A COMPARISON STUDY BETWEEN *TDMA* AND *FDMA* IN DIGITAL WIRELESS SYSTEMS

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Abstract I have revised and explained in the case of digital cellular systems, the difference between *TDMA* and *FDMA*. For *TDMA*, I give a general expression for the frame efficiency and the number of speech channels per frame. For both, I concentrate my study on the spectral efficiency and the capacity. I give the parameters which influence them and their nature. I have also done a qualitative comparison between the two multiple access technologies and have explained why those days *TDMA* is popular

List of symbols
(SI units are implied throughout)

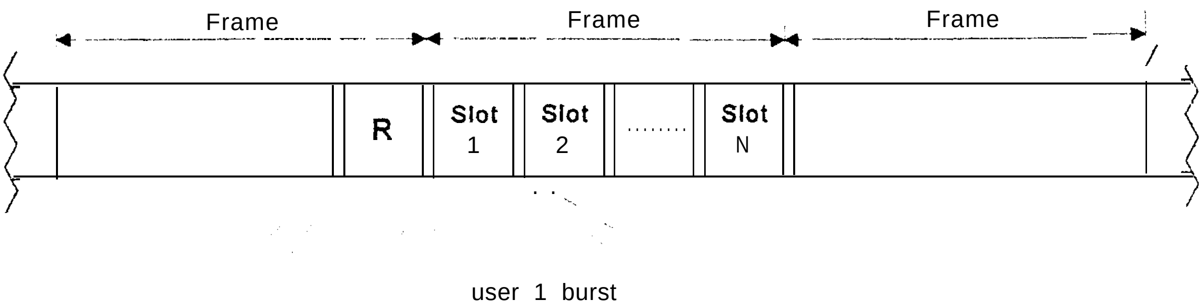
N frequency reuse factor of the system : number of cells in a frequency reuse pattern
B_S bandwidth of the system
B_c radio channel frequency band
N_u number of mobile users in a cell
N_c number of cells per cluster
A_c area of a cell

1 GENERALITIES

Among multiple access technologies, a lot of digital wireless systems use actually Time-Division Multiple Access (*TDMA*) and Frequency-Division Multiple Access (*FDMA*). In *TDMA*, one user (mobile user) takes all the frequency bandwidth but during a precise interval of time. So different users can transmit or receive messages, one after one in the same bandwidth but at different time slots. Each user occupy a cyclically repeating time slot and a *TDMA channel* may be thought as a particular time slot that reoccurs every frame, where N time slots comprise a frame. Fig. 1 shows a generally used *TDMA* frame structure.

In *FDMA*, a channel corresponds to a frequency band and we assign individual channels to individual users. So in *FDMA* all the entire bandwidth is divided in different frequency bands or channels which is allowed (on request) to each user. No user can share the same frequency band at the same time, guard bands are maintained between adjacent signals spectra to minimise cross talk between channels. In digital wireless systems, users can communicate through channels in full duplex (transmit and receive simultaneously). We have two categories of full duplex :

- *FDD* : frequency division duplexing which provides two distinct bands of frequency for every user. The forward band provides traffic from the base station to the mobile, and the reverse provides traffic from the mobile to the base ;
- *TDD*: time division duplexing uses time instead of frequency to provide both a forward and reverse link. If the time split between the forward and reverse time slots is small, the transmission and reception of data appears simultaneously to the user.



Guard time	Reference burst	Guard time	Preambule	Traffic data	Guard time

FIG. 1 TDMA frame structure

Now is the time to study the two multiple access techniques in a view of these two important parameters : spectral efficiency and capacity. But, first let's go to an important parameter : efficiency of the *TDMA* frame. This parameter measures the percentage of transmitted data that contains speech information as opposed to providing overhead for the access scheme.
From Fig. 1, we can write b_{OH}, the number of overhead bits per frame as :

$$b_{OH} = N_r b_r + N_t b_p + (N_t + N_r) b_g \qquad (1)$$

where :

- N_r = number of reference bursts per frame ;
- N_t = number of traffic bursts (slots) per frame ;
- b_r = number of overhead bits per reference burst ;
- b_p = number of overhead bits per preamble per slot ; and
- b_g = number of equivalent bits in each guard time interval.

