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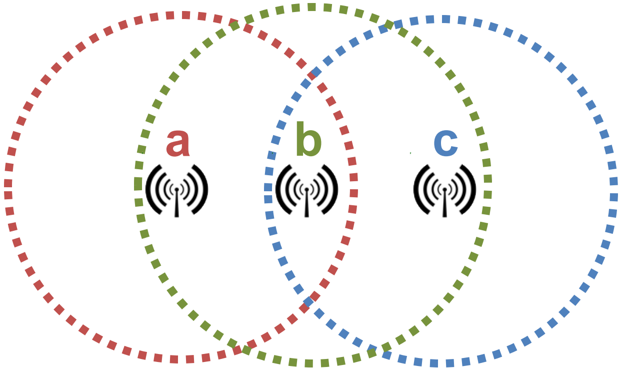
Data Link Layer

Media Access Control

Gianfranco Nencioni



Outline

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- Media Access Schemes
  - Carrier Sense Multiple Access (CSMA)
  - Code Division Multiple Access (CDMA)
  - Orthogonal Frequency Division Multiple Access (OFDMA)
  - Non-Orthogonal Multiple Access (NOMA)

Multiplexing vs Multiple Access

- Multiplexing:
  - Function that permits two or more data sources to share a common transmission medium
  - Each data source has its own channel
  - How to divide a larger-capacity channel into multiple smaller-capacity subchannels
  - Physical Layer

- Multiple Access
  - Function that allows multiple users to share a transmission channel
  - Each user has a subchannel
  - Data Link Layer

Multiple Access Schemes

- Which terminal starts transmitting?
- How long can a terminal transmit?
- How can a collision be resolved?
- Which terminal should receive?

Multiple Access Schemes

Contention-Based Schemes

- Aloha
- Slotted Aloha
- Carrier Sense Multiple Access (CSMA)
- CSMA / Collision Detection
- CSMA / Collision Avoidance

Conflict-Free Schemes

Fixed Allocation

- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)
- Orthogonal Frequency Division Multiple Access (OFDMA)
- Non-Orthogonal Multiple Access (NOMA)

Token Based

- Token Ring
- Token Bus

Hybrid Schemes

Reservation Based

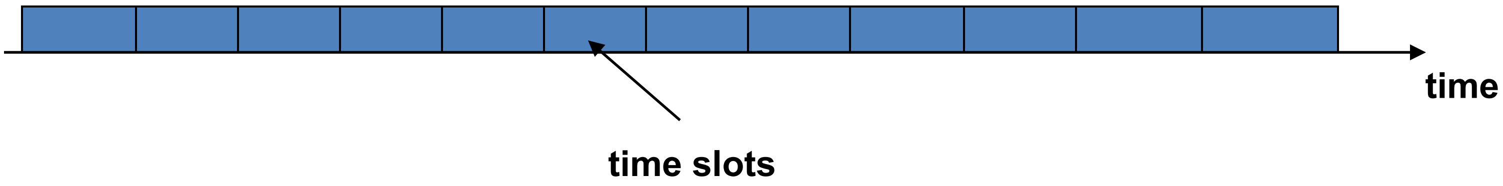
- Packet Reservation Multiple Access
- Resource Auction Multiple Access
- Dynamic TDMA

Self study

ALOHA and Slotted ALOHA

- **ALOHA**
  - Start transmitting whenever you have a frame to send.
  - Retransmit if the transmission is unsuccessful.

- **Slotted ALOHA**
  - Wait until the beginning of the first time slot for transmission.



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Carrier Sense Multiple Access (CSMA)

Carrier Sense Multiple Access (CSMA)

- The transmitter senses the media and, if it is idle, transmits immediately;
- If the media is busy, …

1-Persistent CSMA

- The transmitter continues sensing the media and transmits when it becomes idle.

Non-Persistent CSMA

- The transmitter waits (without sensing) a random period and then repeats the algorithm.

p-Persistent CSMA

- The transmitter continues sensing the media and, when it becomes idle, transmits with probability equal to *p;*
- It does not transmit (prob. *1-p*), the transmitter waits the next time slot and, if the media is idle, transmits with the same probability *p*, and so on.

CSMA with Collision Detection (CSMA/CD)

- Monitor for collisions during the transmission;
- In a collision occurs, go to collision detected procedure;

Collision detection procedure

- Continue the transmission (jam signal);
- Increment the retransmission counter;
- Calculate and wait a random backoff period based on the number of collisions;
- Go to the main procedure;

CSMA/CD: Exponential Backoff

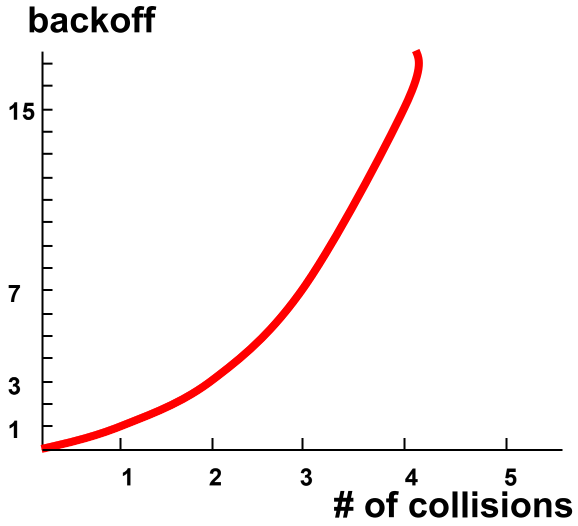
After the n^{th} collision, the transmitter waits the number of slots chosen at random from the interval between **0 and 2^n-1**

A **time slot** have to be chosen as follows:

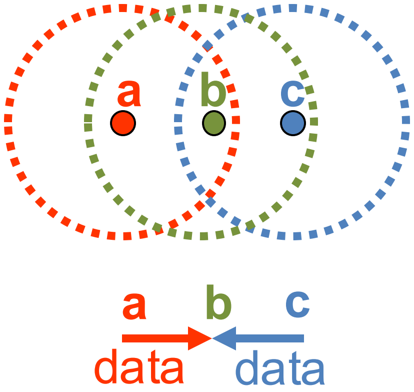
$$t = 2\tau$$

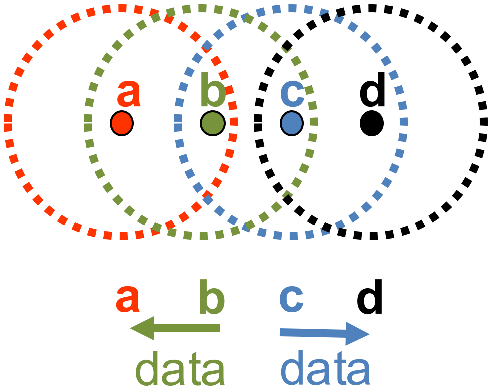
where τ is the worst case propagation time on the media.

Example: IEEE 802.3 or Ethernet



Problems: Hidden and Exposed Terminals





a and **c** are **hidden terminals**

primary interference

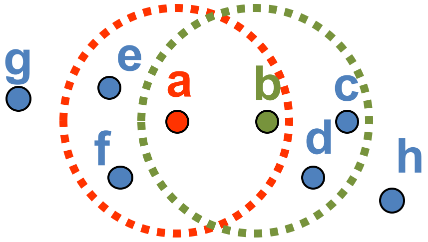
c is an **exposed terminal**

overhearing

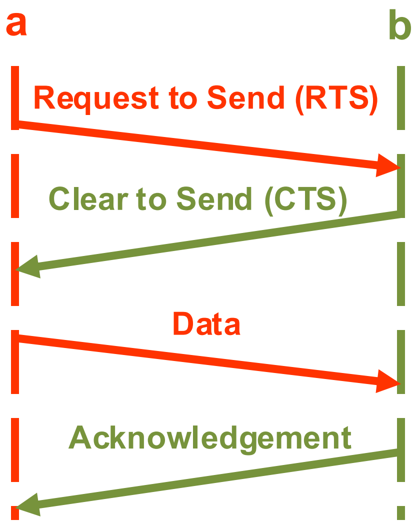
CSMA with Collision Avoidance (CSMA/CA)

- CSMA/CD unreliable due to **hidden terminal problem**
- In wireless, **monitoring while transmitting** is very challenging
- If media is busy, CSMA/CA behaves as non-persistent CSMA
- Other functionalities:
  - Request to Send/Clear to Send (RTS/CTS)
  - Distributed Coordination Function (DCF)
  - Point Coordination Function (PCF)

CSMA/CA: RTS/CTS



Solve hidden terminal problem



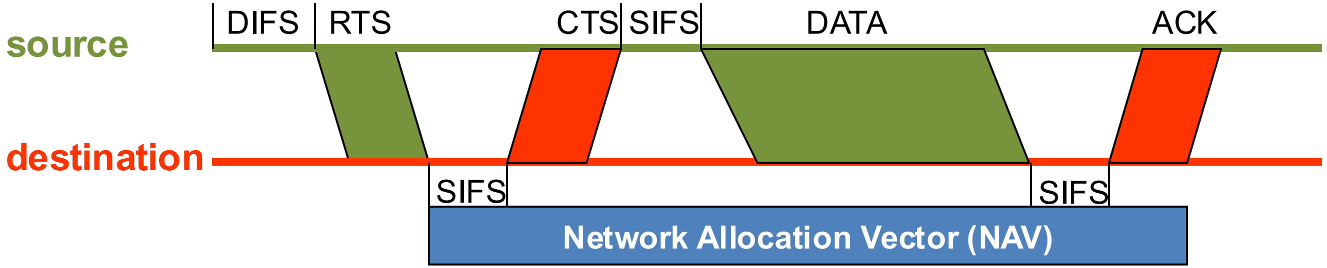
Example: Multiple Access with Collision Avoidance Wireless (MACAW)

V.Bharghavan, A.Demers, S.Shenker, L.Zhang, "MACAW: A Media Access Protocol for wireless LAN's", in Proceedings of ACM SIGCOMM'94, pp. 212-225, 1994.

