Spectrum Efficiency in Cellular

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Abstract—**The spectrum efficiency in cellular can be measured by a parameter called here radio capacity. Using radio capacity, it can be shown that splitting analog channels does not increase the spectrum efficiency in cellular radio systems, but using digital cellular channels does. A simple evaluation method of judging spectrum efficiency in different digital systems is introduced. Also, several new concepts of spectrum efficiency in cellular are described.**

I. Introduction

SINCE THE FREQUENCY spectrum is a limited resource, we should utilize it very effectively. In order to approach this goal, we have to clearly define spectrum efficiency from either a total system point of view or a simple fixed point-to-point link perspective. For most radio systems, spectrum efficiency is the same as channel efficiency, the maximum number of channels that can be provided in a given frequency band. This is true for a point-to-point system that does not reuse frequency channels, but cellular mobile radio does. Therefore, in cellular mobile radio systems:

$$\text{spectrum efficiency} \neq \text{channel efficiency}.$$

The system capacity is directly related to spectrum efficiency but not to channel efficiency [1].

Evaluation of any communication system is based on its voice quality. The specified voice quality can be determined by a subjective test, usually based on a subjective mean opinion score (MOS) [2], [3]. For example, a voice quality is deemed acceptable based on 75 percent of total listeners' judgment that the voice quality is good or excellent (the top two scores among five merit scores). A specified voice quality then can be tested on any communication systems with their given channel bandwidth B_c to determine a required carrier-to-interference ratio $(C/I)_s$. Since the different modulation schemes will affect $(C/I)_s$ and the transmitted power can be set based on the $(C/I)_s$ at the receiving end. Therefore, $(C/I)_s$ and B_c are the only parameters to be used to evaluate spectrum efficiency of each system as described in this paper. A simple but very effective formula for evaluating the spectrum efficiency of each system called radio capacity has been derived in this paper.

II. Radio Capacity in Cellular Systems

A parameter named radio capacity by Lee [4] is derived in this section and used to measure the spectrum efficiency.

In cellular systems, although the frequency reuse scheme proves increasing the system capacity, it also creates the co-channel interference from co-channel cells. The co-channel cells are the cells within them when the same set of frequency channels is used. We may show the co-channel cells in Fig. 1. The number of co-channel cells in the worst case is six at the first tier surrounding the desired cell, then another six at the second tier, and another six at the third tier. We concentrate only on the first tier of six co-channel since the co-channel cells at the first tier dominate the interference [5]. Let the distance between the two adjacent co-channel cells be called D. The cell radius is R. A required D/R ratio for avoiding co-channel interference is called co-channel interference reduction factor q_s

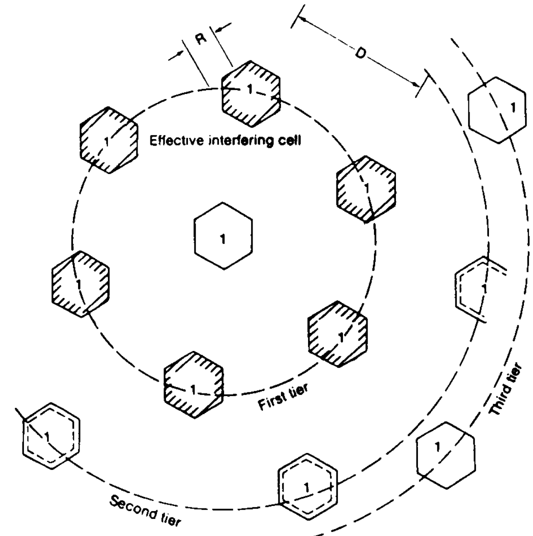

Fig. 1. Six effective interfering cells of cell 1.

$$q_s = (D/R)_s.$$

q_s can be found from the required $(C/I)_s$ as shown in the following derivation. Since the interference in a worst case comes from six dominate interferers, then the C/I can be expressed as

$$C/I = \frac{C}{\sum_{k=1}^{6} I_k + n} \tag{1}$$

where C is the received carrier power in a desired cell, n is the local noise, and I_k is the interference from one of six co-channel cells at the first tier. There are two conditions to be