The total number of bits per frame is :

$$b_T = T_f \times R_{rf} \qquad (2)$$

where :

- T_f = frame duration ; and
- R_{rf} = bit rate of the radio-frequency channel

Then the frame efficiency is:

$$\eta_F = (1 - b_{OH} / b_T) \times 100\% \qquad (3)$$

We have a very good *TDMA* frame efficiency when η_F is up to 90%.

We give in Table 1 a short list of multiple access technologies used in different wireless communications systems.

TABLE 1 *Some Multiple Access Technologies used in Digital Wireless Systems*

Digital Wireless System	**Multiple Access Techno-Logy**	**Radio frequency channel bit rate (Kbs)**	**Modu-lation**	**Frequency band**	**Radio frequency channel band width**	**Voice rate (Kbs)**	**Voice channel per RF channel**
GSM Pan-Europe	*TDMA* *FDD*	**270.833**	GMSK	**890-960** MHz	**200 KHZ**	13.4	8
Digital *IS-54*	*TDMA* *FDD*	**48.6**	*xi4* - DQPSK	824-894 MHz	30 KHz	7.95	3
CT-2 Cordless	*FDMA* *TDD*	*72.0*	BFSK	864-868 MHz	100 KHz	32	1
DECT Cordless	*TDMA* *FDD*	*1152.0*	GFSK	1880-1900 MHz	1728 KHz	32	12

The number of speech channels per *TDMA* frame can be calculated as foilows :

$$\frac{\text{Number oj' speech channels}}{\text{frame}} = \frac{\text{(Number of speech information bits oj' the radio frequency channel)}\,/\,\text{(frame)}}{\text{(Number of bits per speech channel)}\,/\,\text{(frame)}} \qquad (4)$$

. Because the total number of bits of the radio frequency channel per frame is given by (2), then if we consider only speech information bits (so we consider $\eta_F R_{rf}$ in place of R_{rf}) we must write :

$$\textit{Number of speech information bits ofthe rudio frequency channel/frame} = \eta_F \cdot R_{rf} \cdot T_f \qquad (5)$$

and

$$\textit{Number of bits per speech channel/flame} = R \,.\, T_f \qquad (6)$$

where R is the bit rate of each speech **channel.**

Using (5) and (6), we can write (4) as :

$$\frac{\textit{Number of speech channel}}{\textit{TDMA frame}} = N_{SchF} = \frac{\eta_F R_{rf}}{R} \tag{7}$$

In the next section, we will review expressions of spectral efficiencies of both *TDMA* and *FDMA*.

2 SPECTRAL EFFICIENCY

The spectral efficiency measures how the multiple access technique used in the wireless system allows a better (efficient in using) use of the bandwidth with respect to time or to frequency. Another parameter is the spectral efficiency with respect to modulation which measures how the radio plan or the modulation scheme is efficient. This parameter depends on the frequency reuse factor. The overall spectral efficiency of a multiple access technique is a combination of the last one and one of the first ones. As we can deduce, we have :

- Spectral efficiency with respect to time for *TDMA*.
- Spectral efficiency with respect to frequency for *FDMA*.
- Spectral efficiency with respect to modulation for both *TDMA* and *FDMA*.
- Overall spectral efficiency of a multiple access technology which is a combination of the spectral efficiency with respect to modulation and the one with respect to time (in case of *TDMA*) or to frequency (in case of *FDMA*).

For *TDMA* either *FDMA*, the spectral efficiency with respect to modulation or the modulation efficiency can be calculated in channels/MHz/km^2 or in Erlangs/MHz/km^2. The spectral efficiency with respect to modulation in channels/MHz/km^2 does not depend on B_S the bandwidth of the system, it can be calculated as follows :

$$N_m = \frac{\textit{(Total number of radio channels in the system)}}{\textit{(Bandwidth of the system) (Total urea)}} \tag{8}$$

$$N_m = \frac{\frac{B_S}{N \cdot B_c} \cdot N_c}{B_S \cdot N_c \cdot A_c} = \frac{1}{B_c \cdot N \cdot A_c} \tag{9}$$

; this because the total number of radio channels in the system equals the one in a cell multiplied by the number of cells in a cluster .