CSMA/CA: DCF

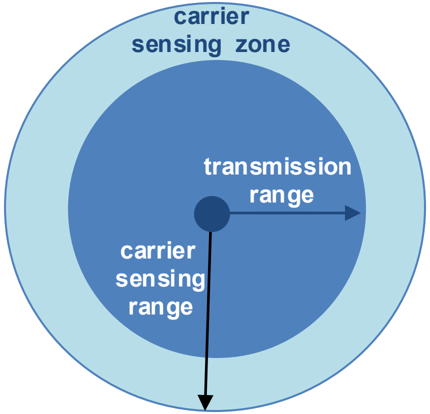
Distributed Coordination Function (DCF) selects the waiting time before transmitting in an idle media

DIFS: DCF Interframe Space
SIFS: Short Interframe Space



- During DIFS, monitoring of the media
- During SIFS, packet processing
- RTS contains the transmission duration, which is used to set the NAV (a counter) in the other terminals

CSMA/CA: Issues



- Terminals in carrier sensing zone sense the transmission but they cannot decode it
- These terminals will use Extended Interframe Space (EIFS) instead of DIFS
- EIFS ensures the transmission of the ACK can proceed without interference

RTS, CTS, frames and inter frame spaces introduce:

- additional **overhead** and
- additional **delay**.

Exercise

- Make C code for:
  - Aloha
  - 1-persistent CSMA
  - p-persistent CSMA
  - CSMA/CD with Exponential Backoff

C Code for Aloha

```
Aloha(int medium, int frameQueue) {
    Frame frame;
    while(1){
        if(frame=getFrame(frameQueue)){
            sendFrame(medium, frame);
            frame=null;
        }
    }
}
```

C Code for CSMA

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```
CSMA(int medium, int frameQueue) {
    Frame frame;
    while(1){
        if(frame=getFrame(frameQueue)){
            do{
            }while(!isMediumFree(Medium))
        sendFrame(medium, frame);
            frame=null;
        }
    }
}
```

C Code for p-persistent CSMA

```
pCSMA (int medium, int frameQueue, float p) {
    Frame frame;
    while(1){
            if(frame=getFrame(frameQueue)){
                do{
                }while(!isMediumFree(Medium)&&!bernouliSuccess(p));
                sendFrame(medium, frame);
                frame=null;
            }
      }
}
```

C Code for CSMA/CD with Exponential Backoff

```
CSMAcd(int medium, int frameQueue, float t) {
   Frame frame;
   while(1){
        if(frame=getFrame(frameQueue)){
            float n=t;
            while(frame){
               do {
               }while(!isMediumFree(Medium));
               if(sendFrame(medium, frame))
                  frame=NULL;
               else{
                   wait(randomTime(n));
                   n*=2;
                }//if sendFrame
            }//while (frame)
        }//if (frame)
    }//while 1
}
```

Multiple Access Schemes

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Contention-Based Schemes

- Aloha
- Slotted Aloha
- Carrier Sense Multiple Access (CSMA)
- CSMA / Collision Detection
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Conflict-Free Schemes

Fixed Allocation

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Hybrid Schemes

Reservation Based

- Packet Reservation Multiple Access
- Resource Auction Multiple Access
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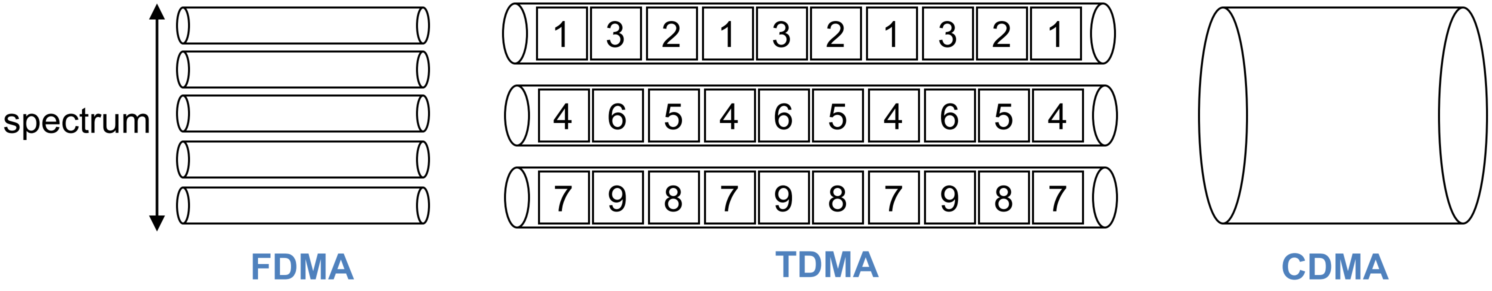
Conflict-Free Multiple Access Schemes



1. Frequency Division Multiple Access:
   Channel = Frequency

2. Time Division Multiple Access:
   Channel = Frequency + Time Slice

3. Code Division Multiple Access:
   Channel = Code

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Code Division Multiple Access (CDMA)

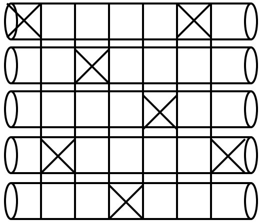
CDMA

- Based on the concept of **Spread Spectrum (SS)**
  - Spread the information of a signal over a wider bandwidth
  - Initially developed for military and intelligence purposes
  - The signal is further modulated by using a sequence of digits, called **pseudonoise spreading code**

- Types of Spread Spectrum:
  - Frequency Hopping (FH)
  - Direct Sequence (DS)

FHSS

The signal is broadcasted over a seemingly random series of radio frequencies



FHSS

Kinds of FHSS:

a. Slow Hopping $T_c \geq T_s$

b. Fast Hopping $T_c < T_s$

T_c: "hop" time
T_s: symbol time

FHSS: Performance

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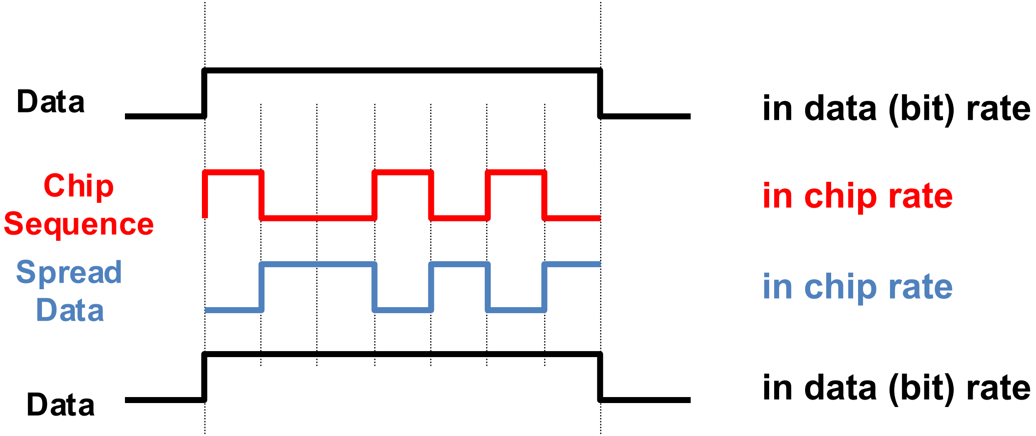
Process Gain is the gain in signal-to-noise ratio (or the ratio between spread and unspread bandwidths)

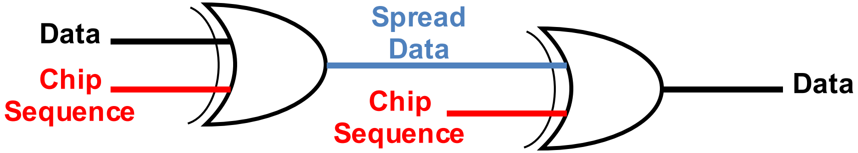
$$\boldsymbol{G_p = 10 \log C} \text{ (dB)}$$

where ***C*** is the **number of frequency channels** used.

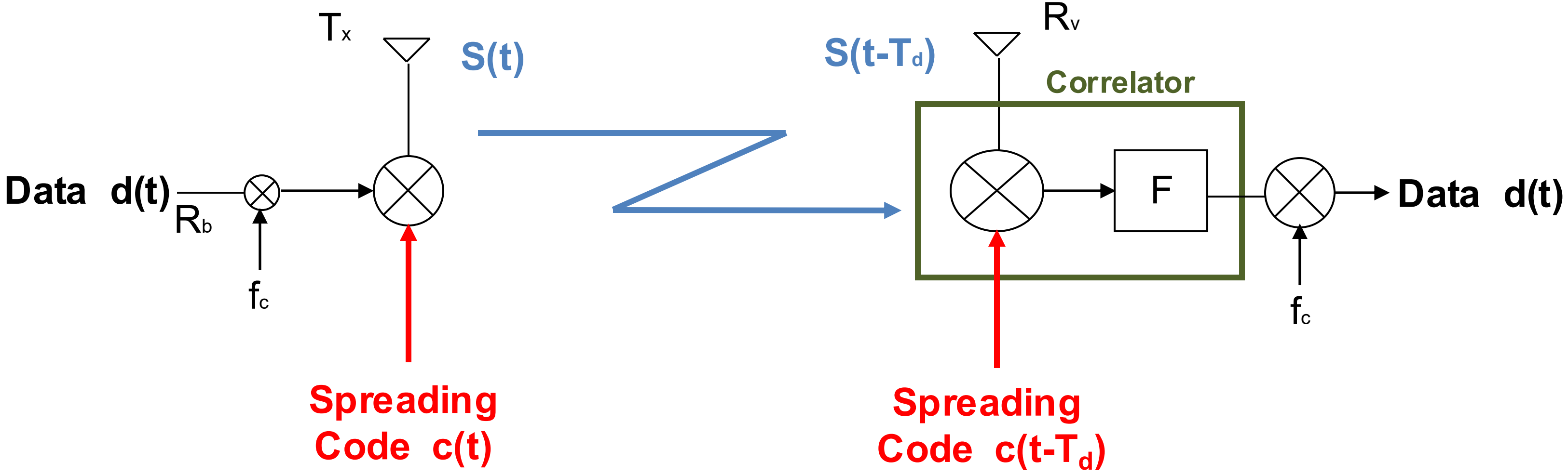
DSSS

Each bit in the original signal is represented by multiple bits (*chips*) in the transmitted signal



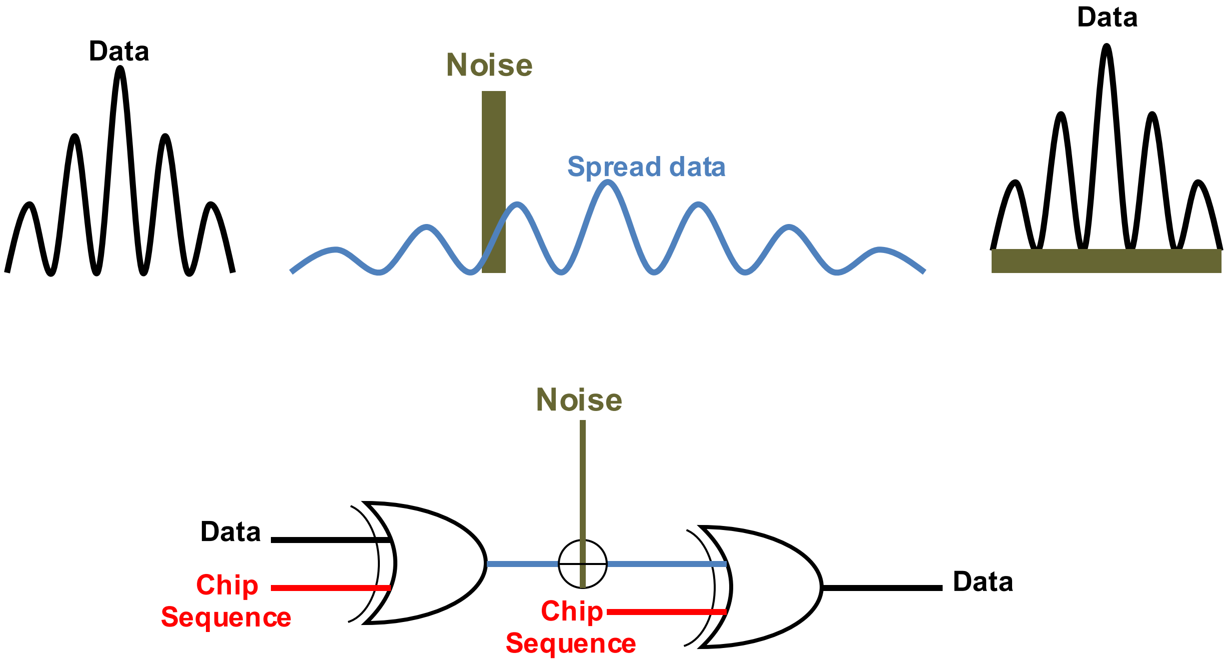


DSSS System



T_x
S(t)
Data d(t)
R_b
f_c
Spreading Code c(t)
$S(t-T_d)$
R_v
Correlator
F
Data d(t)
f_c
Spreading Code $c(t-T_d)$

DSSS: Performance



DSSS: Performance

Process Gain

$$\boldsymbol{G_P = 10 \log (B_{ss}/B)} \text{ (dB)}$$

where

$\boldsymbol{B}$ is the bandwidth required for the data rate;

$\boldsymbol{B_{ss}}$ is the bandwidth where the signal is spread.

DS-CDMA Codes

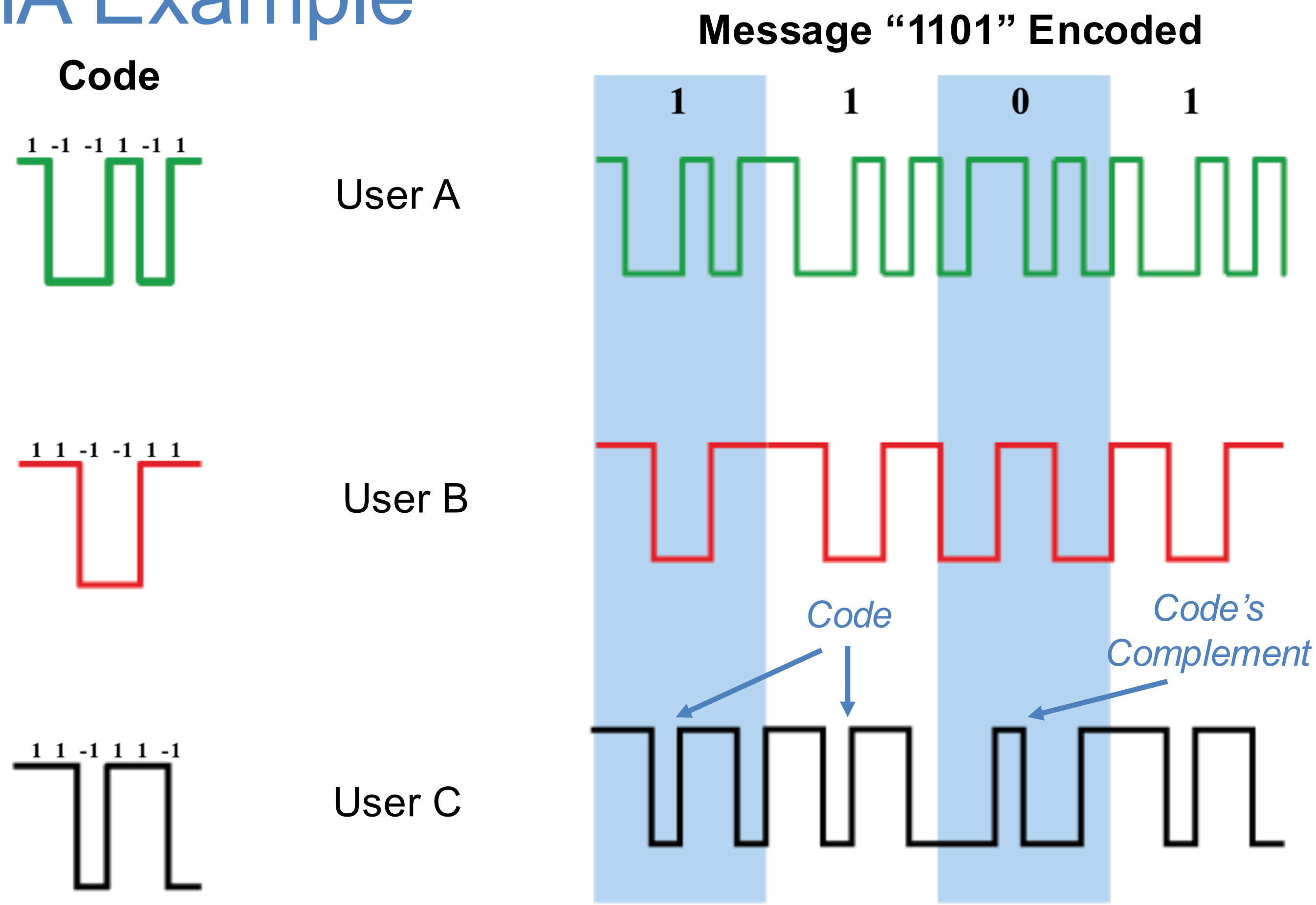
A spread spectrum code on DS-CDMA is a bit sequence (a sequence of 1s and -1s).

