Physical layer models and techniques for software radio

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References

- [1] Theodore S. Rappaport, *Wireless Communications*, 2ed, Prentice Hall, 2002
- [2] J.G. Proakis, *Communication Systems* (Fifth edition), McGraw-Hill, New York, 2008.
- [3] Andrea Goldsmith *WIRELESS COMMUNICATIONS*, Stanford University, 2005
- [4] David Tse and Pramod Viswanath, *Fundamentals of Wireless Communication,* Cambridge University Press, 2005

Contents

- Definition of “Telecommunication System” (TLC-system).
- Multiple Access methods.

1. Telecommunication systems

- **Telecommunication** is the transmission of signs, signals, messages, words, writings, images and sounds or information of any nature by wire, radio, optical or other electromagnetic systems.
- **Wireless telecommunication** occurs when the exchange of information between communication participants includes the use of radio technologies.
- Main Telecommunication system elements are: transmitter(s), channel(s). receiver(s)

1. Point-to-Point telecommunication systems

- ***1.1. POINT TO POINT (PTP) TELECOMMUNICATION SYSTEM.***
- A **PtP** TLC-system is composed of:
  - Single **transmitter** .
  - One or more **intermediate regenerators**, placed to extremes in **one or more line sections**. All these line sections form the communication **channel**.
  - Single **receiver**.
- Each **line section** is associated with **one or more physical media for signal propagation** (coaxial cables, telephone cables, optical fibers, ether, high-voltage line for electricity distribution, etc.)
- In case of the **PtP** TLC-system, the **channel** is a **dedicated resource** used to connect the unique transmitter with the unique receiver.

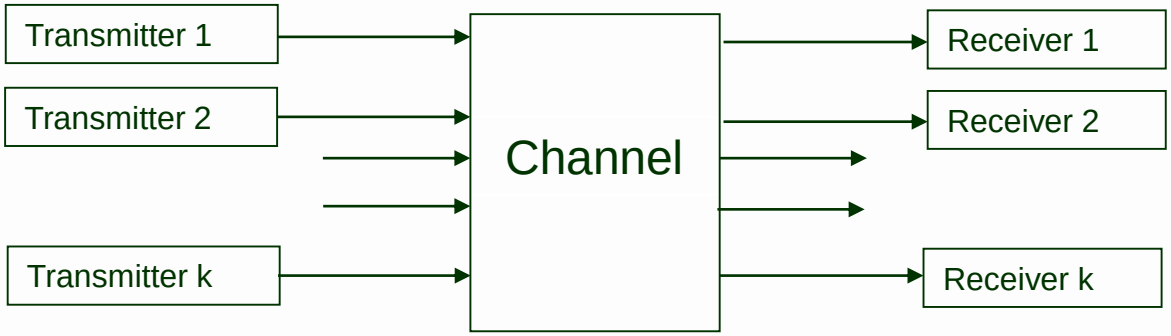
1. Multi-user telecommunication systems

- ***1.2. MULTI-USER TELECOMMUNICATION SYSTEM.***
- **Multi-user** TLC-system is composed of:
  - One or more **transmitters** set.
  - One or more intermediate **regenerators**, placed to extremes in **one or more line sections**. All together, these sections form the communication **channel**.
  - One or more **receivers**.
- In **multi-user** TLC-systems, the channel is a **shared resource** among different transmitters and/or receivers in the system.

1. Examples

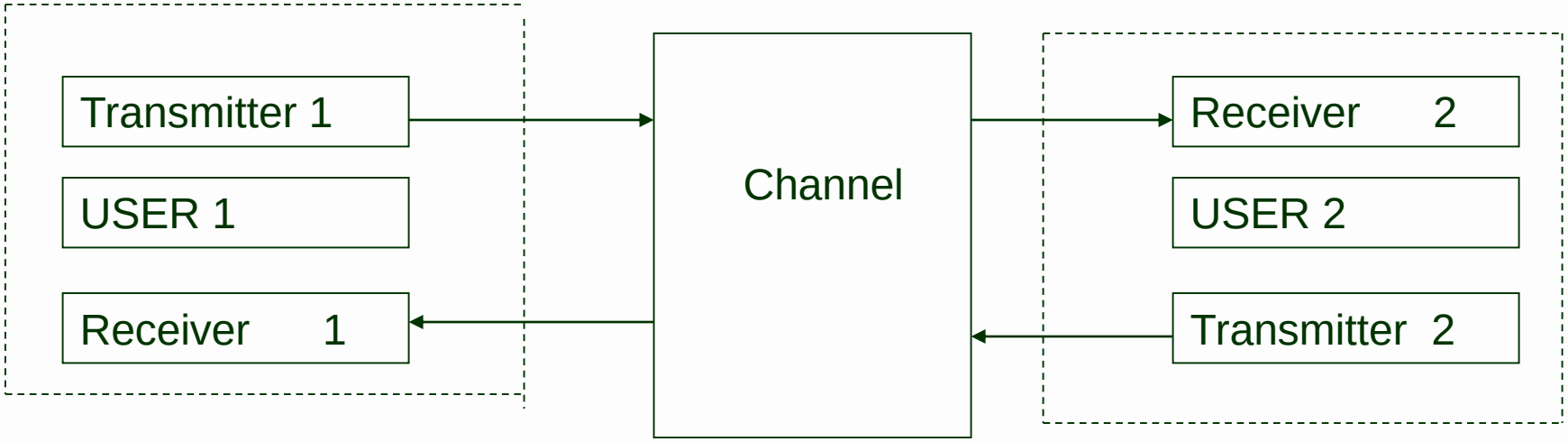
- ***1WAY PTP COMMUNICATION SYSTEM AND 1WAY MULTI-USER COMMUNICATION SYSTEM.***
  - **PtP communication system.**

  - **Multi-user communication system (one way).**



1. Examples

- ***2 WAY PTP COMMUNICATION SYSTEM AND 2 WAY MULTI-USER COMMUNICATION SYSTEM.***



- This is a **general** system communication configuration.
- **Transmitter and receiver** concepts are replaced by **user** concept. The user can transmit and receive data messages (e.g. modem).