Formula (9) confirms that this N_m here does not depends on B_S. The other spectral efficiency with respect to modulation calculated in Erlangs/MHz/km^2 is :

$$N_m = \frac{\textit{(Total traffic carried by the system)}}{\textit{(Bandwidth of the system) (Total area)}} \tag{10}$$

$$N_m = \frac{\left(\textit{Total traffic carried by } \left(\frac{B_S/B_C}{N}\right) \textit{radio channels}\right)}{B_S \cdot A_c} \qquad (11)$$

As we know, the total traffic carried by $(B_s/B_c)/N$ channels depends not only on B_S, B_c and N but also on the blocking probability. Then to calculate this N_m, we have to know the blocking probability and the relation between B_S and the total traffic. This relation (non linear j is not an easy one. Knowing that the blocking probability is a criteria of quality of services and, B_c and A_c are generally fixed, the only parameter we can modify in common in equations (9) and (11) is N. That is why we said that the spectral efficiency with respect to modulation depends on N the frequency reuse factor. The right affirmation would be to say that the good way to increase N_m, is to play on N.

About the spectral efficiency with respect to time (for *TDMA*) or to frequency (*FDMA*). To calculate it, we must remember the definition : the spectral efficiency with respect to time-frequency domain is the ratio of the total time-frequency domain dedicated for speech transmission to the total time-frequency domain available to the system. **The spectral efficiency of *TDMA* is influences by Guard times and synchronisation sequences and the one of *FDMA* by guard bands and signalling channels.** In wideband *TDMA*, the total available bandwidth is shared by all users, each at his allowed time. If we have :

N_{Sch}=	number of speech channels in the covered area ;
T =	duration of a time slot ;
T_f =	frame duration ; and
N_T =	number of time slots per frame.

The spectral efficiency with respect to time of wideband *TDMA* is time for speech transmission $N_T T$ divided by total frame duration T_f.

In the case of narrowband *TDMA*, there is a factor in the expression because individual users channels don't use the whole available bandwidth. Then, this factor is a frequency domain efficiency equals to unity when $B_u N_u$ is equal to B_S (the case of wideband *TDMA*). B_u and N_u are respectively the bandwidth of an individual user during his time slot and the number of users sharing the same time slot but having access to different frequency subbands. For *FDMA*, we calculate the spectral efficiency with respect to frequency by dividing the total frequency used for speech $N_{Sch}B_c$ by the one of the system B_S. As we can realise, contrary to the spectral efficiency with respect to modulation, the one to frequency or to time are dimensionless numbers. Table 2 gives formulas of spectral efficiencies.

TABLE 2 Formulas of spectral efficiencies

	Wideband TDMA	Narrowband TDMA	FDMA
Spectral efficiency (dimensionless number)	$\eta_t = \frac{T\,N_T}{T_f}$	$\eta_t = \frac{T\,N_T}{T_f}\left(\frac{(B_u N_u)}{B_s}\right)$	$\eta_f = \frac{N_{Sch}\,B_c}{B_S}$
Overall spectral efficiency (in channels/MHz/km² or in Erlangs/MHz/km²)	$\eta = \eta_m \cdot \eta_t$		$\eta = \eta_m \cdot \eta_f$

We have also introduced the overall spectral efficiency η which is a combination of the spectral efficiency with respect to modulation and the one with respect to time (*TDMA*) or to frequency (*FDMA*). So before finishing this section, let's give the exact relation between the overall spectral efficiency η called simply spectral efficiency, the cell capacity N_u (see section 3)and the speech channel bit rate (R). The units of η here are bits/sec/Hz. We have by definition :

$$\text{Overall spectral efficiency } \eta = \frac{\text{Total channels}}{\text{Required bundwidth}} = \frac{\text{Total traffic}}{\text{Required bundwidth}} = \frac{\text{Total bits transmitted}}{\text{Required bundwidth}} \quad (12)$$

Then we can find the well known fundamental formula :

$$\text{Overall spectral efficiency } \eta = \frac{N_u \times R}{B_s} \text{ bits/sec/Hz} \quad (13)$$

3 CAPACITY

We can continue with another important parameter of a digital cellular system : capacity. Principally we have : the multiple access scheme capacity, the radio capacity and the cell capacity, The multiple access technology capacity is the number of simultaneous mobile users that it can accommodate. This can be calculated easily by remembering that for example in *FDMA*, each user has an allowed bandwidth except two guard bands at the edges. So the number of users is the total bandwidth except guard bands $B_S - 2B_{guard}$ divided by the allowable radio channel bandwidth B_c. The reasoning is the same in the case of *TDMA*, here we must remember that we can have many mobile users or speech channels (n_{Sch}) sharing the same bandwidth but at different time. En this paper, n_{Sch} will be considered as the maximum number of speech channels or mobile users per radio channel.