```
-1 -1 -1  1 -1 -1  1  1 -1  1 -1  1  1  1  1
```

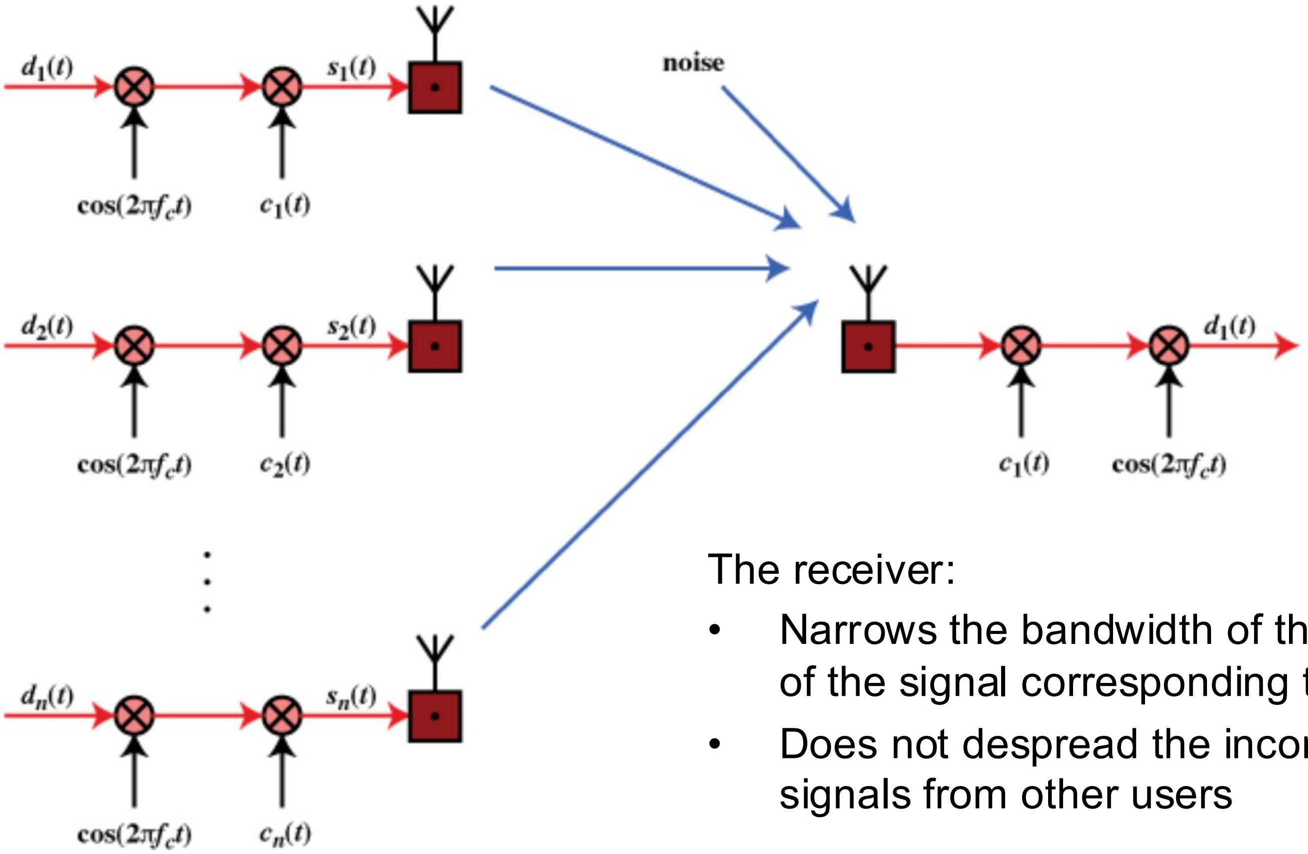
CDMA sequences can be categorized as:

- Pseudo Noise (PN) sequences
  - Short codes
  - Long codes
- Orthogonal codes

CDMA Example



DS-CDMA Environment



The receiver:

- Narrows the bandwidth of the portion of the signal corresponding to user 1
- Does not despread the incoming signals from other users

PN Sequences

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- Resulting signal is noise like
- Predictable way to be generated
  - Both from transmitter and receiver
  - Deterministic algorithm with initial value (**seed**)
- **Period** of a sequence is the length of the sequence before it starts repeating

Maximum Length Sequence

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Balance property: The difference in the number of 1s and -1s in a pseudonoise cannot be higher than one.

