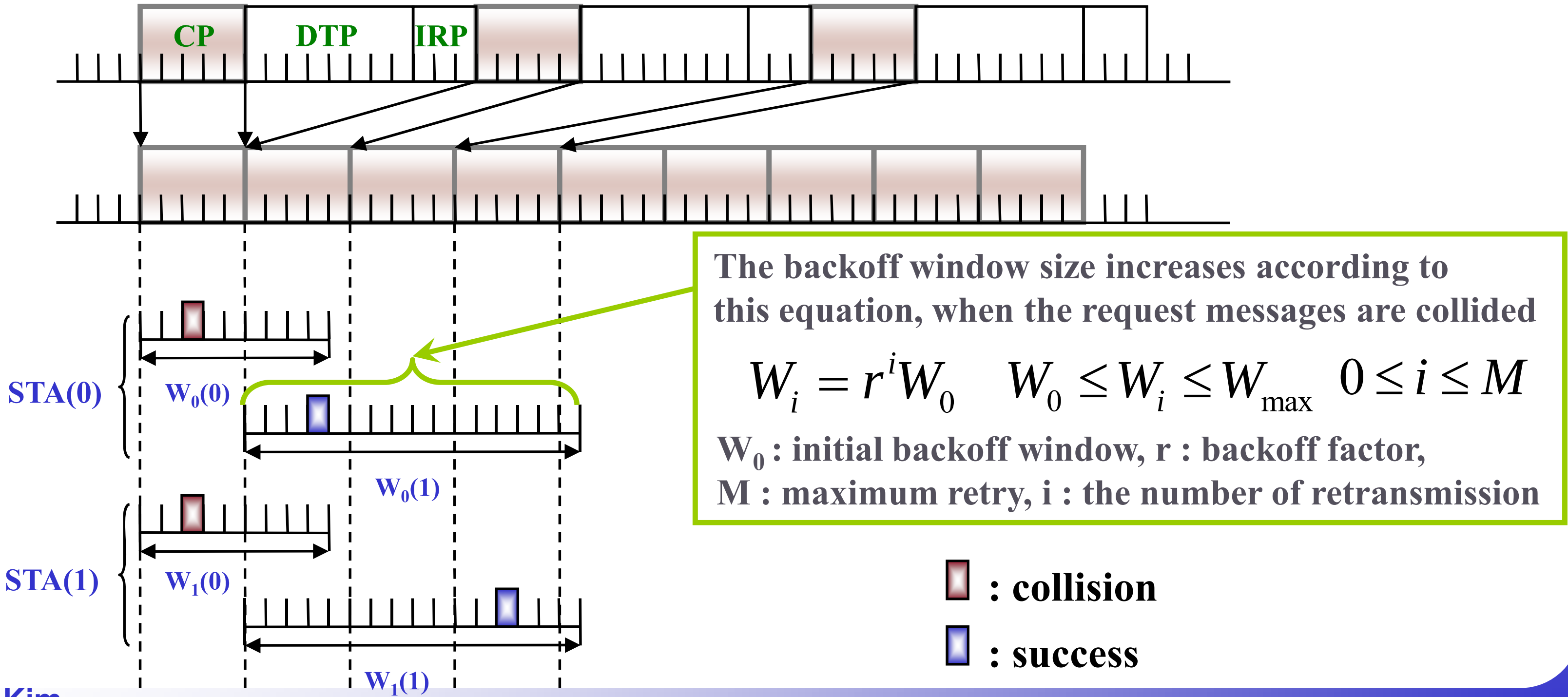
- **Binary Exponential Backoff Algorithm** is applied when the collision is occurred
- The frames are divided by **bandwidth allocation MAP message** according to the usage.
- Uplink Frame Structure



S. M. Oh and J. H. Kim, "The Optimization of the Collision Resolution Algorithm for Broadband Wireless Access Network," in *Proc. ICACT'06*, Vol 3, Pyong Chang, Korea, Feb. 20-22, 2006, pp. 1944-1948.

Initial Backoff in IEEE 802.16 SC

- **Problem**
  - **The bandwidth request message is randomly transmitted for the data transmission in the contention period for the IEEE 802.16 MAC protocol**
  - **IEEE 802.16 MAC protocol performance is affected by initial backoff window size [11]**
- **Frame Structure**



Performance Analysis of IEEE 802.16 SC MAC Protocol (1)

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Throughput (S)

$$S = \binom{N}{1} p_t (1-p_t)^{N-1}$$

- p_t는 하나의 Station이 임의의 slot으로 패킷을 전송할 확률
- N : Station 수

Average delay (D)

•D_i 는 i 번째 대역폭 요청메시지를 재전송하는 SS가 임의로 선택한 backoff counter

$$\bar{D} = E\left[\left\{\sum_{i=0}^{N_R-1}\left(\left\lfloor\frac{D_i+1}{CP}\right\rfloor \times F + D_i + 1 - \left\lfloor\frac{D_i+1}{CP}\right\rfloor \times CP\right) + \left(\left\lfloor\frac{D_{N_R}}{CP}\right\rfloor \times F + D_{N_R} - \left\lfloor\frac{D_{N_R}}{CP}\right\rfloor \times CP\right)\right\} \middle| \text{no drop}\right].$$

i 번째 재전송 시 지연시간

$\lfloor (D_i+1)/CP \rfloor$

: i 번째 재전송에서 지연되는 프레임의 수

$D_i + 1 - \lfloor (D_i+1)/CP \rfloor \times CP$

: 마지막 프레임에서 남아있는 backoff counter

N_R번째 재전송 시 지연시간

$\lfloor D_{N_R}/CP \rfloor$

: i 번째 재전송에서 지연되는 프레임의 수

$D_{N_R} - \lfloor D_{N_R}/CP \rfloor \times CP$

: 마지막 프레임에서 남아있는 backoff counter

Average delay

$$\bar{D} = F \times \left\{ \frac{W_0}{2(1-r)} \times \left(1 - \frac{(1-p_c)r}{1-p_c{}^{M+1}} \sum_{n=0}^{M} (rp_c)^n \right) + \frac{1}{2} \times \left(\frac{p_c}{1-p_c} - \frac{(M+1)\, p_c{}^{M+1}}{1-p_c{}^{M+1}} + 1 \right) - 1 \right\} \times \frac{1}{CP}$$
$$- \frac{1}{2} \times \left(\frac{p_c}{1-p_c} - \frac{(M+1)\, p_c{}^{M+1}}{1-p_c{}^{M+1}} + 1 \right) \times (F - CP).$$

- M : Maximum retry
- r : Backoff factor (Binary exponential backoff $r = 2$)