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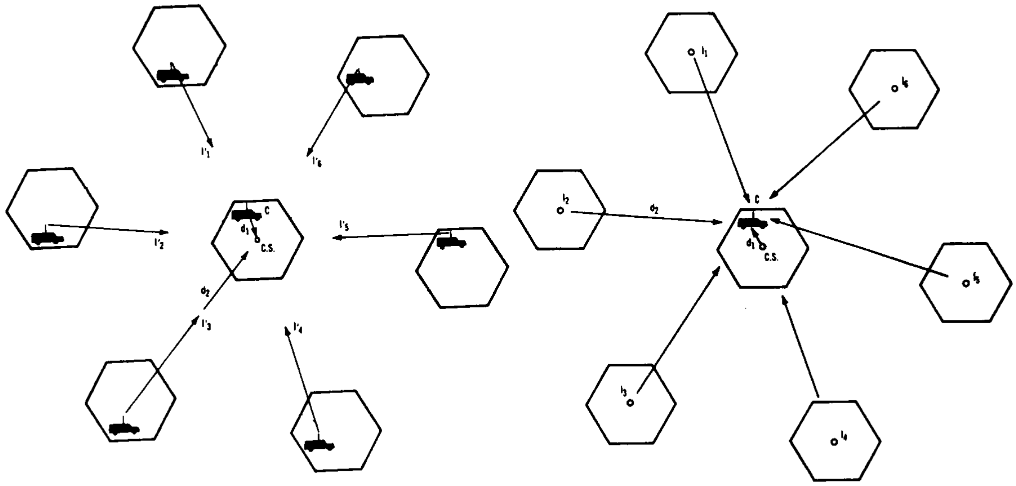

(a) (b)

Fig. 2. Interference scenario. (a) Case 1: at a desired cell site. (b) Case 2: at a desired mobile unit.

disclosed as shown in Fig. 2. One is all the co-channel mobile units interference with the desired cell site, and the other condition is all the co-channel cell sites interference with the desired mobile unit.

For our analysis, let

$$C = \mathcal{L} R^{-\gamma} \tag{2}$$

and

$$I_k = \mathcal{L} D_k^{-\gamma} \tag{3}$$

where D_k is the distance from a transmitter (at cell site or mobile unit) of a kth co-channel cell to a receiver (at cell site or mobile unit) located in the center cell as shown in Fig. 1. γ is the path loss slope in a mobile radio environment, $\mathcal{L}$ is a constant. The local noise n can be neglected. Substituting (2) and (3) into (1) yields

$$C/I = \frac{R^{-\gamma}}{\sum_{k=1}^{6} D_k^{-\gamma}}. \tag{4}$$

Since all D_k are not much different from D, which is the separation between two co-channel cell sites, we let $D_k = D$ for simplifying the derivation in (4) be

$$C/I = \frac{R^{-\gamma}}{6 \cdot D^{-\gamma}}. \tag{5}$$

Assume that all C/I values have to be greater than $(C/I)_s$, then

$$\frac{1}{6}\left(\frac{R}{D}\right)^{-\gamma} \geq \left(\frac{C}{I}\right)_s \tag{6}$$

or

$$\left(\frac{R}{D}\right)_s^{-\gamma} = 6\left(\frac{C}{I}\right)_s. \tag{7}$$

The co-channel interference reduction factor q_s is obtained from

$$q_s = \left(\frac{D}{R}\right)_s = \left(6\left(\frac{C}{I}\right)_s\right)^{1/\gamma}. \tag{8}$$

Let K be a number of cells in a frequency reuse pattern. Then the relationship between q_s and K can be found from the hexagon-cell configuration as [3]

$$q_s \triangleq \sqrt{3K}. \tag{9}$$

The radio capacity is defined by [4]

$$m = \frac{B_t}{B_c \cdot K} \quad \text{number of channels /cell} \tag{10}$$

where B_t is the total allocated spectrum for the system. In the present cellular, B_t = 12.5 MHz for each carrier operator and B_c is the channel bandwidth. Substituting (8) and (9) into (10) results in

$$m = \frac{B_t}{B_c \frac{q_s^2}{3}} = \frac{B_t}{B_c\left(\frac{6}{3^{\gamma/2}} \cdot \left(\frac{C}{I}\right)_s\right)^{2/\gamma}}. \tag{11}$$

In the mobile radio environment, we may assume a fourth power rule, i.e., $\gamma = 4$ [6], then (11) becomes

$$m = \frac{B_t}{B_c\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_s}} \quad \text{number of channels/cell.} \tag{12}$$

Equation (12) is called radio capacity by Lee [4]. It is the most general equation. From this equation, we can convert to a different representation of radio capacity m from a dimension generally known as the number of channels per cell.