```
-1  -1  -1   1  -1  -1   1   1  -1   1  -1   1   1   1   1
```

(15 chips, 7 of them are -1s, and 8 of them are 1s.)

Run property: 50% of runs must be -1 runs, and the other 50% must be 1 runs, and $1/2^n$ of runs must be *n* length runs.

```
-1  -1  -1   1  -1  -1   1   1  -1   1  -1   1   1   1   1
```

***Run**: sub-sequence of consecutive 1s or consecutive -1s*

(8 runs, 4 of them are -1 runs, and 4 of them are 1 runs.)

Auto-correlation property: The number of chips that are the same differs from those that are different by at most 1 when a pseudonoise is compared chip by chip with any cycle of shift of itself.

Auto-correlation

Auto-correlation is the correlation of a code with any cycle of shift of itself.

$$C_k = \sum_{n=1}^{N} a_n a_{n+k}$$

Example: −1 −1 1 1 −1 1 −1 N = 7

$C_0 = 7$ and $C_7 = 7$

$C_1 =$ 1 −1 1 −1 −1 −1 1 = -1

$C_2 =$ −1 −1 −1 1 1 −1 1 = -1

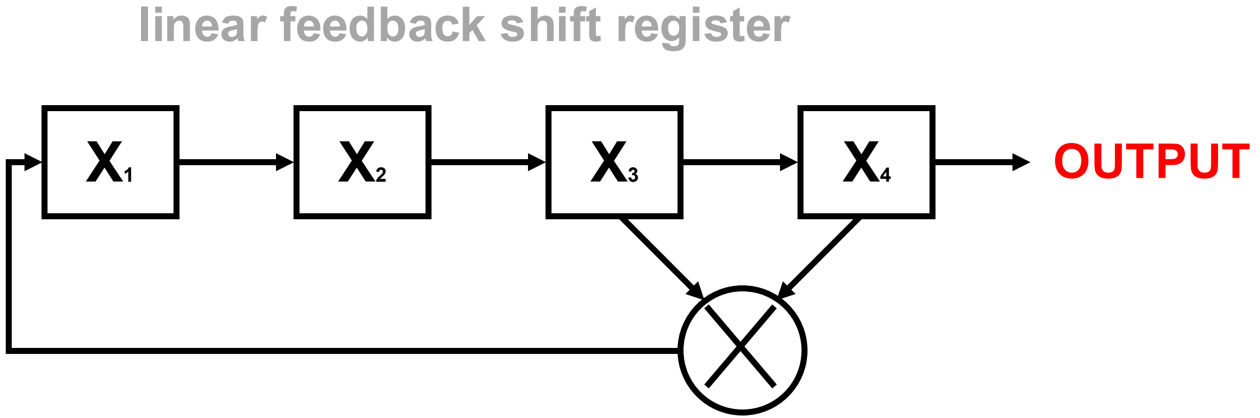
$C_3 =$ −1 1 1 −1 1 −1 −1 = -1

$C_4 =$ 1 −1 −1 −1 1 1 −1 = -1

$C_5 =$ −1 1 −1 −1 −1 1 1 = -1

$C_6 =$ 1 1 −1 1 −1 −1 −1 = -1

Maximum Length Sequence Generator



SEED : 1 -1 -1 -1

OUTPUT : -1 -1 -1 1 1 1 -1 1 1 -1 -1 1 -1 1 -1

Period of the sequence is $p = 2^n - 1$,
where n is the number of bits in the shift register.

Short and Long Codes

- **Short codes** can generally be transferred in the duration of a symbol. In IS-95, the length of short codes is 2^{15}-1, and they can be transferred in **26.67** seconds when chip rate is 1.2888 Mcps. They are generally used in downlink **to identify cells or location areas** in cellular networks.

- In IS-95, the length of **long codes** is 2^{42}-1, and they can be transferred in **44.5 days** when chip rate is 1.2888 Mcps. They are generally used in uplink **to identify mobile terminals**.

Orthogonal Codes

- Orthogonal codes are used for **channelization in downlink**
- Their **autocorrelation** are generally very **low**
- However, their **cross correlation is 0**

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Cross-correlation

Cross-correlation is the correlation of a code with all of the shifted versions of another code.

$$R_k = \sum_{n=1}^{N} a_n b_{n+k}$$

Example: a={ −1 1 −1 1} N=4

b={ −1 −1 1 1} N=4

R_0= 0 and R_4= 0

R_1= 1 1 −1 −1 = 0

R_2= −1 1 1 −1 = 0

R_3= −1 −1 1 1 = 0

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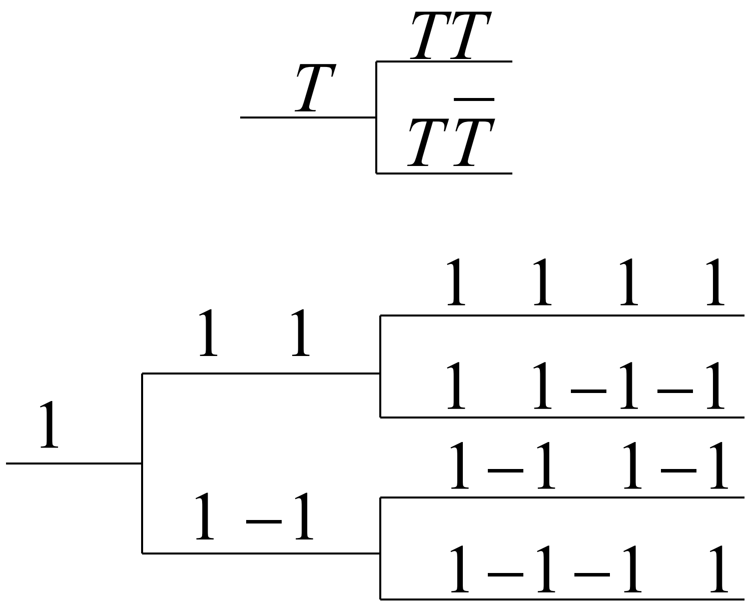
Walsh-Hadamard Codes

$$H_{2n} = \begin{bmatrix} H_n & H_n \\ H_n & \overline{H_n} \end{bmatrix}$$

$$H_1 = [0] \qquad H_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \qquad H_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