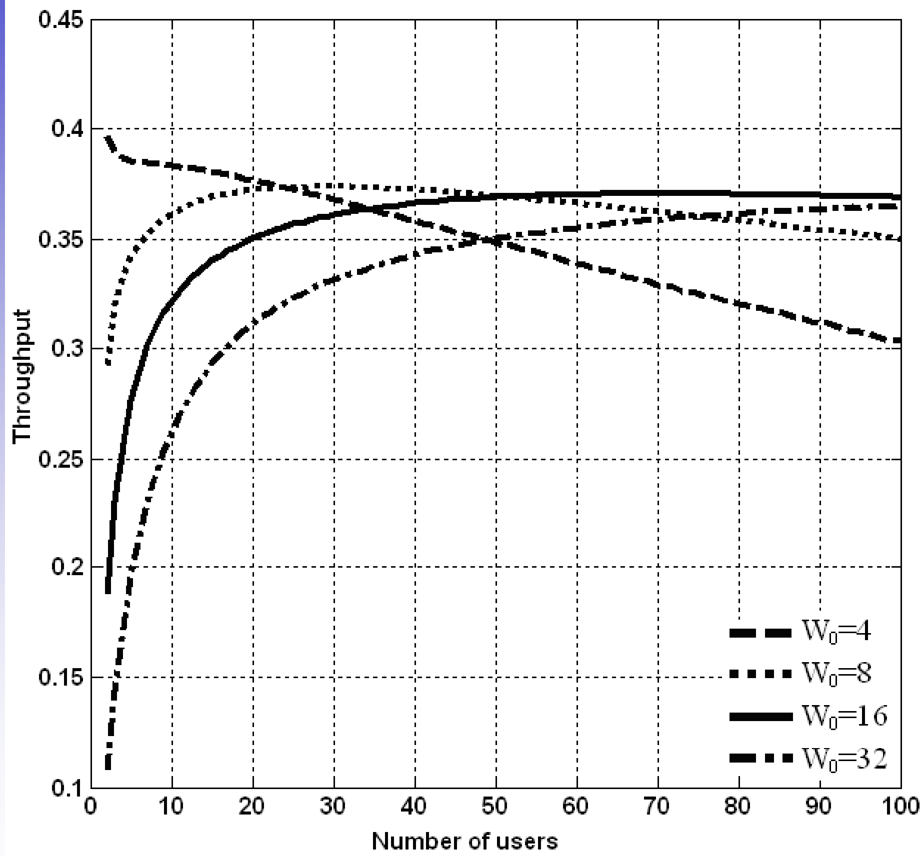
Packet Drop Probability (p_d)

$$p_d = p_c{}^{M+1}$$

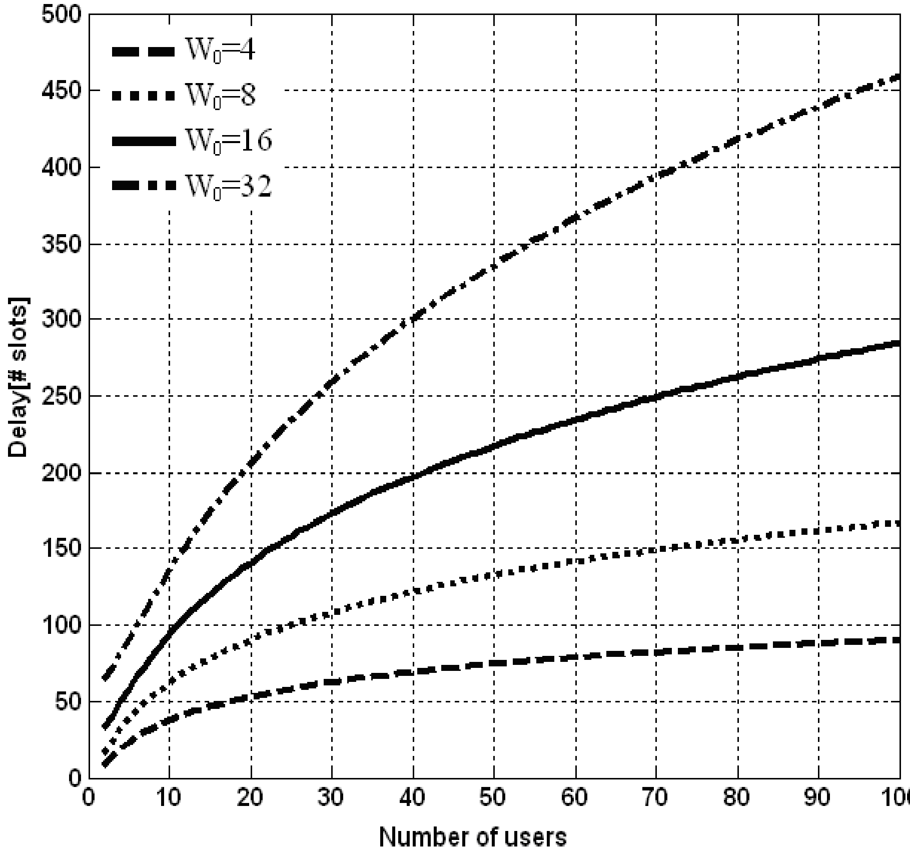
- p_c : 패킷 전송 시 충돌이 발생할 확률

Performance Analysis Results of IEEE 802.16

Throughput and Delay



Throughput according to the number of users (M=6)



Delay according to the number of users (M=6)

Optimal Initial Backoff Window

Cost Function

- **Define for the system performance optimization**
- **Use the weighting factor to consider the required QoS metrix of the services**
- **Applied to calculate the optimal initial backoff window according to the number of users and QoS required parameters**

$$Nor\_inv\_throughput(N) = \frac{S'(N) - S'_{\min}(N)}{S'_{\max}(N) - S'_{\min}(N)}$$

$$Nor\_delay(N) = \frac{D(N) - D_{\min}(N)}{D_{\max}(N) - D_{\min}(N)}$$

$$Nor\_prob.\_drop(N) = \frac{P_d(N) - P_{d\min}(N)}{P_{d\max}(N) - P_{d\min}(N)}$$

$$\begin{aligned} Cost\_Function(N) = {} & WF_1 \times Nor\_inv\_throughput(N) \\ & + WF_2 \times Nor\_delay(N) \\ & + WF_3 \times Nor\_prob\_drop(N) \end{aligned}$$

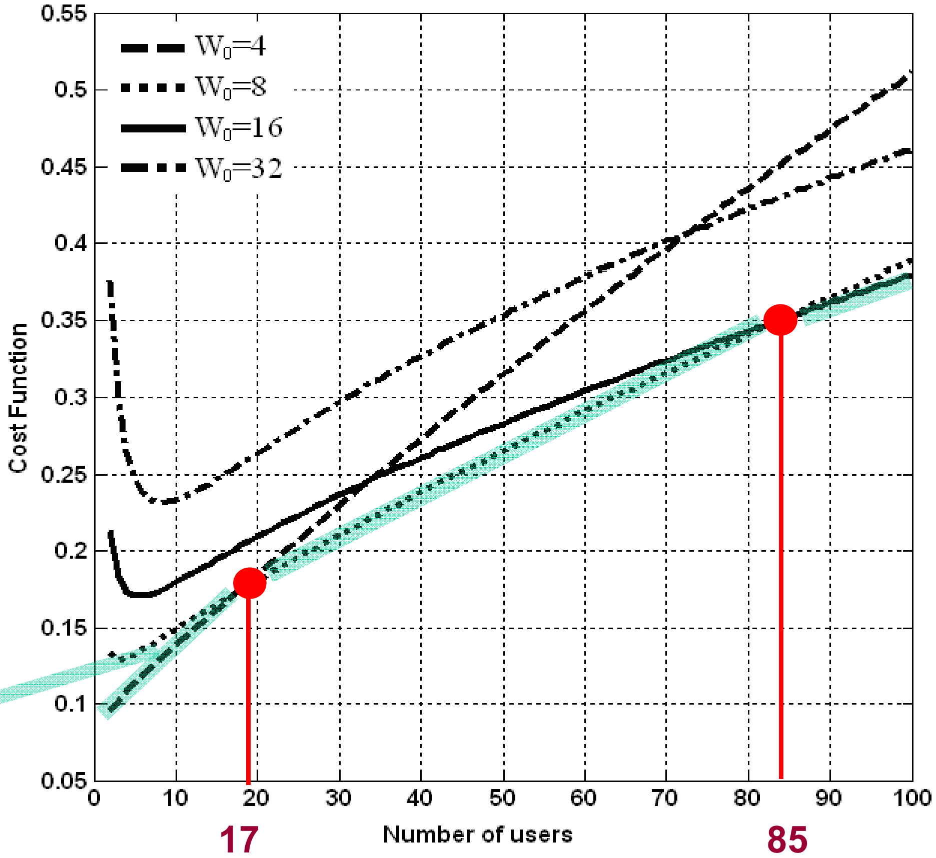
Optimal Initial Backoff Window

Analysis of the Optimal Initial Backoff Window

- The system performance is optimal when the cost function is smallest

The number of users	Optimal Initial Backoff Window
2~17	$W_0 = 4$
17~85	$W_0 = 8$
85~100	$W_0 = 16$