III. Different Units Representing Radio Capacity

The radio capacity m, in general, is quantified by the number of channels per cell. With different given conditions, the radio capacity also can be represented in different units.

Case 1 Assume that a given blocking probability (grade of service) is P_B in the system. The radio capacity m_1 will be obtained from Erlang B model by inserting the number of channels per cell m and the blocking probability P_B as follows:

$$m_1 = f(m, P_B) \text{ [Erlang/cell]}.$$

The notation $f(x)$ means a function of x.

Case 2 Assume that a cell area A_1 is in square miles, the radio capacity m_2 will be represented by

$$m_2 = f(m_1, A_1) = f(m, P_B, A_1)$$
$$\text{[Erlang/m}^2 \text{ or Erlang/km}^2\text{]}.$$

Case 3 Assume that an average holding time per each call is T, then the radio capacity can be represented by

$$m_3 = f(m_2, T) = f(m, P_B, A_1, T)$$
$$\text{[number of calls/h/mi}^2\text{]}.$$

Case 4 Assume that the average calls per user in a busy hour is k, the radio capacity can be represented by

$$m_4 = f(m_3, k) = f(m, P_B, A_1, T, k)$$
$$\text{[number of users/mi}^2\text{]}.$$

Case 5 Assume that the total area in a system is A_t in square miles. The radio capacity can be represented by

$$m_5 = f(m_4, A_t) = f(m, P_B, A_1, T, k, A_t)$$
$$\text{[number of users in a system]}.$$

Example: Let m = 45 channels/cell, P_B = 0.02, A_1 = 12.5 mi^2 (i.e., cell radius R = 2mi), T = 100 s, k = 0.8 calls/user in a busy hour, and A_t = 7000 mi^2 wide covered by a system, then using Erlang B model, we obtain m_1 = 35.6 Erlang/cell in an omnidirectional-antenna cell. If a three-sectorized cell uses three 120° directional antennas, one antenna per sector, each sector operates 15 channels, then the Erlang/sector is 9 and $m_1 = 3 \times 9 = 27$ Erlang/cell.

kind of cells	m	m_1	m_2	m_3	m_4	m_5
omnicell	45	35.6	2.86	103	128.75	901250
directional cell	45	27	2.16	77.8	97.25	680750

The other representation of radio capacity such as m_6 (number of calls/h/cell), m_7 (number of users/cell in a busy hour) and m_8 (number of uses/channel in a busy hour) can also be derived from the general radio capacity m

$$m_6 = f(m_1, T) = f(m, P_B, T)$$
$$m_7 = f(m_6, k) = f(m, P_B, T, k)$$
$$m_8 = f(m_6, m).$$

Using the same values shown in the example above, the results of m_6, m_7, and m_8 are

kind of cells	m	m_6	m_7	m_8
omnicell	45	1281.6	1602	35.6
directional cell	45	972	1215	27

The above example illustrates all the different presentation units that can be generated from the number of channels per cell.

IV. Radio Capacities of FM Channels Versus Narrowbanding Channels [1], [7]

A. Radio Capacity of 30 kHz FM Channels

Assume that a 30 kHz FM receiver has a two-branch diversity with a preemphasis/deemphasis device. The required C/I of 18 dB of this receiver can be obtained through a subjective test with a criterion that 75 percent of the listeners evaluate the voice quality as good and excellent while driving in a mobile radio fading environment with various vehicle speeds. From a required C/I, $(C/I)_s$, of 18 dB, we can determine the required signal-to-noise (S/N) ratio at the baseband by the following calculation.

In the fading environment, a 30 kHz FM receiver without a diversity scheme and a preemphasis-deemphasis device, the C/I = 18 dB is converted to the S/N = 15 dB [8] shown in Fig. 3. The improvement of FM with preemphasis/deemphasis is [9], [10]

$$P_{\text{FM}} = \frac{(W_1/W_2)^2}{3} = \frac{(3000 \text{ Hz}/300 \text{ Hz})^2}{3} = 33.3(=)15 \text{ dB}. \quad (13)$$

W_1 and W_2 are the two ends of a voice band. The notation $(=)$ means a conversion between a decibel and a linear ration. The advantage of two-branch diversity receiver is that the baseband signal-to-noise ratio of a two-branch FM shows an 8 dB improvement over the S/N ratio of a single FM channel [3, p. 311] based on a 90% signal level. Then the baseband signal-to-noise ratio of a two-branch FM receiver with a preemphasis/deemphasis device is

$$(\text{S/N})_{2Br\ \text{FM}} = -3 + P_{\text{FM}} + \text{diversity gain} + (C/I)_{\text{FM}}$$
$$= 38.2 \text{ dB}. \quad (14)$$