- Every row is **orthogonal** to every other row and to the logical not of every other row
- Requires tight **synchronization**

Variable-Length Orthogonal Codes



- Codes are **orthogonal** if and neither code lies on the path from the other code to the root

Advantages of CDMA

- CDMA has a **soft capacity** limited by interference. The decrease in interference will directly increase the capacity:
    - Voice channels are generally utilized 3/8 of time.
    - Multi-beamed and multi-sectored antennas can reduce the interference.
- In FDMA and TDMA, some capacity **between frequency channels** is wasted.
- In CDMA, all the **frequencies can be reused** in the neighbouring cells.
- In FDMA and TDMA, the frequency channel must be changed during handoff, i.e., **hard handoff**. This is not necessary in CDMA, i.e., soft handoff.
- CDMA needs **power control** which actually decreases the interference, and increases the capacity.
- CDMA naturally provides **frequency diversity** which means additional security and reliability especially for military systems.

Multiple Access Schemes

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Reservation Based

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Orthogonal Frequency Division Multiple Access (OFDMA)

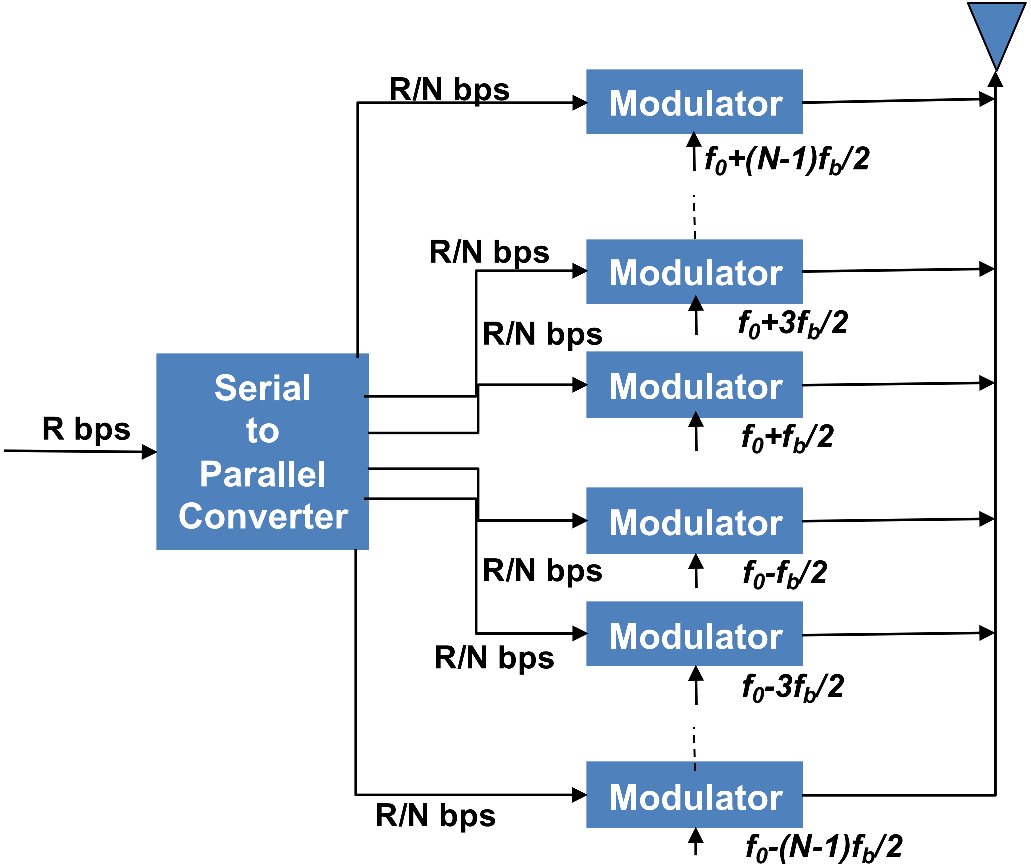
Orthogonal Frequency Division Multiplexing

- Multiple carrier signals at different frequencies
  - Sending some of the bits on each channel
  - Many subcarriers dedicated to a single data source

- Original datastream:
  - R bps – available bandwidth = $N f_b$ – bit duration = $1/R$

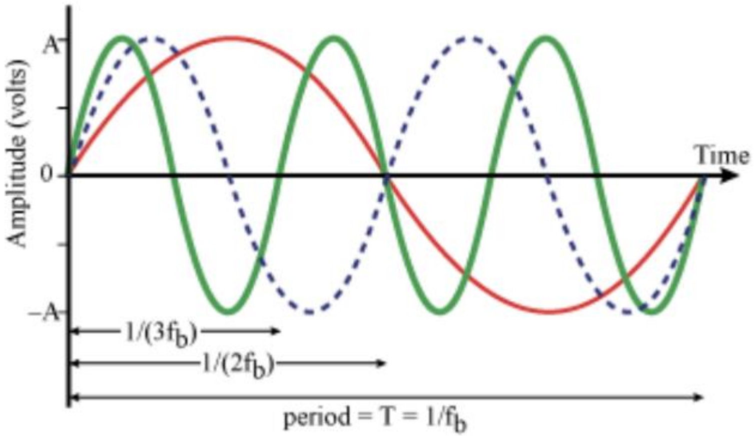
- Splitting into N substreams:
  - R/N bps – available bandwidth = f_b – bit duration = N/R

OFDM: Simplified Transmitter



OFDM: Orthogonality

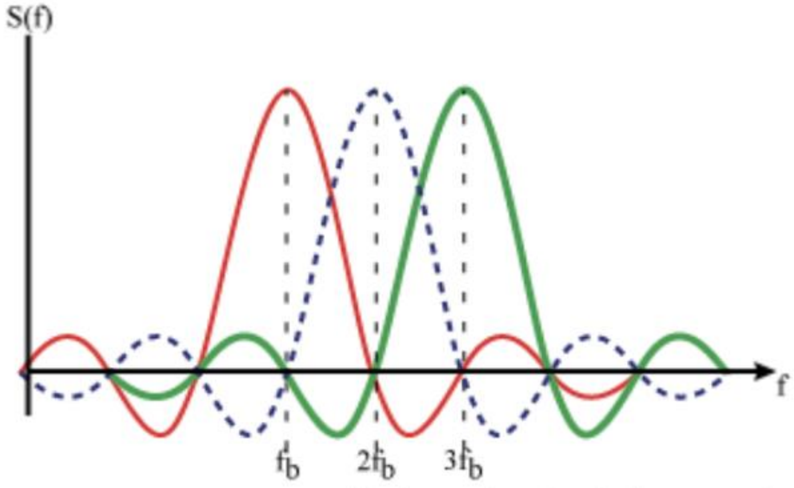
- f_b: base frequency (lowest-frequency subcarrier)
- Other frequency are integer multiples of f_b



- Distribution data over multiple carriers
  - Advanced digital signal processing techniques

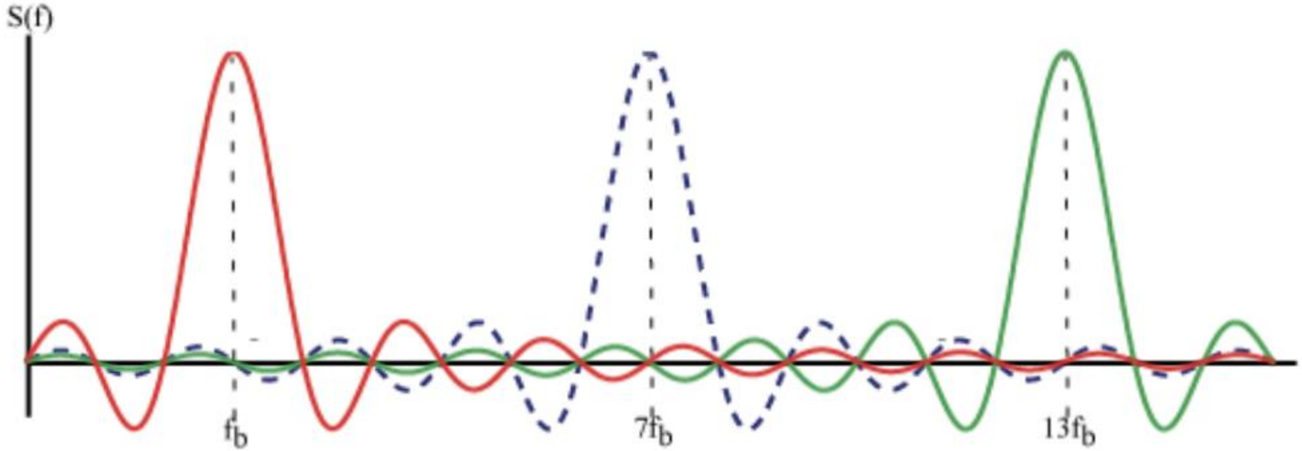
OFDM: Orthogonality

- Relationship among the subcarriers: **orthogonality**
- **Property** of orthogonality:
  - Peaks of the power spectral density of each subcarrier occur at a point at which the power of the other subcarriers is zero



Traditional FDM

- Signal spaced sufficiently apart in frequency to:
  1. Avoid **overlap** in the frequency bands
  2. Provide extra spacing (**guard bands**)



OFDM: Orthogonality

- Improvement of the spectrum utilization
- Minimal interference between adjacent subcarriers