Optimal Curve



Cost function according to the number of users (WF_1=0.33, WF_2=0.33, WF_3=0.33)

WINNER

-. Vision/Concept

-. Frame Structure

-. System Architecture

-. SLC

-. ARQ

-. MAC

-. Scheduler

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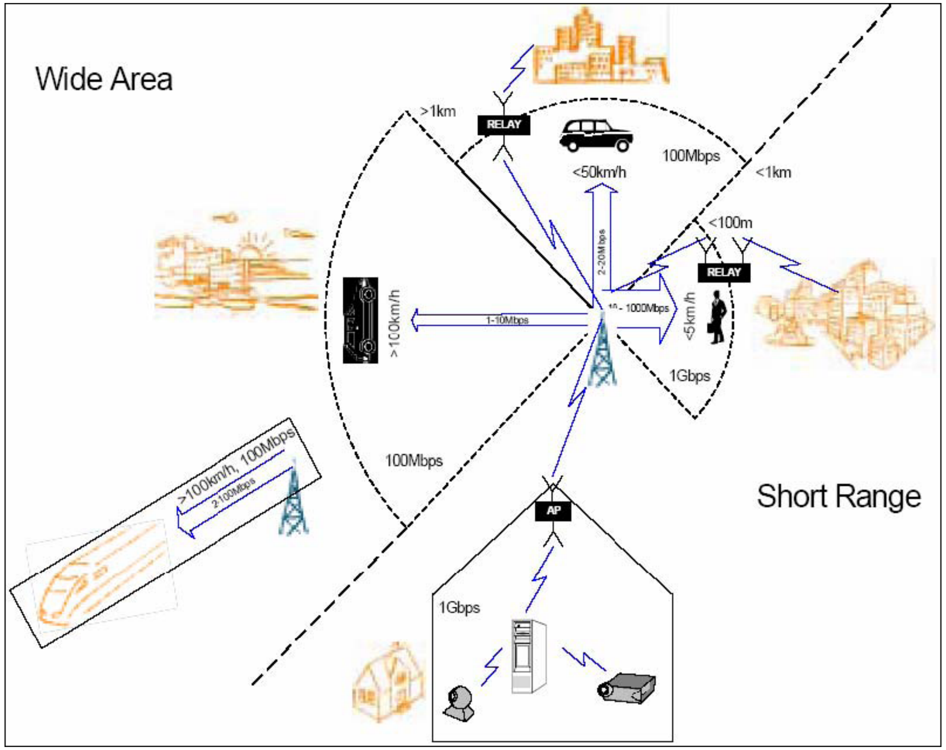
WINNER Goal

- **To develop a single new ubiquitous radio access system concept**
- **Scalable or adapted to a comprehensive range of mobile communication scenarios from short-range to wide-area**
  - Ranges, mobility, environments, and user densities.



WINNER Concept

- **Constitution**
  - **WINNER is a consortium of 41 partners coordinated by Siemens under IST (Information Society Technology) in EU.**
- **WINNER system concept**
  - **Single new ubiquitous radio access system**
  - **Self-contained, allowing WINNER to target the chosen requirements without the need for inter-working with other systems**
  - **Cooperation, inter-working and infrastructure reuse may be used for mutual benefit (Cooperation)**
  - **First deployment expected at the earliest in 2010, widespread from 2015**
  - **1st Phase (2004~2005), 2nd Phase (2006~2007), 3rd Phase(2008~2009)**
  - **System Modes**
    - TDD
    - FDD
    - Peer-to-peer

MAC Frame Structure (1)