This is an expected level for a reasonable voice quality [11, p. 371]. For introducing a parameter $\eta = (C/N)\cdot(B_c/W_1)$ then the baseband $(S/N)_{\text{FM}}$ in a nonfading case can be expressed as [11]

$$(\text{S/N})_{\text{FM}} = \frac{3}{8}\left(\frac{B_c}{W_1}\right)^2 \cdot \eta = \frac{3}{8}\left(\frac{B_c}{W_1}\right)^3 \cdot \left(\frac{C}{N}\right)_{\text{FM}} \quad (15)$$

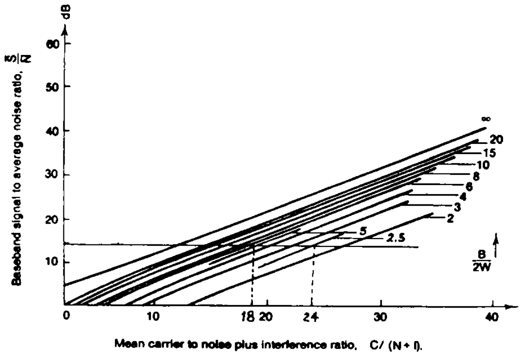

Fig. 3. C/I versus S/N of FM channels fading environment.

where $W_1 = 3000$ Hz. Equation (15) is plotted in Fig. 4. For a 30 kHz FM channel, $B_c/W_1 = 10$ and $S/N = 38$ dB corresponding to $C/N = 12.5$ dB in a nonfading case.

In a fading environment, as we have mentioned, a requirement of $(C/N)_s$ or $(C/I)_s$ has to be 18 dB in a two-branch diversity receiver equipped with a preemphasis/deemphasis device to obtain the same voice quality as one requiring only a $(C/N)_s = 12.5$ dB in a nondiversity receiver with no preemphasis/deemphasis but operating in a nonfading environment.

To find a radio capacity of this 30-kHz FM receiver, only $(C/I)_s$ and B_c are needed. But keep in mind that $(C/I)_s = 18$ dB at the RF band is equivalent to $S/N = 38$ dB at the baseband. Substituting $(C/I)_s = 63$ (which is 18 dB), $B_c = 30$ kHz, and $B_t = 12.5$ MHz into (12), then

$$m = \frac{B_t}{B_c\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_s}} = 64.3 \text{ channels/cell.} \tag{16}$$

B. Radio Capacity of 3-kHz SSB Channels

When a 30-kHz FM channel is replaced by six 3-kHz single sideband (SSB) channels, the channel efficiency counted by the number of channels increases six times. However, the spectrum efficiency of these two systems remains the same as shown below.

The SSB receiver is a linear modulation receiver [12]. It means that the required $(C/I)_s$ value at the RF will be the same value of S/N at the baseband. For calculating the $(C/I)_s$ of a SSB receiver for the same voice quality as the $(C/I)_s = 18$ dB of a 30-kHz FM receiver, we simply use

$$(S/N)_{\mathrm{FM}} = (S/N)_{(\mathrm{SSB})} = 38 \text{ dB.} \tag{17}$$

Since $B_c = 3$ kHz, $W_1 = 3$ kHz then the parameter η can be simplified as $\eta = (C/I)\cdot(B_c/W_1) = C/N$. In a nonfading case [11]

$$(S/N)_{\mathrm{SSB}} = (C/N)_{\mathrm{SSB}} = 38 \text{ dB.} \tag{18}$$

Equation (18) is plotted in Fig. 4. $(C/I)_{\mathrm{SSB}} = 38$ dB is needed for a qualified voice quality in a nonfading case [12]. Normally $(C/I)_{\mathrm{SSB}}$ in a fading case should be higher than 38 dB just as the same $(C/I)_{\mathrm{FM}}$ in a fading case is higher than that in a nonfading case. We may apply $(C/I)_{\mathrm{SSB}} = 38$ dB in a fading case if the best fading-remove scheme is used, i.e., $(C/I)_{\mathrm{SSB}} = 38$ dB can be used as if in a nonfading case. Substituting $B_c = 3$ kHz, $(C/I)_s = 38$ dB into (12). The radio capacity m becomes

$$m = \frac{B_t}{B_c\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_s}} = 64.25 \text{ channels/cell.} \tag{19}$$

Comparing the radio capacities of both 30-kHz FM channels shown in (16) and 3-kHz SSB channels shown in (19), we found that they are almost the same. Therefore, the spectrum efficiencies of the two systems are the same.