- Two (carrier) signals, s_1 and s_2, are orthogonal if:

  Average over the bit time of $s_1(t)s_2(t) = 0$

- At the transmitter: $s(t) = s_1(t) + s_2(t)$
- At the receiver:

  Average over the bit time of $s_1(t)s(t) = s_1(t)s_1(t) + s_1(t)s_2(t) = s_1^2(t) + 0$

- f_b must be multiple of $1/T$, where T is the bit time of a subcarrier

OFDM: Implementation

- Modulating single sub-datastream is expensive
- Discrete Fourier Transform (DFT)

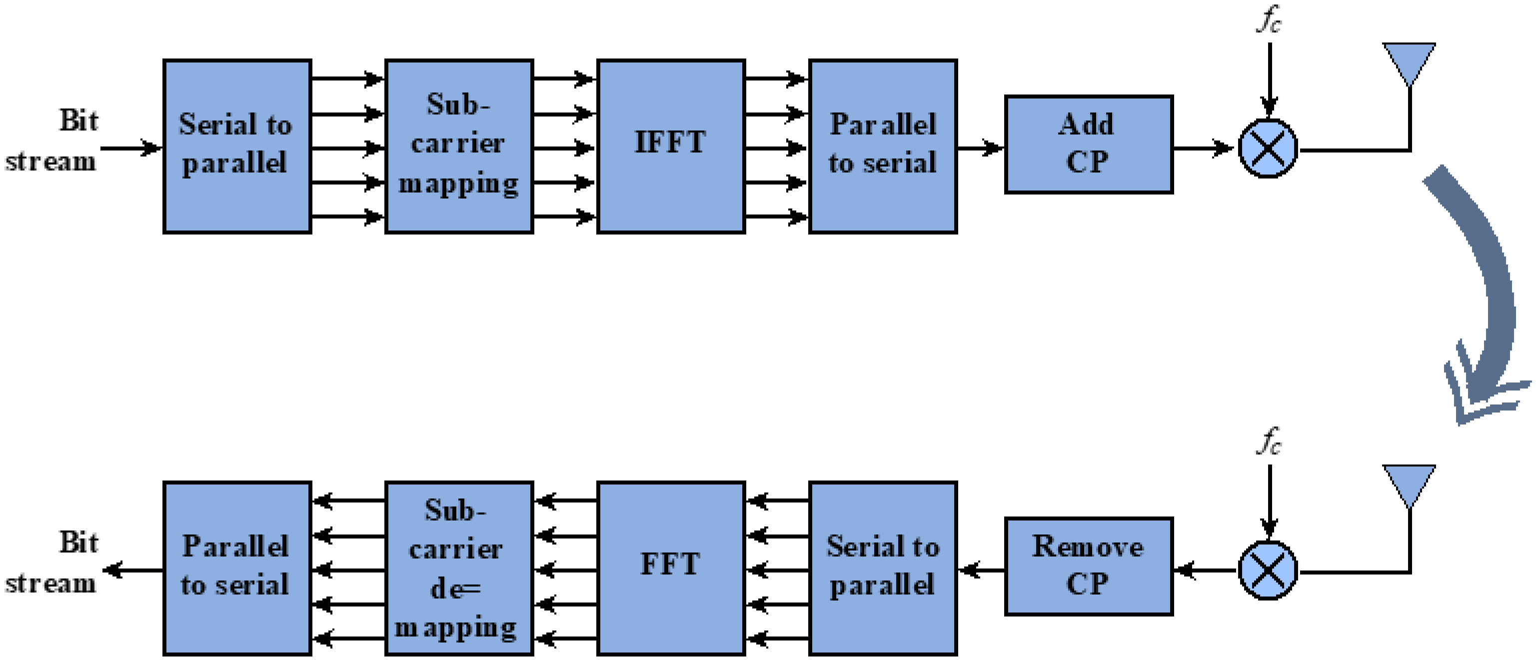
$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-j\frac{2\pi kn}{N}}$$

- Inverse Discrete Fourier Transform

$$x[n] = \sum_{k=0}^{N-1} X[k] e^{j\frac{2\pi kn}{N}}$$

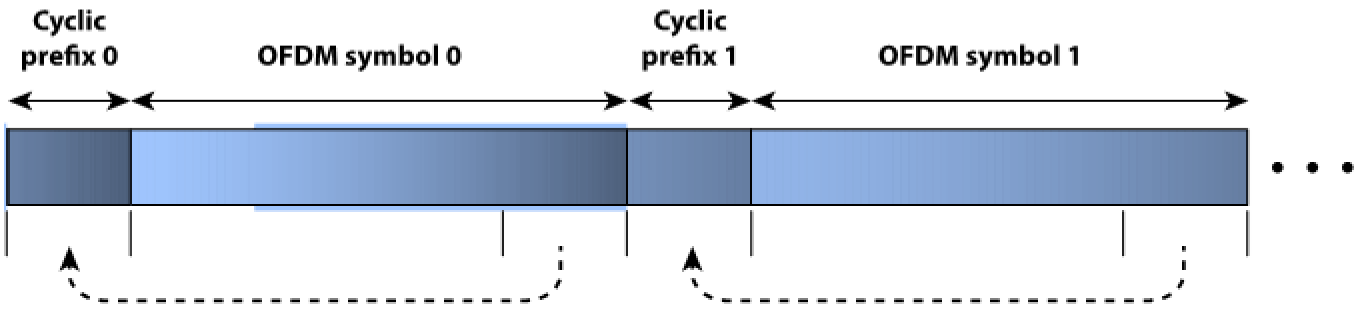
- Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT)
  - Number of data points N is a power of two
  - Computational time is greatly reduced

OFDM: Implementation



OFDM: Implementation

- Use of a **Cyclic Prefix (CP)** to further combat ISI



- Two functions:
  - Additional time, known as guard interval
  - Packed with an actual copy of the data of the OFDM symbol that is being sent

OFDM: Advantages

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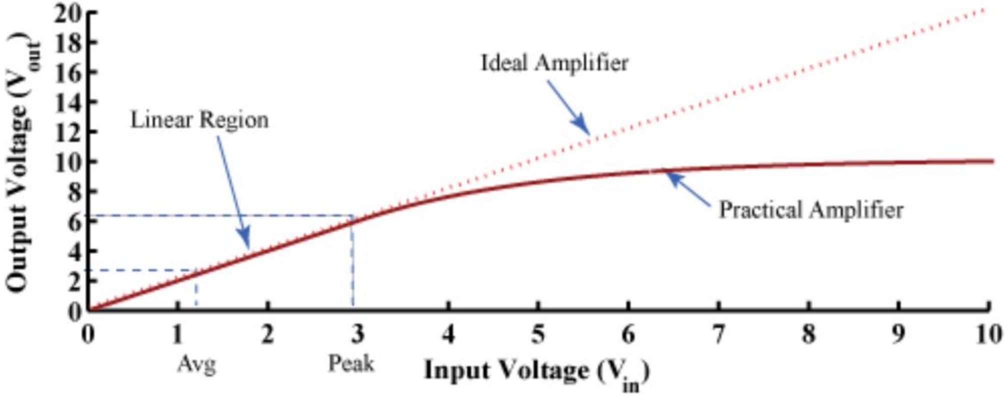
- Frequency **selective fading** only adversely affects some subcarriers and not the whole signal

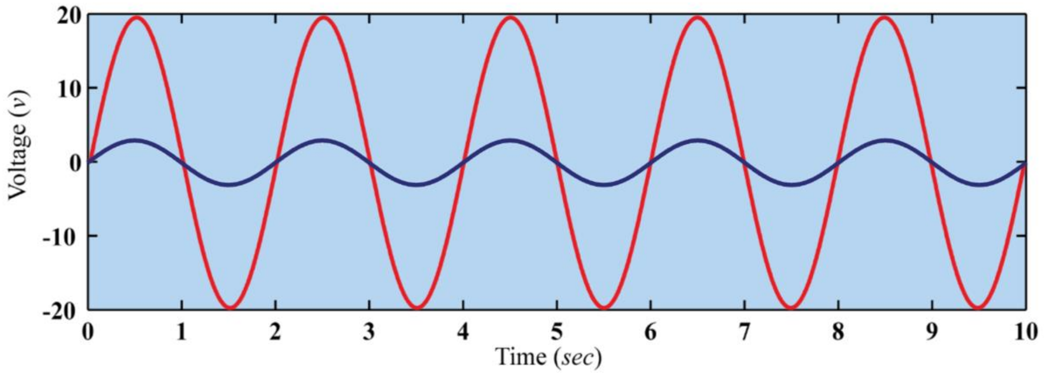
- **ISI** overcome
  - Distance between symbols is greater
  - Equalizer not needed, especially with CP

OFDM: Difficulties

- **Peak-to-Average Power Ratio (PAPR)**
  - Multicarrier signal is sum of many narrowband signals
  - At some time instances, this sum is large and at others it is small
  - Peak value of the signal is substantially larger than the average value
  - Increment of the power amplifier costs



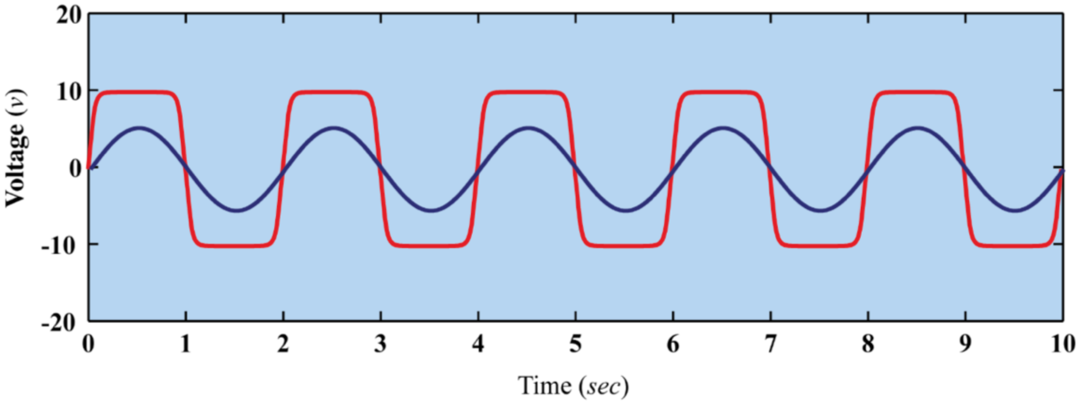
OFDM: Difficulties



Amplifier Input

Amplifier Output

Lost of Orthogonality!



OFDM: Difficulties

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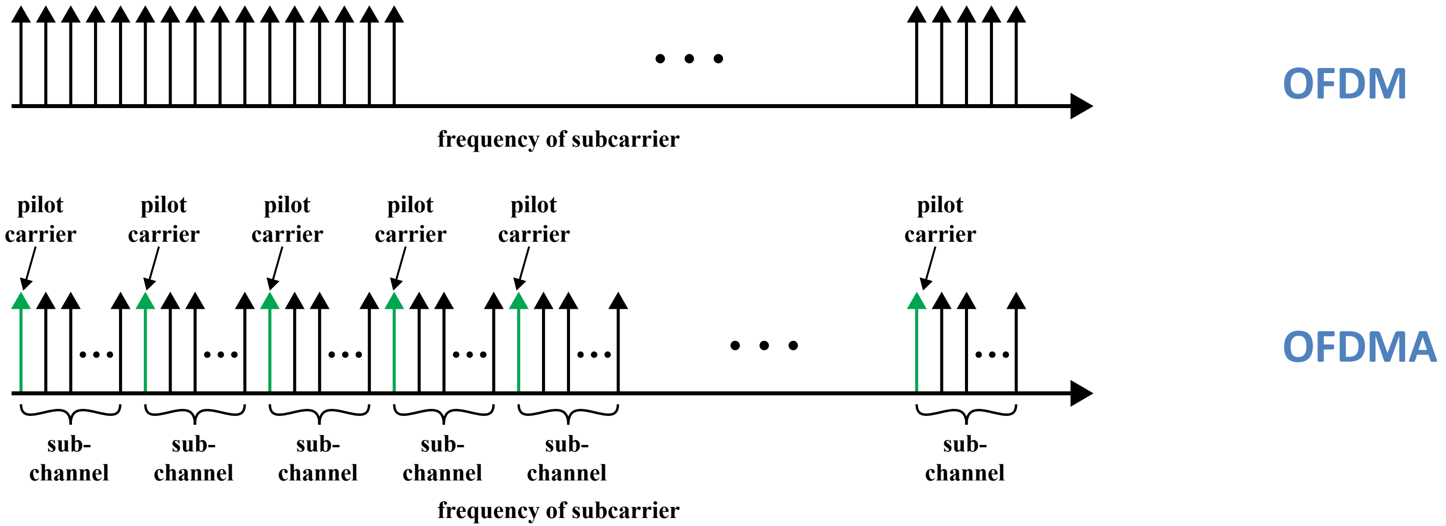
- **Intercarrier Interference (ICI)**
  - For demodulation, time and frequency synchronization is necessary
  - Frequency are spaced closely, frequency sync is stringent
  - Tradeoff between carrier spacing and OFDM symbol length

OFDMA

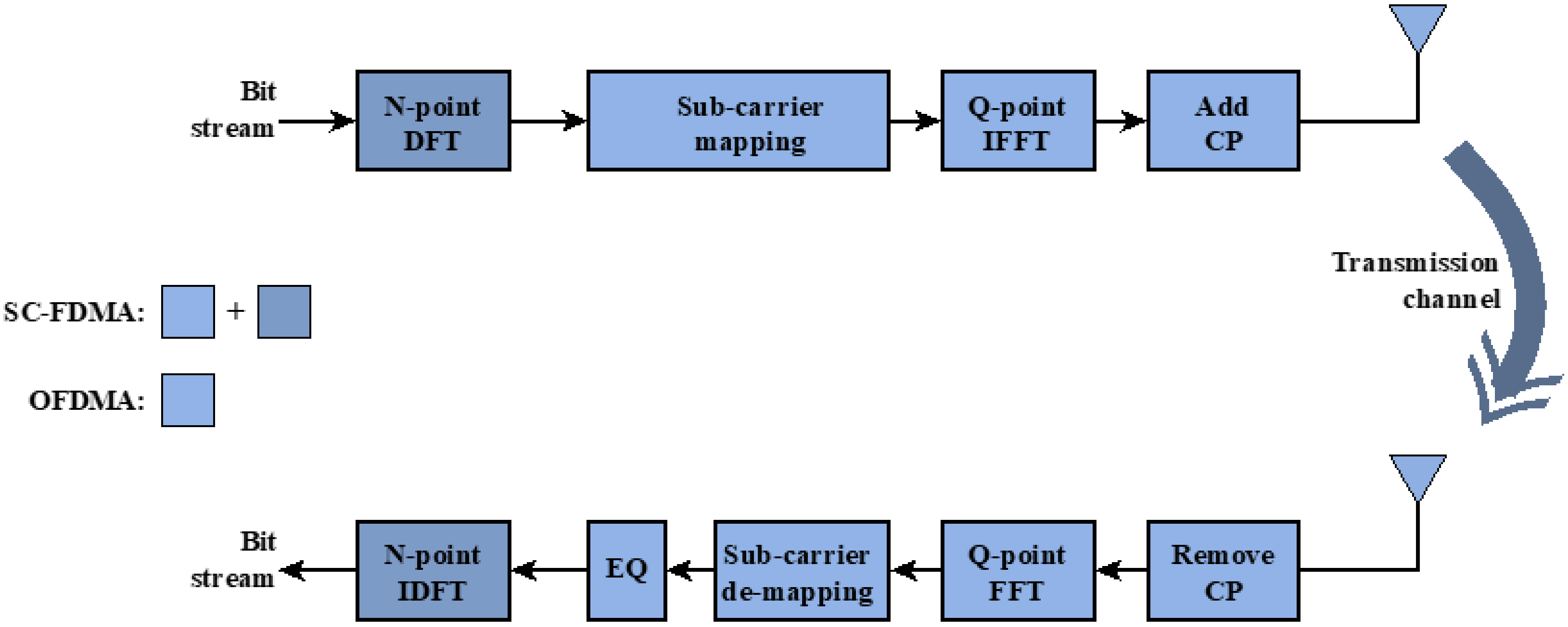
- As OFDM, use of multiple closely-spaced subcarriers
- Subcarriers divided in groups of subcarriers, called **subchannels**
- **Subchannelization**: How subchannels are allocated to a UE
  - Important for power saving



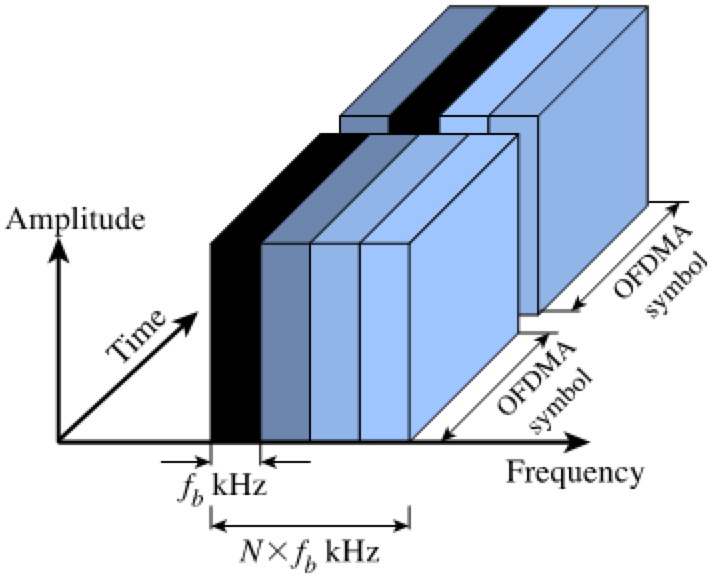
Single-Carrier FDMA (SC-FDMA)

- Similar structure and performance of OFDMA
- Lower PAPR