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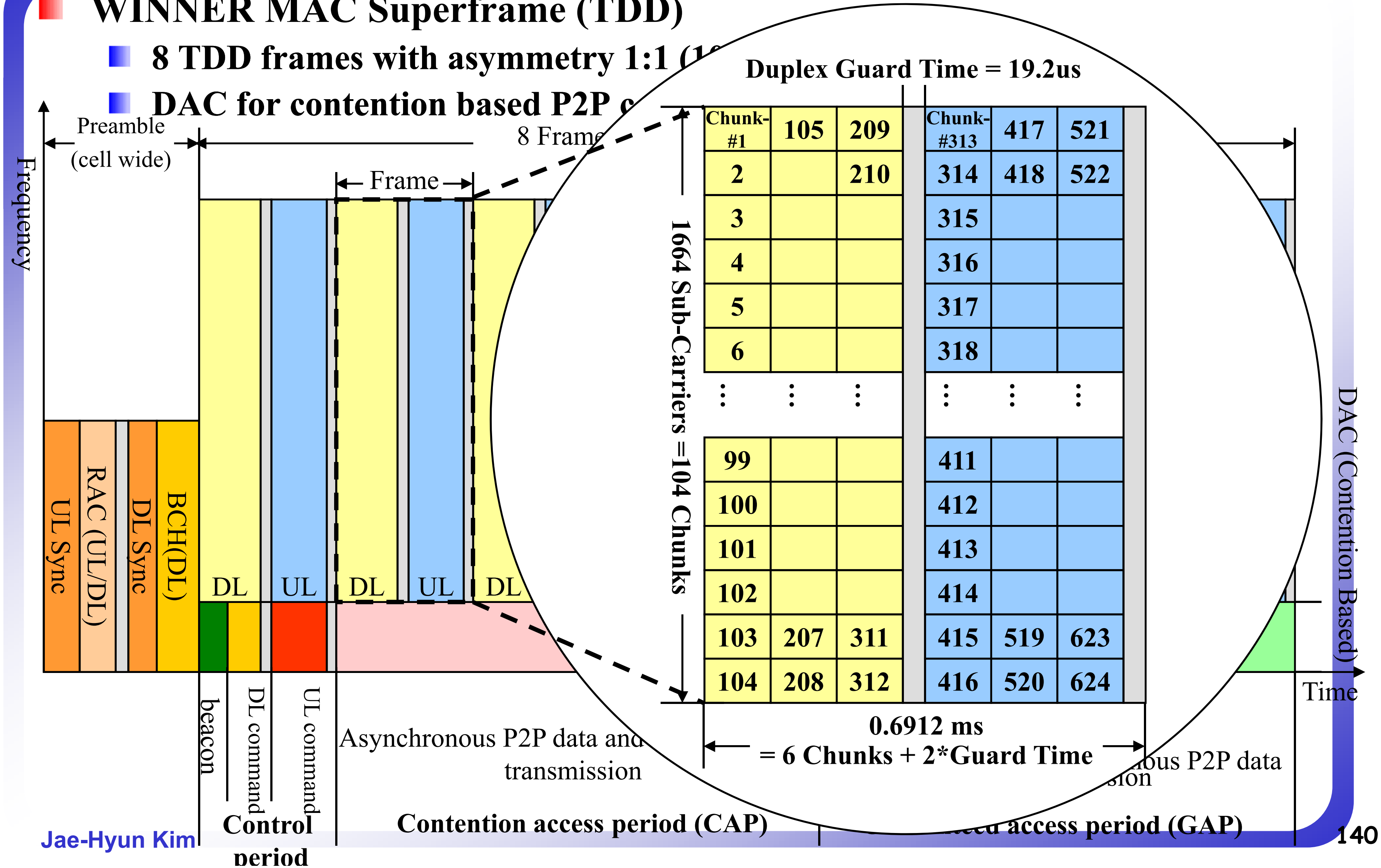
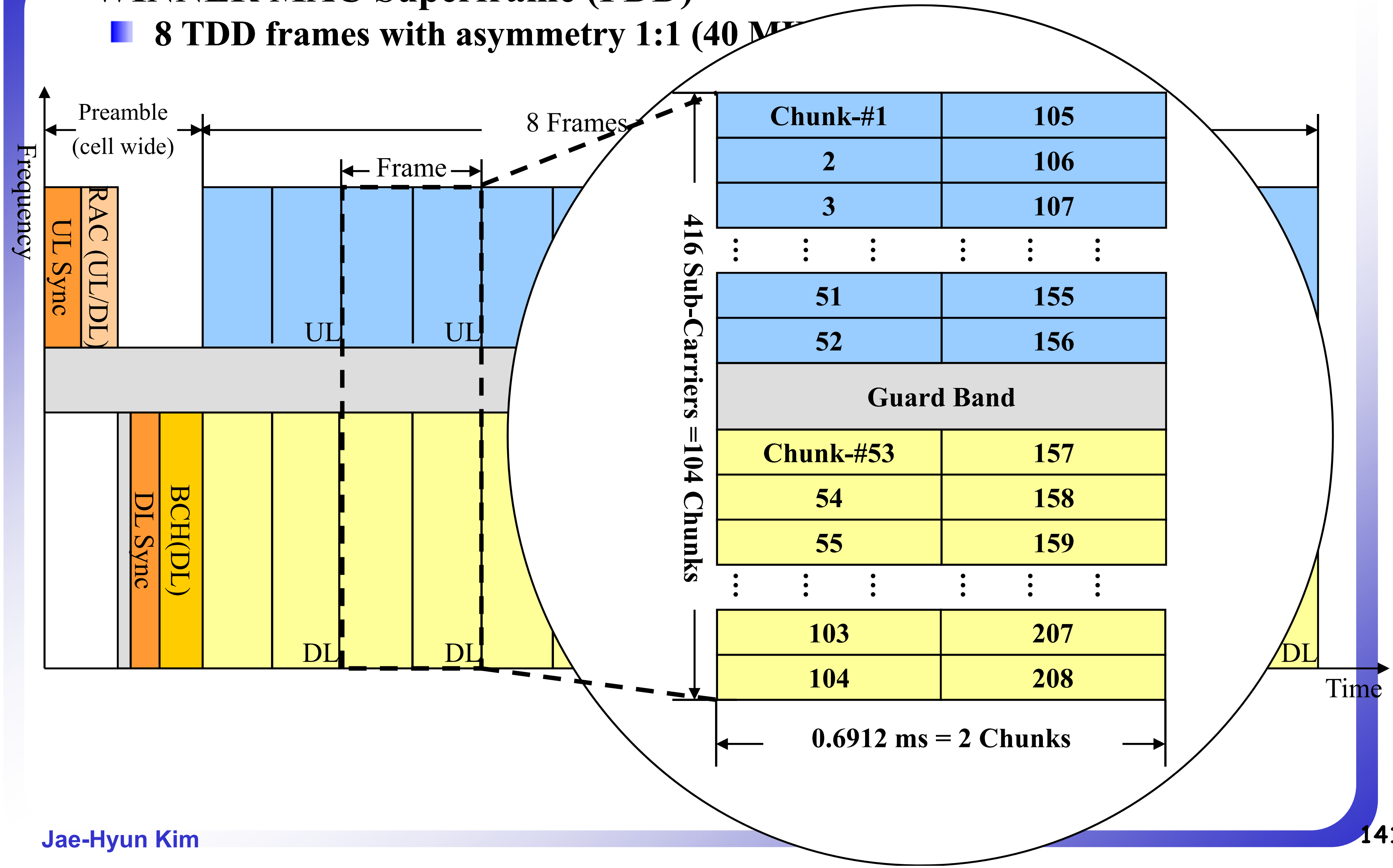
- **WINNER MAC Superframe (TDD)**
  - **8 TDD frames with asymmetry 1:1 (1**
  - **DAC for contention based P2P c**



MAC Frame Structure (2)

- **WINNER MAC Superframe (FDD)**
  - **8 TDD frames with asymmetry 1:1 (40 MHz)**



MAC Frame Structure (3)

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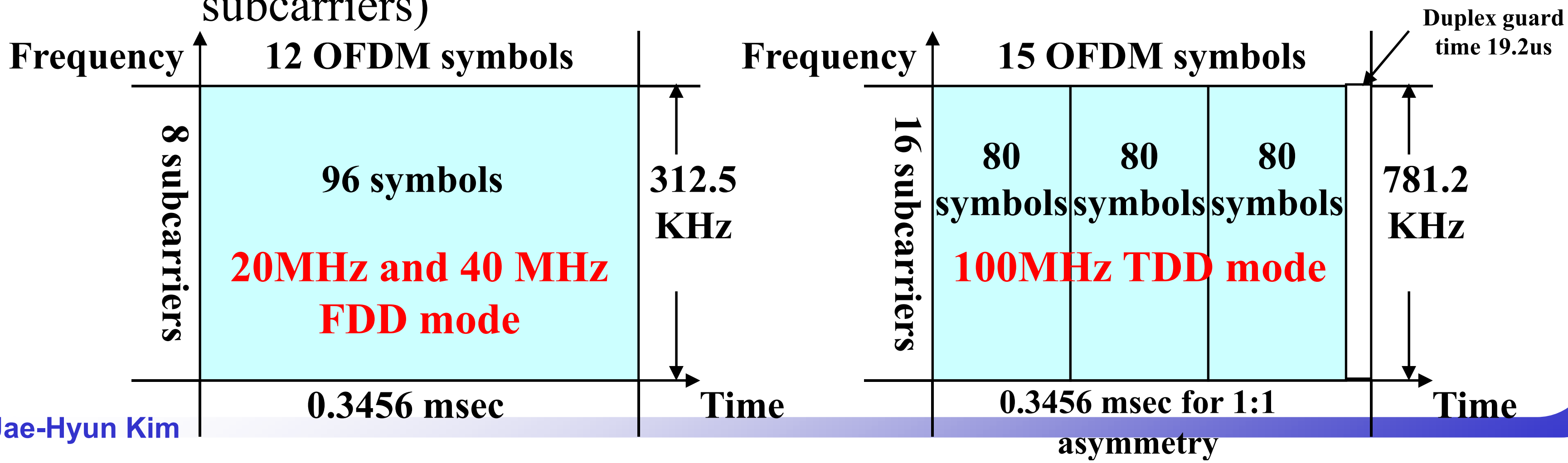
- **Chunk**
  - **Basic time-frequency unit for resource allocation**
  - **FDD Mode : 8 subcarriers by 12 OFDM symbols (312.5 kHz × 345.6 μs) - chunk**
    - 20 MHz : 52 chunks (416 subcarriers usable out of 512 subcarriers)
    - 40 MHz : 104 chunks (832 subcarriers usable out of 1024 subcarriers)
  - **TDD Mode : 16 subcarriers by 5 OFDM symbols (781.25 kHz × 108.0 μs) - chunk**
    - 100 MHz : 104 chunks (1664 subcarriers usable out of 2048 subcarriers)