C. Radio Capacity of 15 kHz FM Channels

When a 30-kHz FM channel is split into two 15-kHz FM channels, the channel efficiency is increasing by two. However, the spectrum efficiencies of using two different channel bandwidths in an FM system are the same. The explanation is shown as follows.

The FM is an exponential modulation, C/I at the RF band is not linearly proportional to S/N at the baseband as shown in Fig. 3. The $(C/I)_s = 24$ dB of a 15 kHz channel is equivalent to $(C/I)_s = 18$ dB of a 30-kHz channel to obtain the same S/N as depicted in Fig. 3. Now assume that the 15-kHz FM channel uses the same diversity scheme and preemphasis/deemphasis device, then let $C/I = 24$ dB, $B_c = 15$ kHz and $B_t = 12.5$ MHz, the radio capacity m of this 15-kHz FM system can be found from (12) as

$$m = \frac{B_t}{B_c\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_s}} = 64.3 \text{ channels/cell.} \tag{20}$$

Comparing (20) with (16), we find that the number of channels per cell does not increase by splitting every 30-kHz channel in half.

From (16), (19), and (20), we may conclude that in analog cellular systems, splitting channels does not increase the spectrum efficiency. Moreover, when splitting channels, due the increase of $(C/I)_s$, the size of cells is reduced. With a given transmitted power at each cell site, more cells are needed in a given area [1]. Therefore, no advantages of splitting analog channels in an analog cellular system.

V. Radio Capacity in Digital Cellular Channels

In digital cellular systems because the voice waveforms can be treated digitally and protected by adding channel coding which can protect different levels of important bits for a low bit-rate transmission. Since the nature of digital signals are not susceptible to the interference, the required $(C/I)_s$ in digital cellular can be lower than that in analog systems for a same voice quality as we have found [13]–[15]. In digital cellular systems, the $(C/I)_s$ is about 10 to 12 dB for a 30 kHz bandwidth and about 16 to 18 dB for a 10-kHz bandwidth. Based on these figures, Table I can be generated.

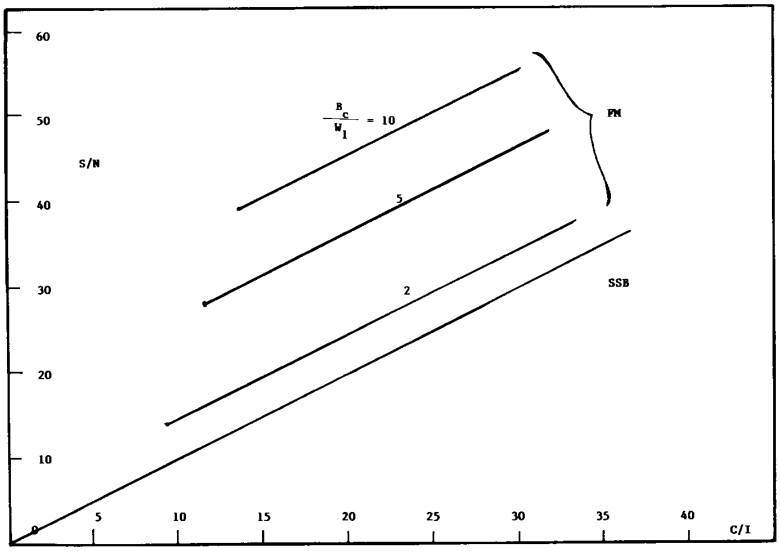

Fig. 4. C/I versus S/N in nonfading case.

TABLE I
DIGITAL CELLULAR CHANNELS

Channel Bandwidth (kHz)	$(C/I)_s$ (dB)	K	D/R	m
30	10	2.58	2.78	161.5
	12	3.27	3.13	127.42
10	16	5.16	3.93	242.25
	18	6.48	4.41	192.9

The increase in spectrum efficiency by using digital cellular channels can be shown in the above table by comparing the radio capacities m with the value shown in (16). Also the concept of increasing spectrum efficiency can be expressed by either keeping a channel bandwidth of 30 kHz and lowering a value of required C/I; or keeping a required C/I of 18 dB and narrowing a channel bandwidth.