1. Telecommunications network

- ***TLC-NETWORK***
  - A **TLC-network** is composed by multiple TLC-system elements (transmitters, receivers, line segments, regenerators, etc.) that exchange information each other.
  - A **mobile TLC-network** is a network where the mobile users exchange information and at least some of the line segments are wireless
  - **Access networks** connect providers to users **while core networks** connect providers to providers.

1. Telecommunications network

- ***ACCESS NETWORKS.***
  - **The access** method is the method that **mobile users** use to connect to the net through the provider.
  - Mobile users are **terminal nodes** of the net, as they rely on the **last segment line of the net**.
  - In case mobile users are residential users the final segment line is called **network last mile,** and in general is shared among several users that connect to the net.

2. Multiple Access methods

- ***2.1. MULTIPLE ACCESS CONCEPT.***
  - Terminal nodes in a TLC-system are generally linked to the network by **multiple access methods**.
  - **Single access** imposes that, when **a user** transmits data messages through transmission channel, it blocks the access to communication channel to **other users**.
  - Furthermore, transmitted messages **can be received by all users** sharing the channel (broadcast), whether they are interested or not in receiving them. Example of radio broadcast is given by **radio-taxi** and police communication systems.
  - Multiple access is based on **transmission channel sharing policy**.
  - In **oldest multiple access methods** (e.g. TDMA, FDMA) transmission medium is not **physically** but only **virtually** shared.
  - In general, the concept of sharing is in **wide sense**, meaning the **transparent mode** the users “see” simultaneous transmission of their messages on the same line segment of a channel.

2. Multiple Access methods

- ***2.2. MULTIPLE ACCESS VS. SINGLE ACCESS.***
  - Multiple access systems are designed to achieve a **simultaneous transmission** (in wide sense) for a reasonable number of users.
  - Multiple access systems allow **private** communication between two users (other users, which are not interested in it, do not take part in the communication).
  - To this end, a **virtual circuit** is allocated between two users.
  - Virtual circuit isn't pre-allocated to the user. User can achieve the allocation of **any circuit** and can use **different circuits for different communications**.
  - In general, virtual circuits are **on demand assignment**: users get their virtual circuit by First-In-First-Out (FIFO) policy.

2. Main Multiple Access methods

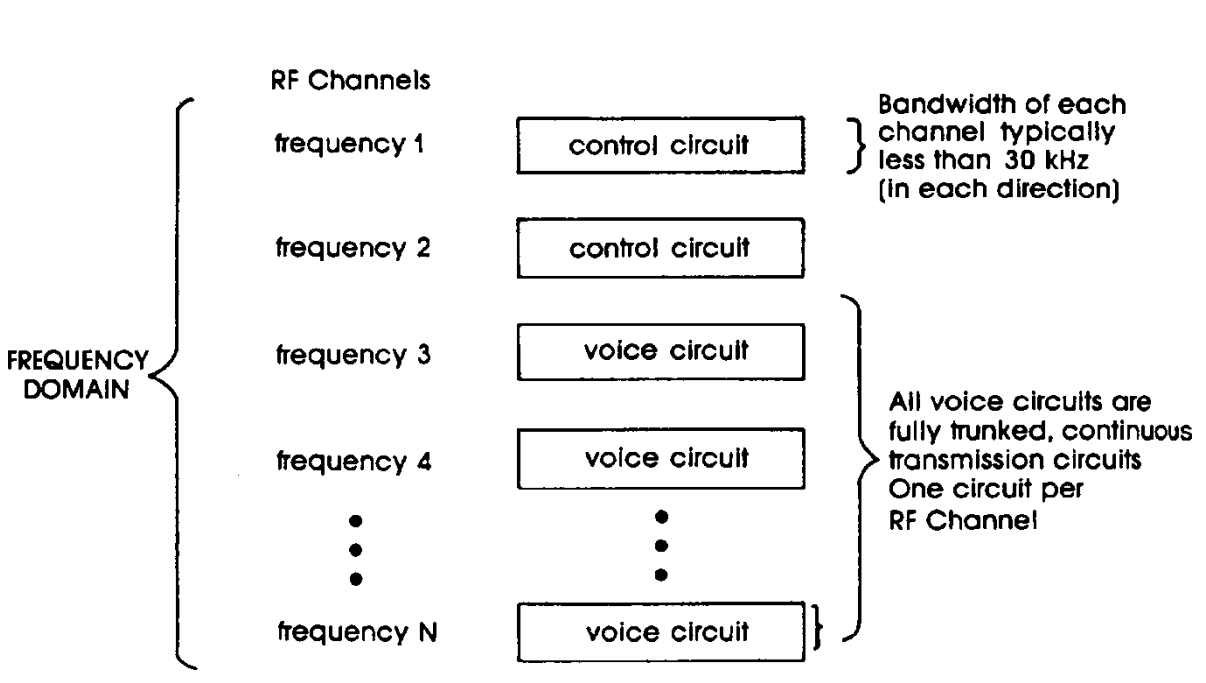
- ***2.3. MAIN MULTIPLE ACCESS METHODS.***
  - Principal multiple access methods are:
    - **Frequency Division Multiple Access (FDMA).**
    - **Time Division Multiple Access (TDMA).**
    - **Code Division Multiple Access (CDMA).**
  - There are other methods: **hybrid methods**, which use two or more of above mentioned techniques (e.g. GSM uses conjunction of two techniques: TDMA/FDMA)
  - More recently other Not Ortogonal Multiple Access (NOMA) methods have been defined (e.g. for 5G and Mimo)