MAC Frame structure (4)

- **Frame (691.2 µs)**
  - **Set of the chunks**
  - **In the TDD mode**
    - A downlink period (108.8 µs *3chunks) + duplex guard time (19.2 µs) + uplink period (108.8µs *3chunks) + duplex guard time (19.2 µs) = 691.2 µs
    - For wide-area cellular and metropolitan deployment scenarios
  - **In the FDD mode**
    - A downlink chunk followed by an uplink chunk
    - $T_{frame} = 2*T_{chunk} = 691.2$ µs
    - For short-range cellular, isolated deployment scenarios and peer-to-peer communication

IST-2003-507581 WINNER D2.10 ver. 1.0, *Final report on identified RI key technologies, system concept, and their Assessment*, Dec. 2005

MAC Frame Structure (5)

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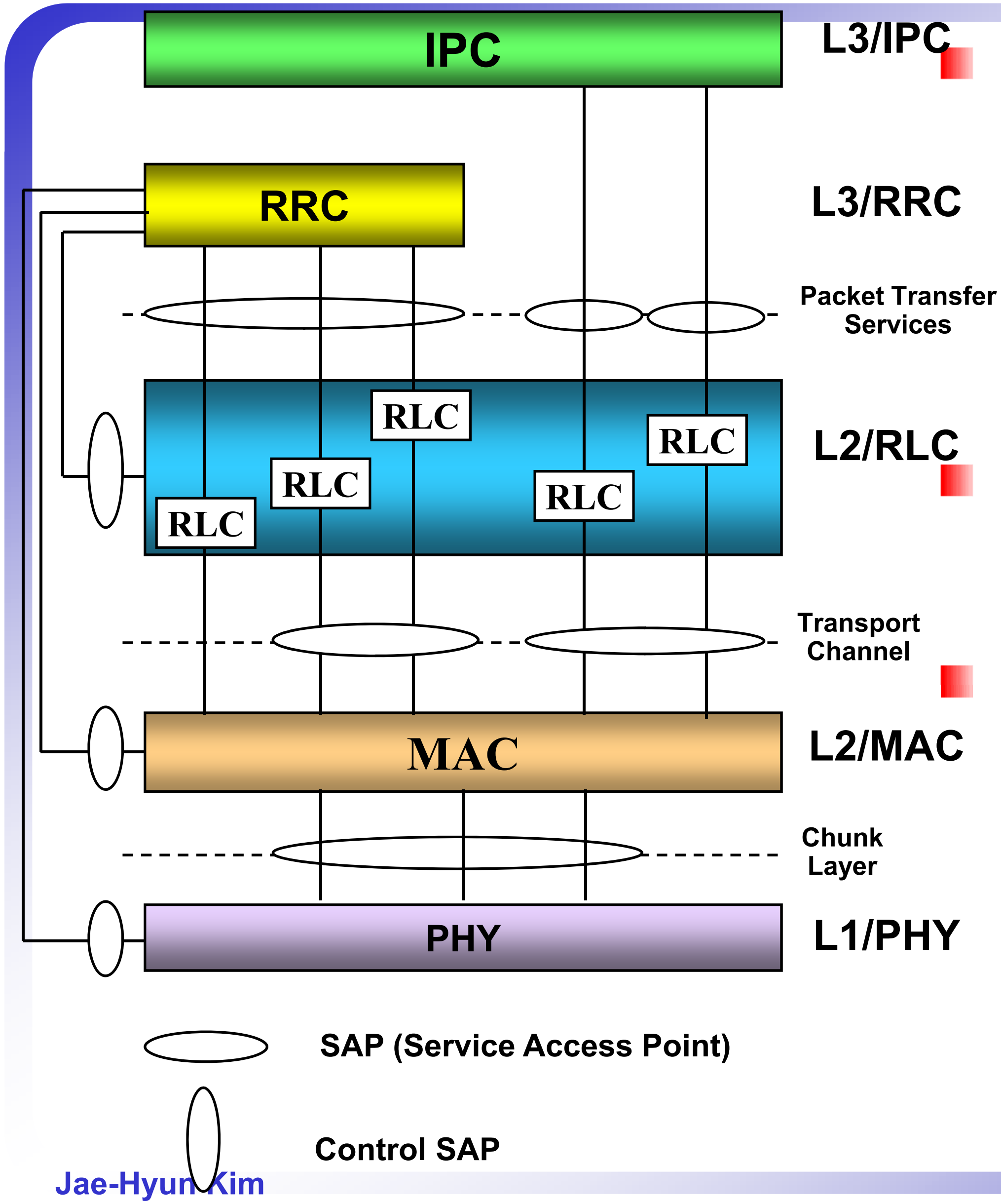
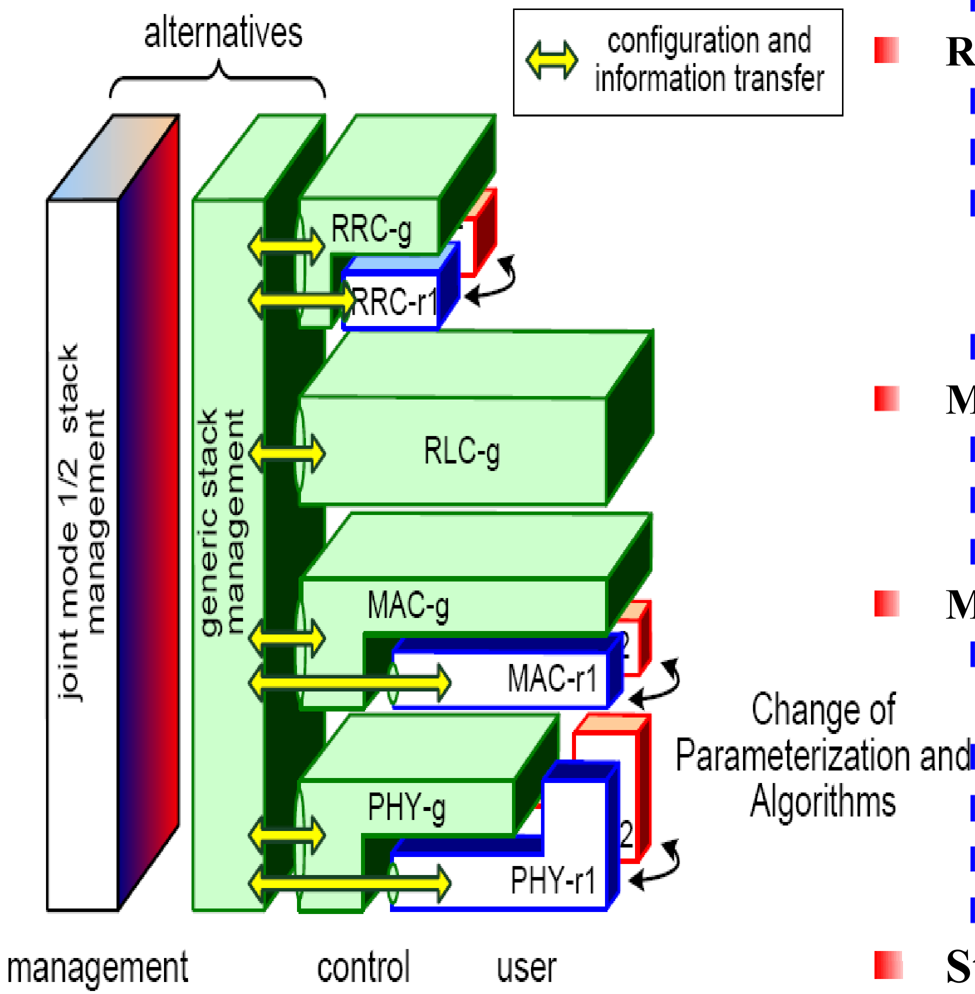
- **Preamble**
  - **Synchronization (UL Sync, DL Sync)**
    - UL Sync
      - Three OFDM symbols
    - DL Sync
      - Four OFDM symbols
      - The first symbol
        - T-pilot, used for coarse synchronization
  - **RAC (Random Access Channel)**
    - Initial access to Base station or Relay node
    - Can used for BS-to-BS and RN-to-BS control signaling in TDD system
  - **BCH (Broadcast Channel)**
    - Contains a control message for overall resource allocation used within this superframe