- Used only in **uplink**, because of the increased time-domain processing
- Extra DFT operation
  - Spreading of the data symbols over all the subcarriers carrying information
- Much higher data rate for each subcarrier, but sending the same data stream on each subcarrier
- Better name: SC-OFDMA-TDMA

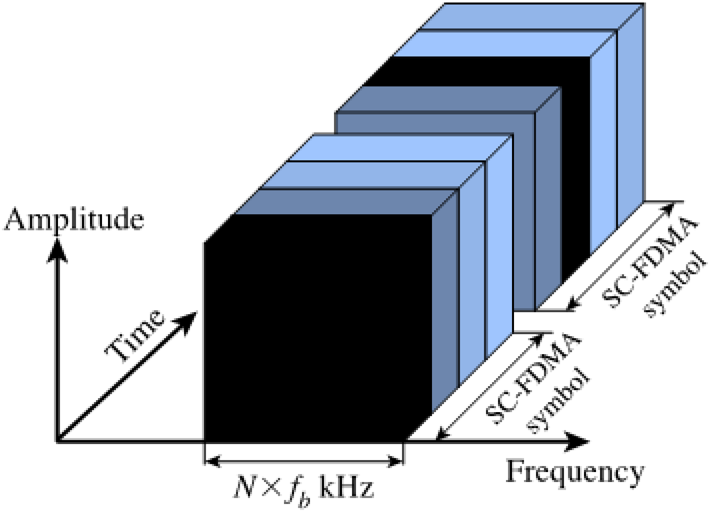
Simplified Block Diagram



OFDMA vs SC-OFDMA



OFDMA



SC-FDMA

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Non-Orthogonal Multiple Access (NOMA)

NOMA

- To support **more end users** with **diverse service requirements** than the total number of available orthogonal radio resources

- Two categories of NOMA:
  - **Code domain**
    - Same time-frequency resources, like CDMA but different spreading sequences
  - **Power domain**
    - Allocating different power levels of the signal to each user at the transmitter side

- Simultaneous transmissions thanks to
  - **Superposition Coding** at the transmitter
  - **Successive Interference Cancelation** at the receiver

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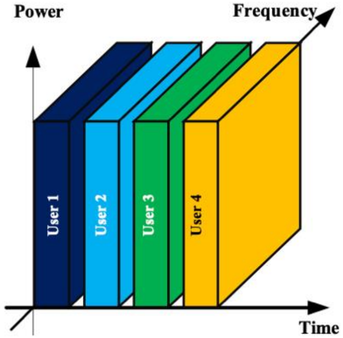
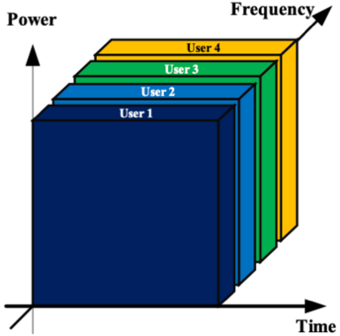
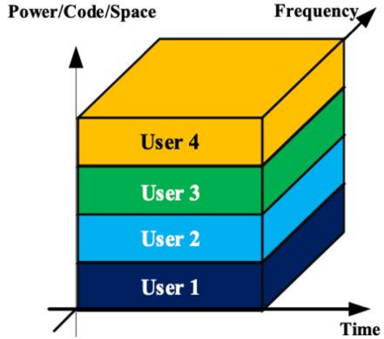
Comparison with other Multiple Access Schemes



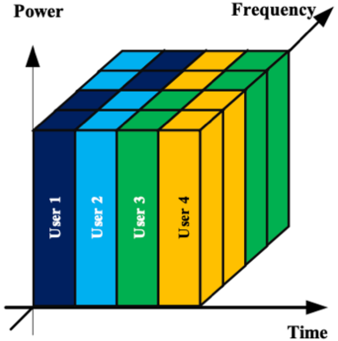
TDMA



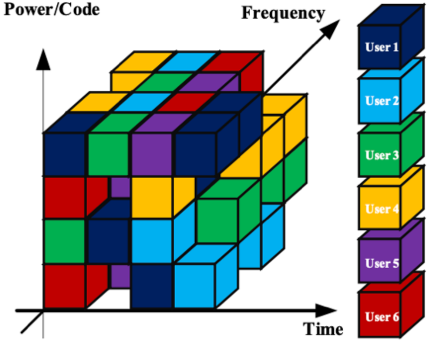
FDMA



CDMA



OFDMA

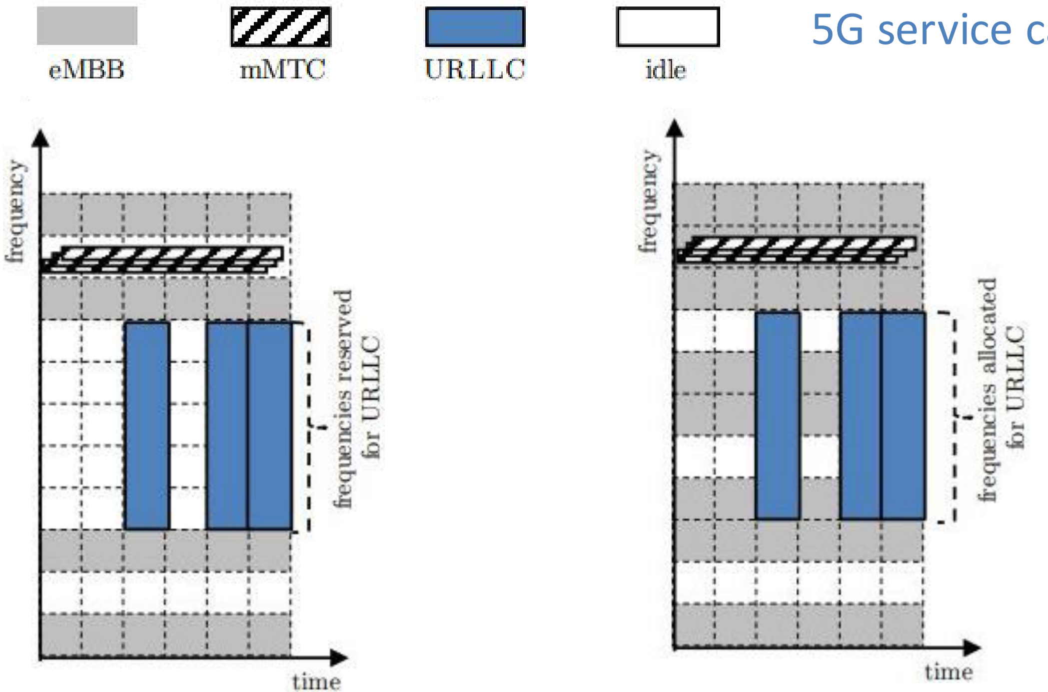


NOMA

Source: Y. Chen et al, 'Toward the standardization of non-orthogonal multiple access for next generation wireless networks,' IEEE Communications Magazine, vol. 56, no. 3, pp. 19–27, 2018.

Different Service Requirements

5G service categories



OMA **NOMA**

Source: P. Popovski, et al., '5g wireless network slicing for embb, urllc, and mmtc: A communication-theoretic view,' IEEE Access, vol. 6, pp. 55 765–55 779, 2018.

Multiple Access Schemes

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Contention-Based Schemes

- Aloha
- Slotted Aloha
- Carrier Sense Multiple Access (CSMA)
- CSMA / Collision Detection
- CSMA / Collision Avoidance

Conflict-Free Schemes

Fixed Allocation

- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)
- Orthogonal Frequency Division Multiple Access (OFDMA)
- Non-Orthogonal Multiple Access (NOMA)

Token Based

- Token Ring
- Token Bus

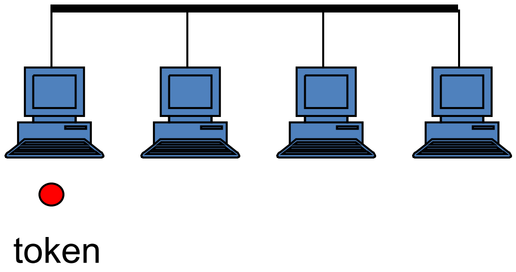
Hybrid Schemes

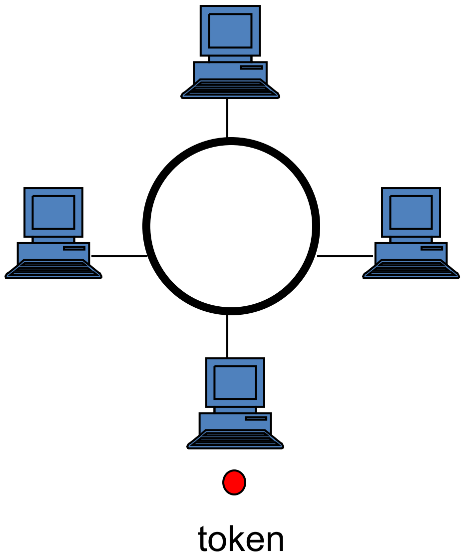
Reservation Based

- Packet Reservation Multiple Access
- Resource Auction Multiple Access
- Dynamic TDMA

Self study

Token-Based Conflict-Free Schemes





- A token is passed around the network