2. Multiple Access methods

- ***2.4. FREQUENCY DIVISION MULTIPLE ACCESS (FDMA).***
  - The first multiple access method. It's mostly used in **analog transmissions** (for example to transmit **radio and television** signal).
  - FDMA is used in some **digital transmission** applications too.
  - FDMA method is based on a simple concept: total available spectrum is split **into a number of separate channels**. Each channel can support **virtual circuits**.
  - Each user can access any of these channels - however this is overviewed by the **system controller** (a supervisor).

2. Multiple Access methods

- ***2.4.1. EXAMPLE OF FDMA ARCHITECTURE FOR VOICE SIGNAL TRANSMISSION.***



2. Principal Multiple Access methods

- ***2.4.2. CHARACTERISTICS OF FDMA SYSTEMS FOR DIGITAL TRANSMISSION.***
  - **Frequency agility**: each user must be able to tune on any of the available channels, this operation is controlled by a system supervisor to avoid the collisions.
  - **Continuous transmission**: FDMA system transmits in continuous way until the message is completed.
  - **Simultaneous transmission and reception**: FDMA system must transmit and receive in simultaneous way. This requires duplexer circuitry that must be installed on terminal level and on base-stations.
  - **Low information transmitted redundancy**: FDMA multi-user digital transmission requires **fewer header bits** for transmission message, because the controller needs to do only **several simple operations** (no synchronism recovery operations like in TDMA systems)

2. Multiple Access methods

- ***2.4.2. CHARACTERISTICS OF FDMA SYSTEMS FOR DIGITAL TRANSMISSION.***
  - **Hardware infrastructures very expensive**: this cost is justified by fact that there is a single channel for each carrier. So for each channel, a **separate transmission-reception system** needs to exist on base-station level.
  - **Vulnerability to co-channel interference**: needs to be reduced as much as possible in order to obtain maximum spectral efficiency. The channels with **low bandwidth** are **more vulnerable** to co-channel interferences.
  - **High complexity of Hand-off operation**: FDMA transmission is continuous, **hand-off operation** (when a user must pass from one circuit to another while the transmission is active) is very difficult without dropping the transmission for a few moments. A service break is a big problem for any digital transmission data.

2. Multiple Access methods

- ***2.4.2. CHARACTERISTICS OF FDMA SYSTEMS FOR DIGITAL TRANSMISSION.***
  - **Lower hardware flexibility than new technology**: the biggest problem of FDMA architectures is the inability to adapt the hardware to the technology evolution. Update of the devices can be done only by replacing all old hardware.
  - **Lower flexibility for new services**: FDMA systems can transmit using low bit-rate (FDMA systems are optimized for voice transmission). Possible solutions – e.g. creating a channel beam (more channels formed a beam) - is discarded because the terminal would be very complex.

CONCLUSION → ***FDMA isn't suitable for requirements for new digital transmission techniques.***

2. Multiple Access methods

- ***2.5. TIME DIVISION MULTIPLE ACCESS (TDMA).***
  - **TDMA** is based on allocation of total available bandwidth to **only communication link** between two users for a determined **time period** (called *slot*).
  - TDMA is extended by **circuit commutation** concept - in this case is configured in a virtual way and not for the duration of the whole period of communication.
  - Actually, when the user activates a communication link, he transmits his data in a “burst” way because periodically the link is “disconnected” from him and dedicated to other users which request it.