WINNER System Architecture



- WINNER system architecture
  - IPC (IP Convergence)
  - RRC (Radio Resource Control)
  - RLC (Radio Link Control)
  - MAC (Medium Access Control)
  - PHY (Physical)
- SAP
  - Allow the higher layer to communicate with its peer entity.
- Control SAP
  - Allow the higher layer to request information and to impact the behavior of the lower layer, e.g., by parameterization.

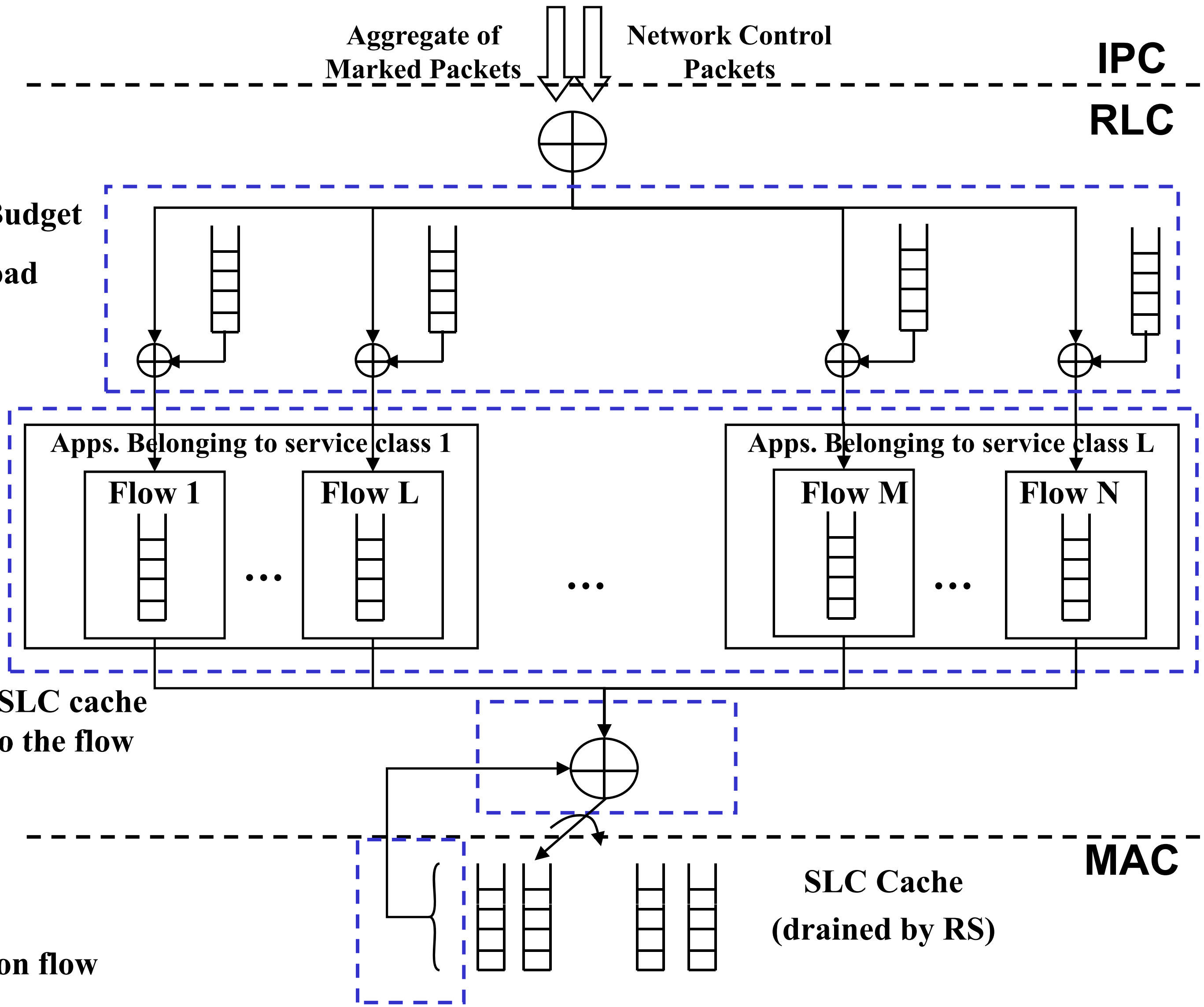
Protocol Reference Architecture



- RRC
  - RRM-related functions
- RLC
  - Flow setup, release and E2E addressing
  - E2E Retransmission Protocol
  - SLC (Service Level Controller) (QoS Control)
    - Service Traffic and PHY dependent
  - Higher-level Segmentation
- MAC-g
  - Segmentation
  - Hop-wise addressing in Multi-Hop setup
  - Hop-wise retransmission protocol
- MAC-r
  - Resource Scheduler (QoS Control)
    - PHY dependent
  - Spatial Scheme Selection
  - Duplex Scheme Implementation
  - Adaptive- / Non-adaptive transfer
  - Broadcast transfer
- Stack Management
  - Handle the overall stack configuration

SLC

- **Flow conditioning**
  - Leaky or Token Budget
  - Slowly adapt in load control
- **Flow Queuing**
  - Active queue management
  - Per-flow queuing
- **Flow Scheduling**
  - Forwarded to the SLC cache buffer according to the flow context
- **Flow Monitoring**
  - Monitor the flow
  - Provide feedback on flow traffic predictions



MAC Design Principle

- Self-organized synchronization of all involved base stations, relay nodes and user-terminals
- Fast transmission and very low retransmission delays
- Adaptive transmission is integrated on all time-scales
- Multi-antenna transmission can be adjusted in a very flexible way per flow
- Operation in spectrum shared with other operators who use the same physical layer WINNER mode
- Superframe and resource partitioning work efficiently in conjunction with inter-cell interference avoidance schemes