- Only the node possessing the token may transmit
- Token released when the node has nothing to send

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Hybrid Schemes

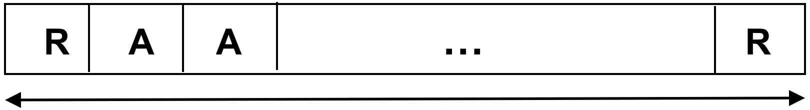
Reservation-Based Hybrid Schemes

- Packet-Reservation Multiple Access – **PRMA**
- Dynamic TDMA – **D-TDMA**
- Resource-Auction Multiple Access – **RAMA**

Qiu, Xiaoxin and Li, Victor O. K.; Dynamic Reservation Multiple Access (DRMA): A new multiple access scheme for Personal Communication System (PCS); Wireless Networks, Vol. 2 Issue 2,Pages 117—128, 1996

PRMA

- Time is divided in frames, which are subdivided in time slot
- Slots can be available or reserved

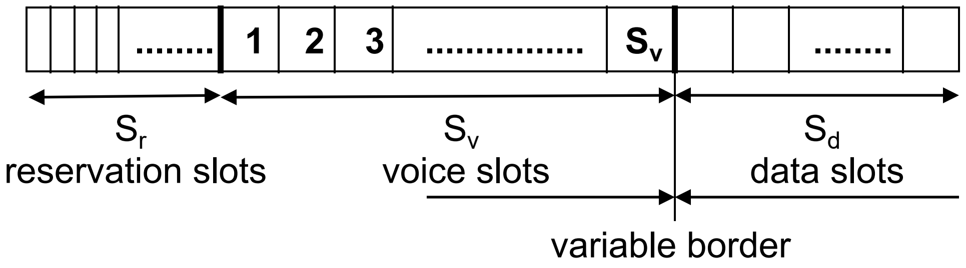


S slots (R: reserved slots, A: available slots)

- Voice and data users contend for available slots
- If voice user succeeds, slot becomes reserved until talk ends
- If data user succeeds, slot is still available
- Characteristics:
  - No dedicated reservation bandwidth
  - Contention detected after the whole packet transmission

D-TDMA

- Frame divided in reservation, voice and data slots

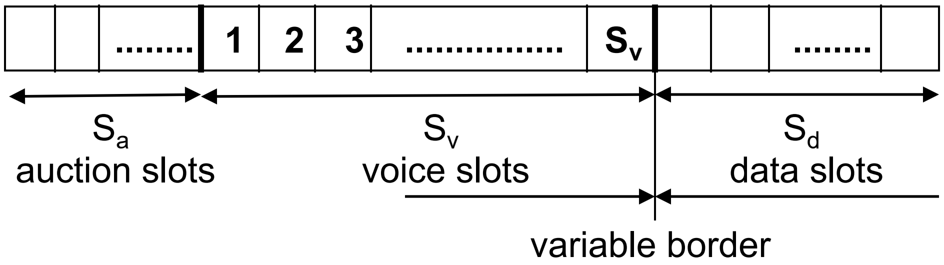


S_r and S_v are fixed, S_d are the remaining slots

- Short reservation packet in a random reservation slot
- Successful voice, assigned to an available voice slot
- Successful data, assigned but not reserved to data slot
- Unsuccessful voice, retry in the next frame
- Unsuccessful data, controlled with retransmission probability
- Higher bandwidth efficiency in resource assignment than PRMA
- Fixed amount dedicated to reservation (dynamical change difficult)

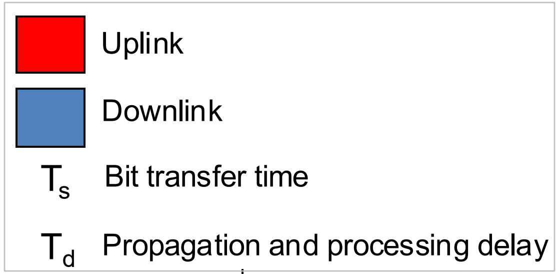
RAMA

- Auction slots instead of reservation slots in D-TDMA

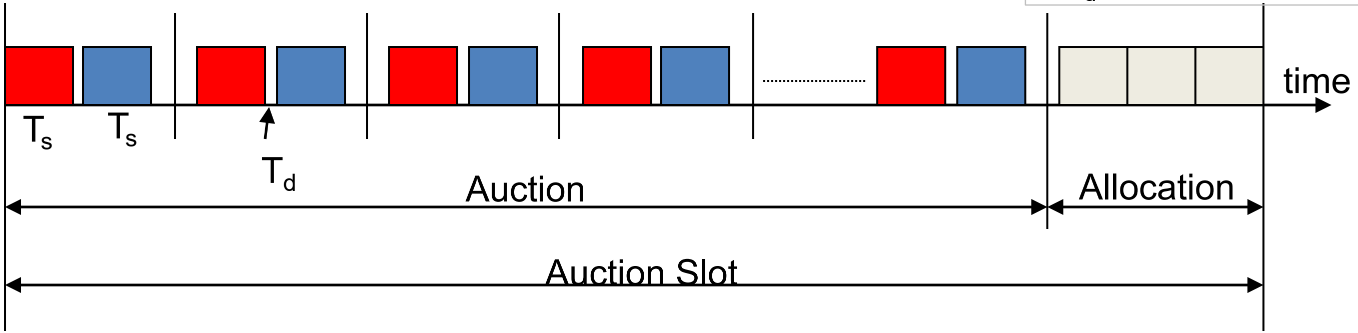


- Channel access strategy:
  - In TDMA, Slotted ALOHA
  - In RAMA, audition procedure to achieve a higher success probability
- Available resources auctioned by basing on requesting **user's ID**
  - Random number + priority digits (voice, data)

RAMA: auction procedure



- Comparison digit by digit



- Announcement highest value, at the end final winner
- Unsuccessful user, retry next auction slot
- Deterministic assignment procedure, good for high traffic
- More complex hardware needed to implement auction procedure
- Same disadvantages of D-TDMA
- It is an extreme case of D-TDMA with no contention failure

Learning Material

- Media Access Schemes
  - Carrier Sense Multiple Access (CSMA)
  - Code Division Multiple Access (CDMA) 5.8, Ch.9
  - Orthogonal Frequency Division Multiple Access (OFDMA) 5.7, Ch.8 13.2
  - Non-Orthogonal Multiple Access (NOMA)