We see that the calculation of the multiple access technology capacity N_S is easy because we just apply the definition with respect to each technology. The other important capacity is the radio capacity which is the number of radio channels per cell. Here the calculation is more complicated because we deal with the famous problem of interferences found in radio planification. In fact, the **number of radio channels per cell will depend on how we build the radio plan, then on the frequency reuse factor N.**

Because we enter here in the domain of interference problems, we deal automatically with : code, modulation, voice activity factor, ... By playing on code, modulation, voice activity factor, we can improve the radio capacity of a digital cellular system. Information compression, variable bit rate control and improved channels assignment algorithms are other techniques used to improve the radio channel capacity.

Considering the definition of the radio capacity, N being the frequency reuse factor (number of cells in a frequency reuse pattern), we have :

$$m \equiv radio\ channels\ cell = \frac{Total\ frequency\ band}{\frac{Total\ frequency\ band}{radio\ channel} \cdot Cell} \quad (14)$$

Then

$$m\ radio\ capacity = \frac{B_S}{B_c \cdot N} \quad (15)$$

This is the simple formula of the radio capacity for *TDMA* either for *FDMA*. As soon as we know to calculate N, we have solved the problem. As we said N is related to the frequency planning. **The value of N is a function of how much interferences a mobile or a base station can tolerate while maintaining a sufficient quality of communication.**

Before showing how to find the value of N, let's go to the most important capacity parameter : the cell capacity. The cell capacity N_u is the maximum number of mobile users per cell.
It is related to the radio capacity trough n_{Sch} the maximum number of speech channels or mobile users in a radio channel. We have :

$$N_u \equiv \frac{users}{cell} = \frac{speech\ channels}{cell} = \frac{(speech\ channels\ radio\ channel)}{cell/radio\ channel} \quad (16)$$

Then

$$N_u = \frac{n_{Sch}}{1/m} = n_{Sch} \cdot m \quad (17)$$

As we can see, the cell capacity depends also on the frequency reuse factor N. **Then what we said for the radio capacity is still applicable for the cell capacity.** Table 3 gives us a summary of all results about capacities.

TABLE 3 *Formulas of capacities*

	Multiple access scheme capacity : *multiple access channels*	**Radio capacity: *radio channels/cell***	**Cell capacity: *users/cell***
TDMA	$N_S = \dfrac{n_{Sch} \cdot (B_S - 2\,B_{guard})}{B_c}$	$m = \dfrac{B_S}{B_c\,N}$	$N_u = \dfrac{n_{Sch} \cdot B_S}{B_c\,N}$
FDMA	$N_S = \dfrac{B_S - 2\,B_{guard}}{B_c}$		

As we said before, N is related to the radio plane. In **digital wireless systems N depends on radio plan, cells configuration, radio propagation (path loss exponent J), modulation and code (energy per symbol, energy per bit, ..) and system configuration.** The demonstrations of the many different expressions of N can be found in books about digital cellulars (see references [1] ,[2]]: here we will give just one, main steps and conditions of application.
If $(C/I)_{min}$ is the minimum carrier-to-interference ratio which gives an acceptable signal quality at the receiver, one can show in the case of hexagonal cells and omnidirectional antennas (then six interferencing cells) that the co-channel reuse factor Q is :

$$Q = \left[6 \left(\frac{C}{I}\right)_{min} \right]^{\frac{1}{J}} \tag{18}$$

Where J is the path, loss exponent, ail equidistant interfering cells having the same path loss exponent equaling J, the one of the cell of reference.
In all books about cellular, we can find that:

$$N = \frac{Q^2}{3} \tag{19}$$

Using (18) and (19), we find :

$$N = \left[\frac{6}{3^{J/2}} \left(\frac{C}{I}\right)_{min} \right]^{\frac{2}{J}} \tag{20}$$

Before continuing, let's remember that, as we can see in Table 3, to increase the radio capacity either the cell capacity we need to reduce N. Because J is constant (J depends on terrain environment), we have to reduce *(C/I)* if we want to increase N_u or m.
This means that if we want to increase the cell capacity either the radio capacity we will increase interferences, then the quality of reception will degrade. **It is well known that by increasing the number of users in a cell, we degrade the voice quality.**