MAC User Plane

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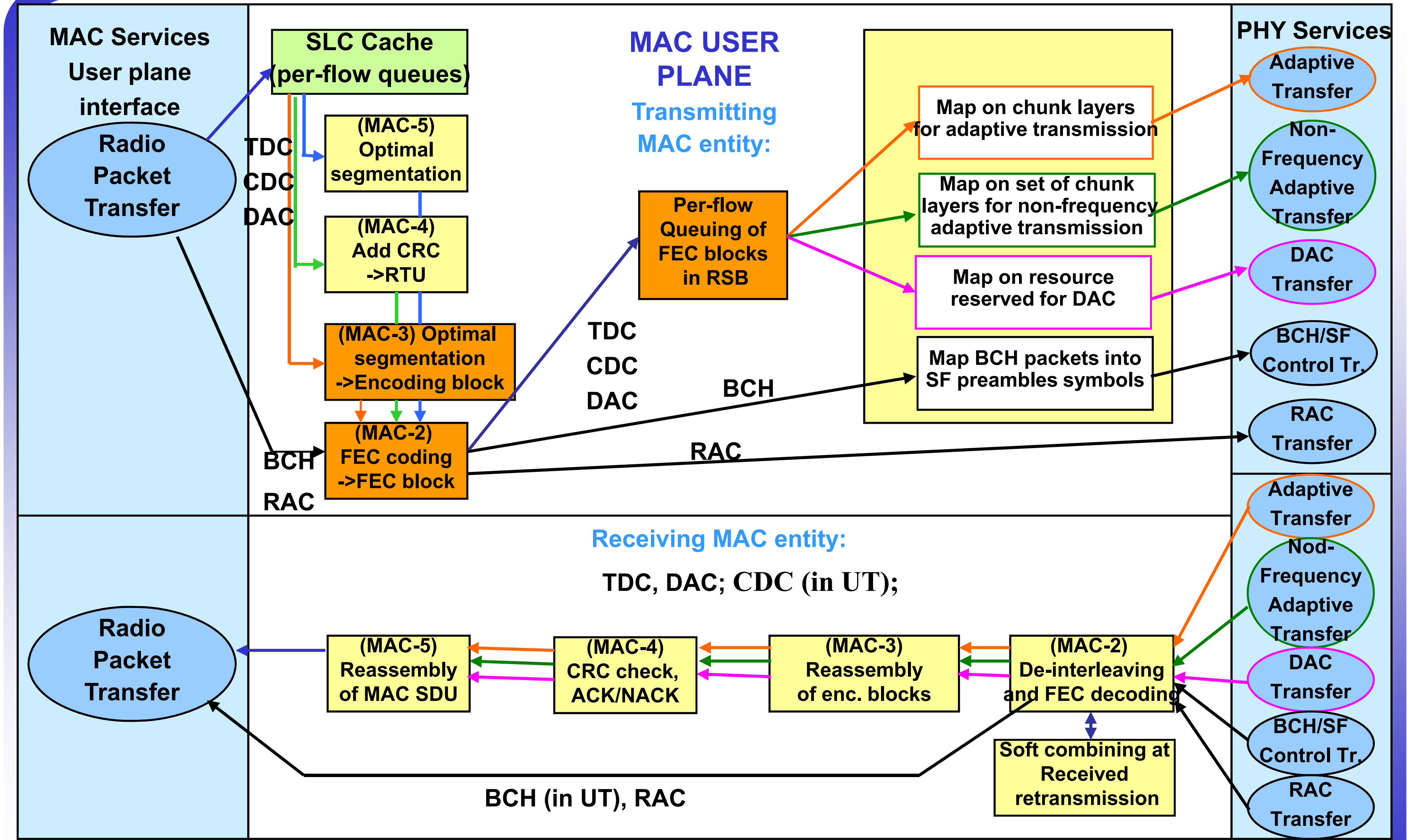

MAC User Plane

- Transmission (segmentation, encoding and buffering)
  - **Protocol sub-layers MAC-1–MAC-5 control the transmission**
  - **Parameterize to describe the different retransmission options (HARQ)**
- Resource mapping
  - **TDC flows**
    - Adaptive transmission
    - Non-frequency adaptive transmission
  - **CDC flows**
    - Non-frequency adaptive transmission
  - **DAC packets**
    - Contention-based physical channel
- Reception (Decoding and reassembly)
  - **Deinterleaving and FEC decoding**
  - **Reassembly of RTU (Retransmission Unit) and CRC check**
  - **BCH and RAC packets are received and decoded separately**