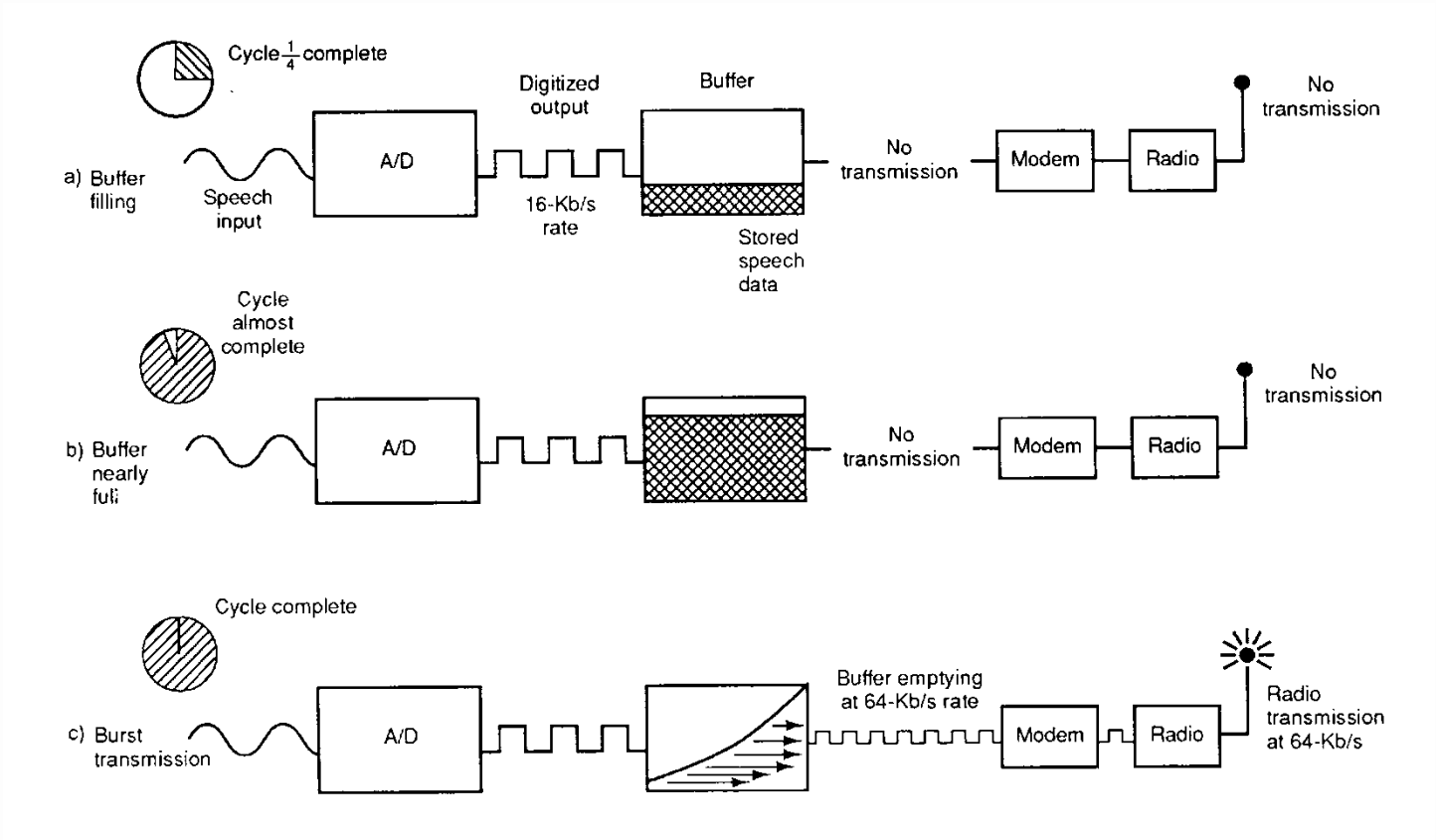
PROBLEM → ***How do you manage this transmission so that the user doesn’t notice of the interruptions?***

2. Multiple Access methods

- ***2.5.1. SYNCHRONOUS TRANSMISSION "BUFFER AND BURST".***
  - This solution is been used since the first TDMA systems.
  - Each user is given a determined **time slot**. Transmission data during this slot are called **burst**. The receiver, in order to obtain this data, synchronizes with base-station **transmitter** and counts the number of time slots until it reaches the time slot it has been assigned.
  - Then, the user activates his receiver in order to **demodulate and to decode** the message into his burst.
  - In the same way, **transmitting user** puts in **a buffer** data to transmit and synchronizes with base-station, waiting for his time slot. When his assigned time slot is reached, the transmitter downloads the data on a **high rate channel,** while reloading the buffer for next burst.