The parameter $(C/I)_{min}$ is fixed by «subjective tests» because acceptable quality is essentially a subjective concept. Between *TDMA* and *FDMA*, we will choose the multiple access technique which will give us the highest C/I value, this value being upper than $(C/I)_{min}$. **To avoid an increasing *N* and then the reduction of cell and radio capacities, one solution is the use of sectorization and directional antennas to reduce the number of interferencing cells** (then the number «*6*» in 18, 19 and 20 will be reduced). This has the consequence that to keep the same overall spectral rfticiency, we must reduce the cluster size. The calculation of C/I in digital wireless systems is :

$$\frac{C}{I} = \frac{E_b R_b}{I} = \frac{E_c R_c}{I} \tag{21}$$

where R_b is channel bit rate, E_b is the energy per bit, R_c is the rate of the channel code and E_c is the energy per code symbol. I is the interference power. Channel means here speech channel.

If **it becomes impossible for increasing capacities to use sectorization and directional antennas, the other solution for a chosen multiple access technique is to reduce the *C/I* ratio, but in keeping it upper than *(C/I)*$_{min}$ and upper than the *C/I* ratio of the non chosen multiple access technique.** As suggested by (21), to reduce C/I, we have to find the right modulation or coding technique which gives the smallest E_b/I or Ec/I ratios. Another different way to increase the cell capacity is to take in consideration only the effective voice activity period measured by the voice activity factor. **The smallest is the voice activity factor, then the highest will be the cell capacity.** To agree with this, we must have a new formula for the cell capacity which is (17) but with a factor in the denominator for representing the voice activity factor. in *TDMA*, the voice activity factor is near one because users share actively time. In *FDMA*, the voice activity factor will depends on : time-delay for channel reassignments,...

in the next section we will do a qualitative study of both *TDMA* and *FDMA*. We will give general advantages and disadvantages of each system.

4 ADVANTAGES AND DESANVANTAGES OF TDMA AND FDMA

After dealing with mathematical expressions, in this part we do a general qualitative study of each system. We will see that the advantages and disadvantages of each system depends on many factors such as : usage, electronic material, . . . For the purpose of comparison, we give Table 3.

TABLE 3 *Advantages and disadvantages for TDMA and FDMA*

Multiple Access Techno-Logy	Advantages	Disadvantages
TDMA	. Permits a flexible bit rate No frequency guard band is required between channels No need for precise narrowband filters Permits utilization of all the advantages of digital techniques : digital speech interpolation, source and channel coding, ... Easy for mobile or base stations to initiate and execute hands off . Guard time between time slots allows to reduce the impact of : clock instability. transmission*time delay, ...	Requires network-wide timing synchronization . Requires signal processing for matched filtering and correlation detection Demands high peak power on the uplink (reverse direction) in transmit mode
FDMA	. A capacity increase can be obtained by reducing the information bit rate and using efficient digital codes Uses low cost hardware technology . No need for network timing . *No* restriction regarding the type of base band (voice or data) or type of modulation	. **The** presence of guard bands . Requires right RF filtering to minimize adjacent channel interference . The maximum bit rate per channel is fixed and small, inhibiting the flexibility in bit rate capability . Does not differ significantly from the analog system

We see that the choice between *TDMA* and *FDMA* will depend on the specific application. in those days, because we now master digital signal processing, *TDMA* has a great success. As we said, TDMA allows the utilisation of all the advantages of digital techniques. Then it is used as a base to be combined with other multiple access techniques, among them the *FDMA*

5 CONCLUSION

In this paper, we have given the expressions of spectral efficiencies and capacities in the case of *TDMA* and *FDMA*. We must know that those expressions are different because in one multiple access technique, users share time and in the other one they share frequency. For *TDMA* either *FDMA*, the overall spectral efficiency is related to the ceil capacity and the latest one to the radio plan. A good radio plan is not easy because we deal with the problem of interferences. But sectorization and directional antennas, powerful modulation and coding schemes, information compression, bit rate control, improved algorithms in channels assignments can allow us to increase the cell capacity of a cellular system which use *TDMA* or *FDMA*.

Besides the fact that both *TDMA* and *FDMA* give advantages and disadvantages, we prefer *TDMA* because as we said, it allows us to have all the advantages of the digital technology. *TDMA* is actually the great competitor of an another newly popular multiple access technology called *CDMA* (Code Division Multiple Access).

7 REFERENCES

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