MAC Control Plane

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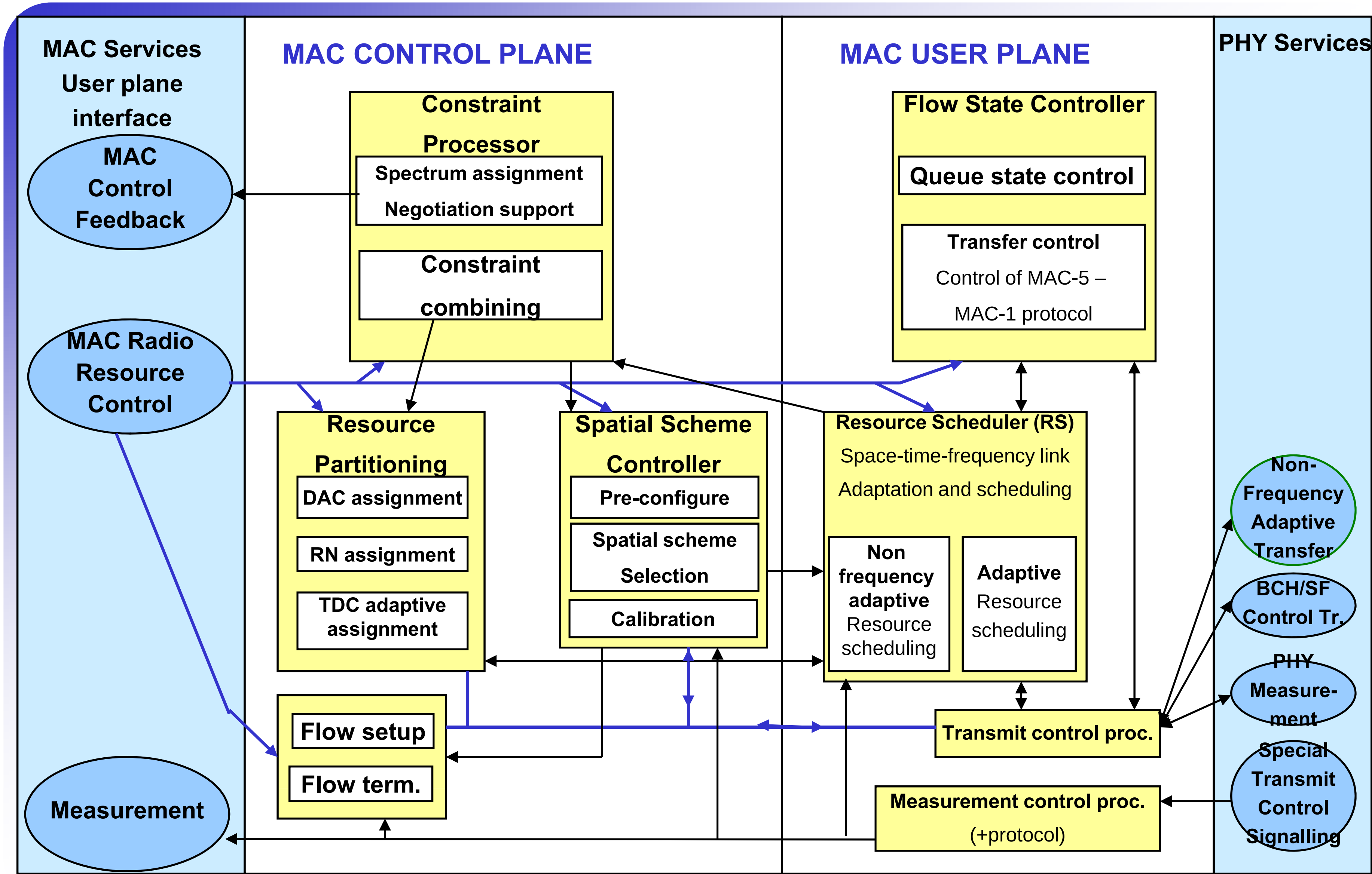
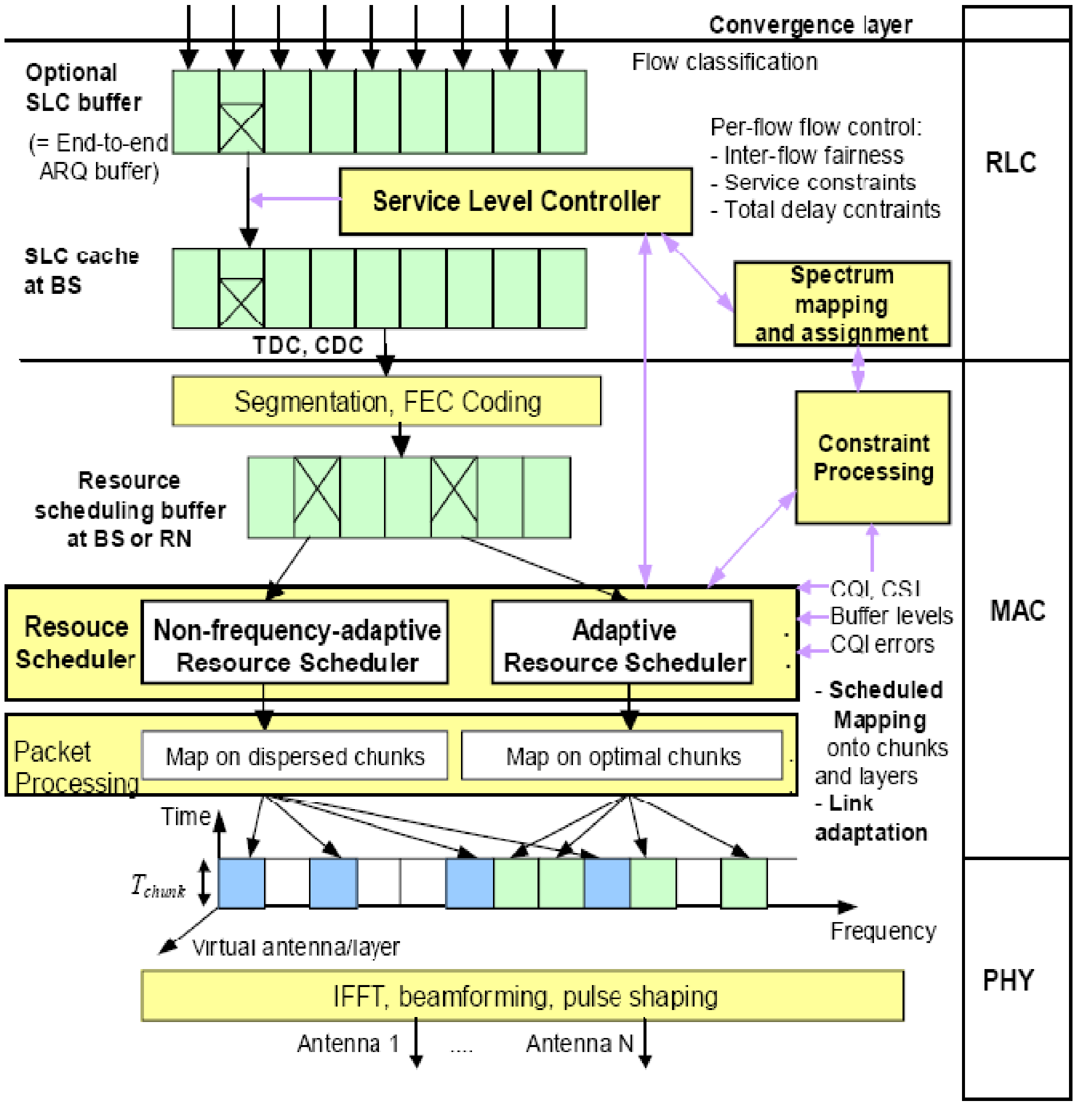


MAC Control Plane

- Resource partitioning
  - Super-frame partitioning to increase the channel efficiency
- Spatial scheme control
  - Select the appropriate spatial transmit scheme for each flow
  - Fix within a super-frame
- Constraint processor
  - Define restricted use of a super-frame's chunks for interference avoidance
  - Measurements that support the spectrum assignment /negotiation at the RLC layer
- Flow setup and termination
  - Perform flow context establishment and release over one hop
- Flow state controller
  - Control the segmentation and FEC coding/decoding of packets
  - Monitor the states of RS queues
  - Control the active/semi-active/passive state for each flow
- Resource scheduler
  - Adaptive and non-frequency adaptive scheduling algorithm
  - Control of spatial link adaptation
  - Power control in both uplinks and downlinks

Two layered scheduler

- Flow scheduler
  - Flow context
  - PHY information (allowable data rate)
- Resource scheduler
  - PHY information (assigned chunk)



Wireless MAC Protocol Performance

Performance Metrics

Throughput

- MAC Level Throughput (Goodput): MAC Layer Data Rate (bits/sec)
- Channel Throughput : The fraction of time that useful information is carried on the channel

Packet Delay (Access Delay)

- The time from the moment a message is generated until it makes it successfully across the channel

Packet Drop Probability

- The probability is that a packet is dropped

Wireless MAC Protocol Performance(1)

- **Performance Analysis Method**
  - **Rigorous Probability Based**
    - Binary Tree Based Algorithm : Switching system, RFID Anti-collision etc. [6, 7]
  - **Markov Chain Model**
    - Slotted Aloha (finite user model) [1], Binary Exponential Backoff algorithm [4] (CSMA/CA)
    - Characteristics
      - Exact analysis method
      - High Computational Complexity

Wireless MAC Protocol Performance(2)

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- **M/G/1 Busy Period Analysis**
  - Slotted Aloha (Infinite user model) [1], CSMA/CA [2,3]
  - Characteristics
    - Difficult to model the system and to find the probability distribution
- **TFA (Transient Fluid Approximation)**
  - Slotted Aloha, CSMA/CA
  - Characteristics
    - Low Computational Complexity, Easy to model the system
    - Need the verification using the simulation
- **Optimization**
  - CSMA, RFID, etc
  - Characteristic
    - Need to parameter optimization

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Thank you !!