2. Multiple Access methods

- ***2.5.2. SYNCHRONOUS TRANSMISSION "BUFFER AND BURST" SCHEME (PURE TDMA).***

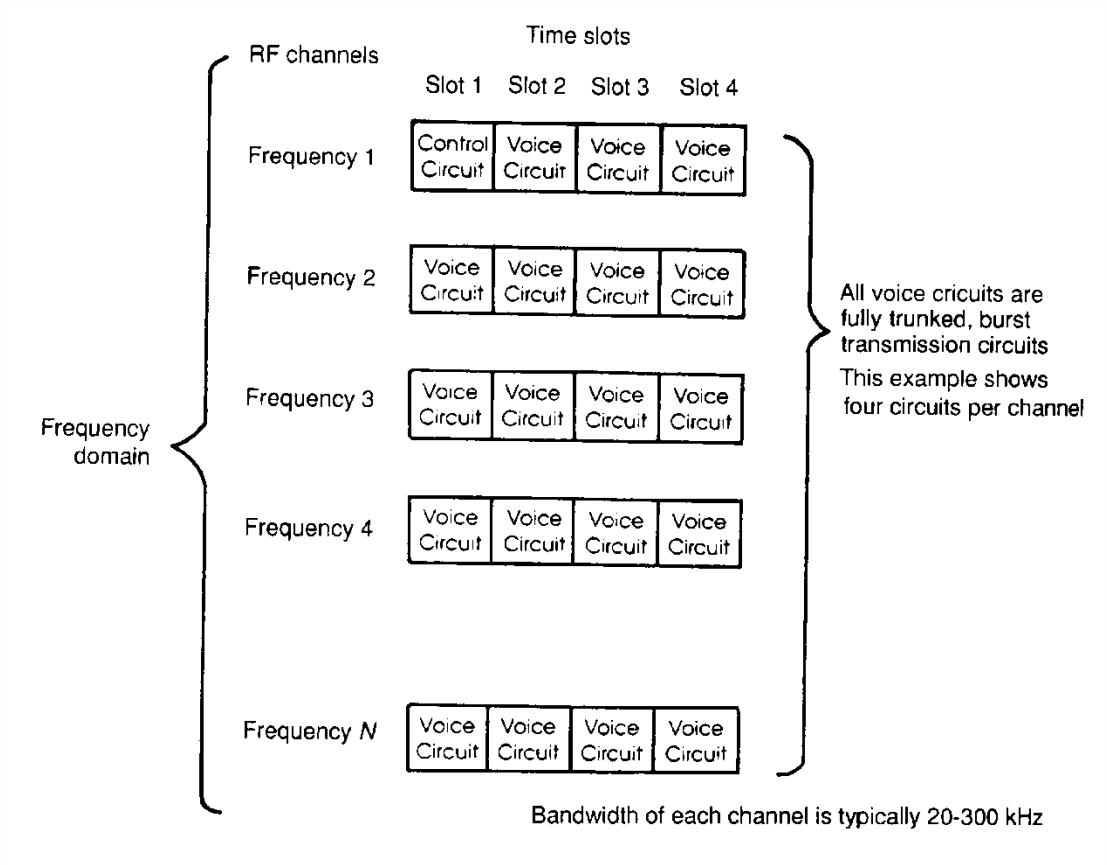


2. Principal Multiple Access methods

- ***2.5.3. MULTIPLE ACCESS FD/TDMA (TDMA-FREQUENCY DIVISION).***
  - In current systems, it uses a particular combination between TDMA and FDMA, to improve the benefits of these two techniques, farther to try to compensate for the problems. Nowadays TDMA means **TDMA-Frequency Division (FD/TDMA)**.
  - A FD/TDMA system can be represented by a **time-frequency matrix** (next slide), where each channel corresponds to a set communication virtual circuit, and each of them is activated by in determined time slot. Transmission protocol for management of the **single circuits** is **synchronous** “buffer and burst”.
  - Bandwidth of each channel typically has a range between **20 and 300 KHz**.
  - Each channel can support from **2 to 30** (or more) virtual circuits.

2. Multiple Access methods

- ***2.5.4. FD/TDMA TRANSMISSION SYSTEM SCHEME (TDMA-FREQUENCY DIVISION).***



2. Multiple Access methods

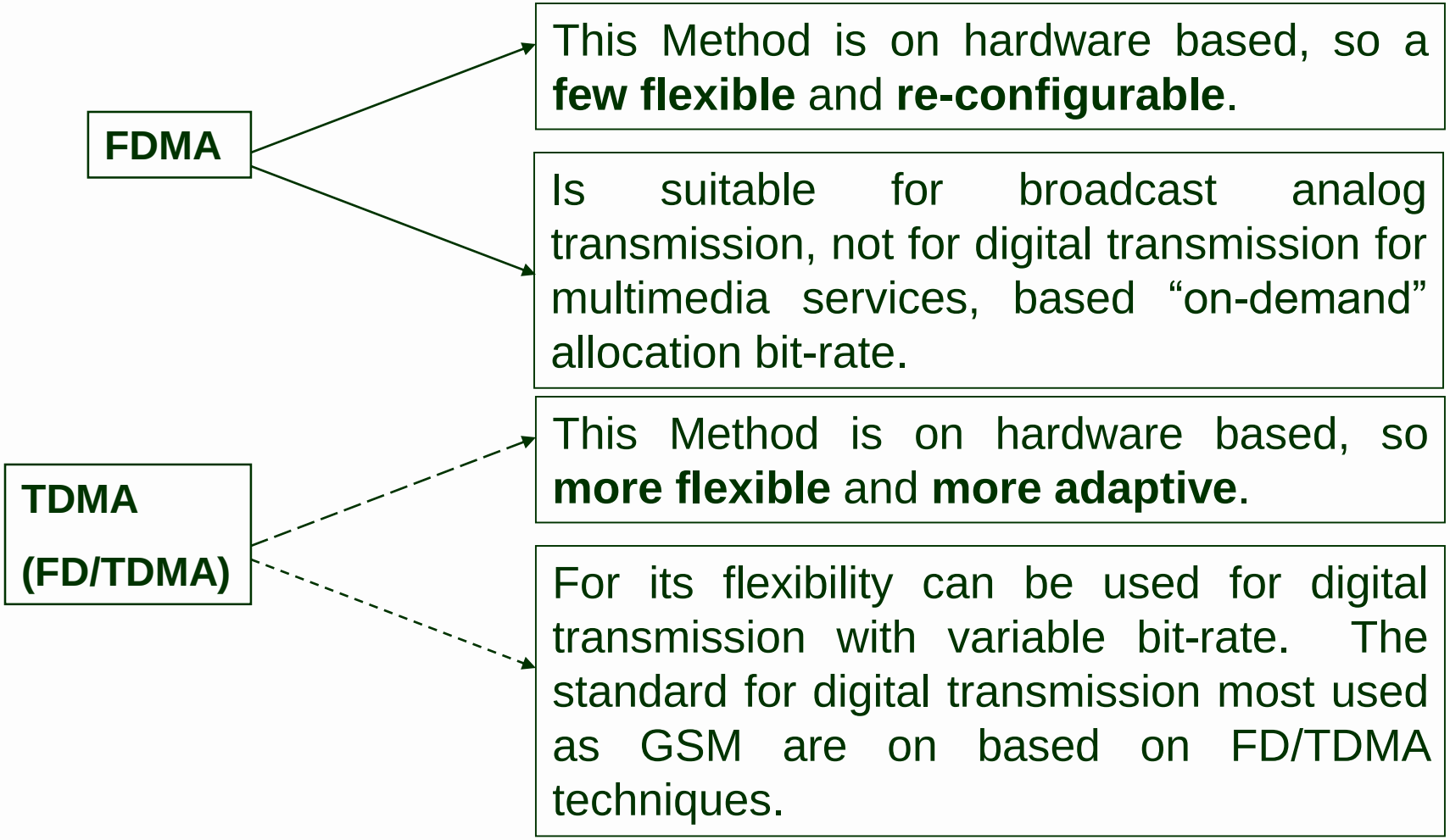
- ***2.5.5. CHARACTERISTICS OF FD/TDMA SYSTEMS FOR DIGITAL TRANSMISSION.***
  - **Discontinuous transmission**: the terminal of residential user transmits (and receives) of the data in discontinuous way, not in continuous way instead as for FDMA systems. This fact leads to hardware design and implementation problems.
  - **More available bandwidth**: the spectral efficient of a FD/TDMA system is higher than FDMA system by a factor equal to the number of circuits to support any carrier.
  - **High redundancy for the information transmitted**: a burst-TDMA transmission format requires that the receiver can re-synchronize at each slot. For this it's necessary "extra byte" called **time guard** to guarantee the distance among users are trying to transmit, **all together**, on the channel in the same time all this is caused by the **propagation delays** for different distances of the users from the base-station.

2. Multiple Access methods

- ***2.5.5. CHARACTERISTICS OF FD/TDMA SYSTEMS FOR DIGITAL TRANSMISSION.***
  - **Cost of the infrastructure**: there are a reduction of radio-frequency devices (as oscillators) this compensates the increase of the cost by introduction of TDMA circuits for each single carrier, the FD/TDMA architecture is a little advantage
  - **Hand-off**: FD/TDMA system can be designed to work a perfect hand-off without to lose any information, because the hand-off can happen during the waiting interval of the slot assigned.
  - **More flexibility**: The TDMA architecture is primarily managed by **software level** (while FDMA architecture is based on hardware). In the architecture based on a software takes some benefits: to change the value configuration of the bit-rate assigned to each users, through re-definition of software for assignment slots, all these operations are done without to change hardware structures. For this the TDMA techniques adapts very well to demand for **new emergent digital services**.

2. Multiple Access methods

- ***2.5.6. CONCLUSIONS OF FDMA AND TDMA.***



2. Multiple Access methods

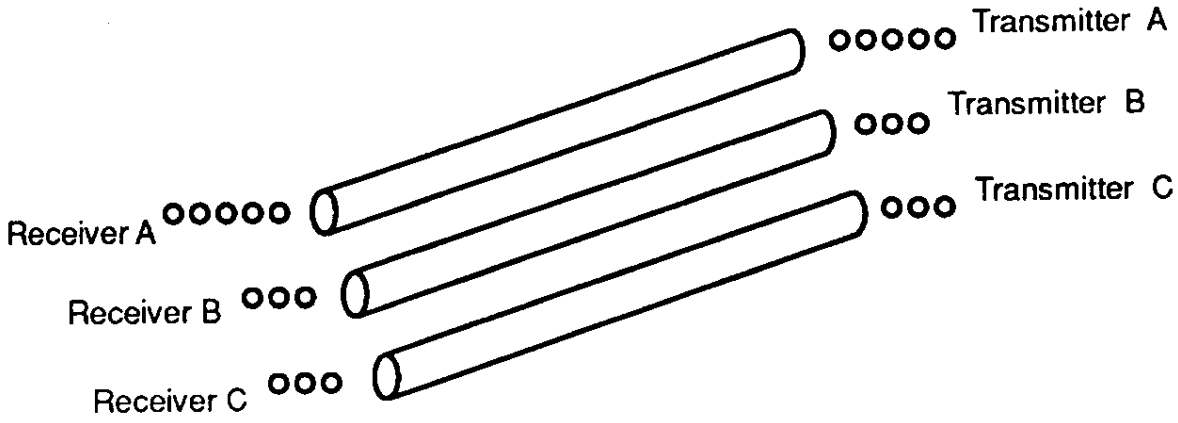
- ***2.6. CODE DIVISION MULTIPLE ACCESS (CDMA).***
  - CDMA is profoundly different to TDMA and FDMA.
  - The first two methods (FDMA and TDMA) have as target to **keep separate** in **frequency or time domain, or both domains** the transmission of individual users, these techniques must manage the sharing of the channel in virtual way.
  - CDMA is based on **actual sharing** of the channel in **physical way**, without any time or frequency restriction.
  - In CDMA different users can transmit their messages in **simultaneous way**, **on the same part of available bandwidth**. An user is separate among the others by a **information hardware encoding**, this encoding is pseudo-random. This indelible signature of the message survives when different transmissions are mixed on channel all together.

2. Multiple Access methods

- ***2.6.1. CDMA RECEPTION AND CO-CHANNEL INTERFERENCE.***
  - A CDMA system requires a receiver able to know exactly the encoding of the information transmitted.
  - CDMA receiver is **adapted** to pseudo-random pattern used to encode the information transmitted. The receiver must replicate the hardware present in the transmitter.
  - In this way is possible decode the information transmitted from a user than all the others users.
  - A user of the CDMA system “can’t read” the information sent from the other user. In CDMA systems in guaranteed the privacy of the messages.
  - In CDMA systems there is a problem: Multiple Access Interference (MAI), it is a form of co-channel interference, itsn’t eliminated but is possible decrease its.

2. Multiple Access methods

- ***2.6.2. METAPHOR TO EXPLAIN THE TDMA AND FDMA MULTIPLE ACCESS METHODS***.
  - Multiple access concept as TDMA and FDMA can be explained like a set of **small tubes don't communicating among them**, through them each users send some small balls of the same shape as those sent by the others. The small balls represent **information bits** and the tube are **transmission channels**.

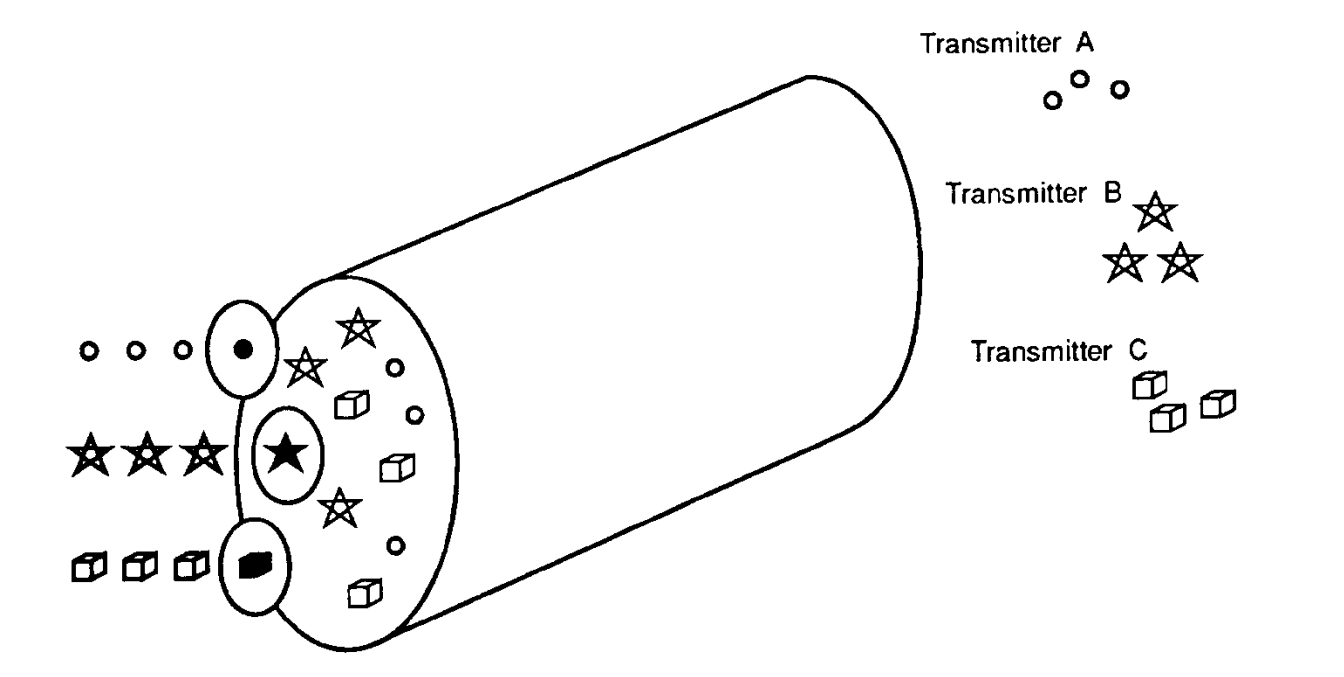


2. Multiple Access methods

- ***2.6.3. METAPHOR TO EXPLAIN THE CDMA MULTIPLE ACCESS METHOD***.
  - CDMA concept can be compared to a set of **packets with different shape** but they contain **objects** with **same shape** (for example small balls).
  - All different packets (for example the shapes can be: spheres, cubes, stars ext.) are sent **all together** on a **only tube**. **The section of this tube is bigger** than the previous small tube of the TDMA FDMA metaphor.
  - The exit of this tube there are **a set of the holes with a shape of the packets** (one hole has sphere shape, one hole has cube shape and so on). Each hole allows the passage of only one packet which shape is the same of the hole.
  - The small balls are transmission bits. The packets with different shapes represent the transmission pseudo-random hardware encoding, the holes represent the adapter receiver.

2. Multiple Access methods

- ***2.6.3. (BIS) METAPHOR TO EXPLAIN THE CDMA MULTIPLE ACCESS METHOD***.

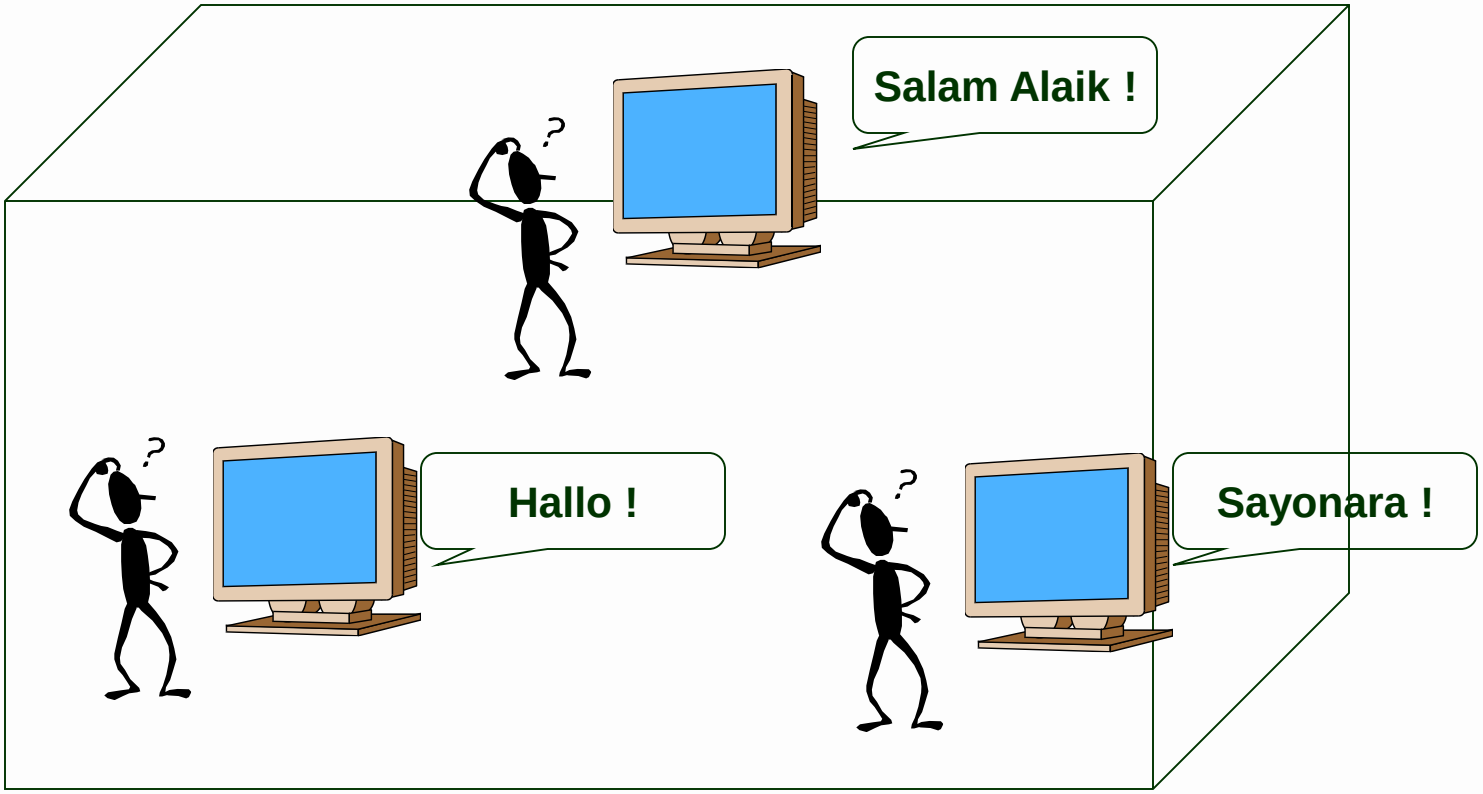


2. Multiple Access methods

- ***2.6.4. METAPHOR TO EXPLAIN THE INTERFERENCE FOR MULTIPLE ACCESS METHODS***.
  - Interference problem for multiple access methods can be explained by three televisions metaphor in the same room.
  - We suppose that there are three televisions, each of these are tuned on different TV-channel, for example: one on English TV-channel, one on Arabic TV-channel, one on Japanese TV-channel.
  - An English man in the room will understand only the English TV-channel, while the others two television will be **pure noise-sources** for him. The same fact will be for Arabic man and for Japanese man.
  - If the televisions keep low volume and the room is large enough, three men can listen their TV-programs without to create noise to the others. If the room is small and the TVs volume is too high there are problems and it's impossible for the tree men to follow their TV-programs for high noise.

2. Multiple Access methods

- ***THREE TELEVISIONS IN THE ROOM METAPHOR.***



2. Multiple Access methods

- ***2.6.4. (BIS) METAPHOR TO EXPLAIN THE INTERFERENCE FOR MULTIPLE ACCESS METHODS***.
  - The elements of the metaphor:
    - Televisions = **transmitters**.
    - Men in the room = **adapting receivers**.
    - Language (English, Arabic, Japanese) = **encoding**.
    - Room = **transmission channel**.
    - Television noise for foreign language than known language = **multiple access interference (MAI)**.
    - Television volume = **transmission power**.

2. Multiple Access methods

- ***2.6.5. CDMA AND SPREAD SPECTRUM COMMUNICATION SYSTEMS (SPREAD SPECTRUM CONCEPT).***
  - The room where, there are three men, must be **large enough** to allow to the people to listen their programs without to create noise to the other.
  - An other thing, in 4.6.3 BIS, the tube must be **large enough** to contain all packets with different shapes.
  - We conclude that transmission channel must occupy a part of spectrum of **appropriate size** to allow to all users to transmit all together without to disturb the others.
  - CDMA is connected to **SPREAD SPECTRUM** concept and to **spread spectrum modulation techniques**, which allow a user to transmit with a **bandwidth larger than** bandwidth required from the one required by **direct narrowband modulation** of the transmitted message.

2. Multiple Access methods

- ***2.6.6. CHARACTERISTICS OF CDMA SYSTEM.***
  - **Flexibility of channel capacity**: in CDMA system, the capacity channel concept is connected to:
    - the number of the users that transmit in simultaneous way on channel;
    - with such transmission power these users work;
    - available bandwidth (with referring to the example of the "three televisions in the room").

  In CDMA systems the **capacity** isn't rigid parameter but it can be configured in **flexible** way as a function of different communication system parameters.
  - **Reduction or deletion of interference by orthogonal codes**: unerasable MAI interference but can be reduced, and in particular cases can be deleted. We come back to three TVs metaphor, the language (English, Arab, Japanese) have different roots . **Orthogonal codes** are defined as codes with little or nothing correlation.

2. Multiple Access methods

- ***2.6.6. CHARACTERISTICS OF CDMA SYSTEM.***
  - **Power control**: in CDMA system where the transmitters “speak” different languages among them (this means to use orthogonal codes), work well only if the televisions are equidistant and the volume level is similar, (preferentially low).
    - If the television that transmits Arab TV-program is near to television that transmits English TV-program, for the English user could be very difficult to understand the English TV-program. So the volume of Arab TV should be lowered or in the other case the volume of English TV should be raised. The optimal solution is put each volume to allow all users to heard and to understand their programs. In the CDMA system this operation is called **power control**. It’s a fundamental control to manage and guarantee optimal performances in radio-mobile environment.