VI. Evaluation of Different Digital Systems

Since the different digital techniques have been applied on the speech codings, channel codings, and modulations with different channel bandwidths specified in individual systems, $(C/I)_s$ of each proposed digital system should be determined by a subjective test [15] through a standard voice-quality evaluation center. After the $(C/I)_s$ is found then a fair evaluation method can be used.

A. Conversion of $(C/I)_s$

Since each digital cellular system has different $(C/I)_s$ and B_c, we can convert $(C/I)_s$ into equivalent $(C/I)_s'$ if new B_c' is different from B_c by the following equation:

$$(C/I)' = (C/I)\left(\frac{B_c}{B_c'}\right)^2. \tag{21}$$

Equation (21) is derived from (12).

B. Evaluation Method

The evaluation method can be illustrated as follows:

Input: manufacture A $B_c = 18$ kHz $(C/I)_s = 17$ dB
manufacture B $B_c = 25$ Hz $(C/I)_s = 13$ dB
manufacture C $B_c = 15$ kHz $(C/I)_s = 20$ dB.

Normalization and Evaluation

Converting all B_c to 15 kHz, then three $(C/I)_s$ change to

manufacture A $B_c = 15$ $(C/I)_s = 1.58 + 17 + 18.58$ dB
manufacture B $B_c = 15$ $(C/I)_s = 4.4 + 13 = 17.3$ dB
manufacture C $B_c = 15$ $(C/I)_s = 20$ dB.

Since the smallest value of $(C/I)_s$ provides the largest radio capacity (see (12)), manufacture B gives the highest spectrum efficiency.

VII. Concepts of Spectrum Efficiency in Cellular

A. Relation Between (C/I) and B_c

We have seen from (21) that by maintaining the same voice quality the channel bandwidth reduces by half, and $(C/I)_s$ increases by four times.

B. Simularity Between Channel Capacity and Radio Capacity

Shannon's well-known channel capacity is expressed as

$$\hat{C} = B_c \log_2 (1 + C/I). \tag{22}$$

Interestingly enough, both the radio capacity m shown in (12) and the channel capacity C shown in (22) involve two parameters B_c and C/I.

The relationship between two different sets of B_c and C/I in channel capacity is (from (22))

$$\frac{\log_2\left(\frac{C}{I}\right)}{\log_2\left(\frac{C}{I}\right)'} = \frac{B_c'}{B_c}. \tag{23}$$

Equation (23) shows that B_c reduces by half, (C/I) increases by squaring itself, i.e.,

$$(C/I)' = (C/I)^2. \tag{24}$$

Since the radio capacity shown in (21) and the channel capacity shown in (22) both involve C/I and B_c, the relationship of C/I and B_c shown in radio capacity (see (21)) and that in channel capacity (see (23)) are similar. Therefore the radio capacity is named.

C. Relationship Between E_b/N_o and B_c in Digital Cellular

The C/I in digital systems can be expressed as

$$C/I = \frac{E_b \cdot R_b}{I} = \frac{E_c \cdot R_c}{I} \tag{25}$$

- R_b rate of speech coding
- E_b energy per bit of each speech coding bit
- R_c rate of channel coding
- E_c energy per bit of each channel coding bit.

Then

$$\begin{array}{ccccc} C/I & \Leftarrow & \dfrac{E_c \cdot R_c}{I} & \Leftarrow & \dfrac{E_b \cdot R_b}{I} \\ \text{determined from the subjective test} & & \text{applied in fading case} & & \text{applied in nonfading case.} \end{array} \tag{26}$$

Substituting (26) into (21) yields

$$C/I\,(C/I)' = \frac{E_c R_c / I}{E_c' R_c' / I'} = \left(\frac{B_c'}{B_c}\right)^2. \tag{27}$$

Assume that the interference level I is the same in the environment, then (27) becomes

$$\frac{E_c R_c}{E_c' R_c'} = \left(\frac{B_c'}{B_c}\right)^2. \tag{28}$$

Since the linear relationship between R_c and B_c always holds

$$R_c = kB_c, \quad R_c' = kB_c'.$$

Then (28) becomes

$$E_c E_c' = (B_c'/B_c)^3. \tag{29}$$

Equation (29) shows that if B_c is reduced by half, the energy per bit has to increase eight times.

VIII. Analysis on Spectrum Efficiency for FDMA and TDMA in an Ideal Case

We may compare the spectrum efficiency between frequency division multiple access (FDMA) and time division multiple access (TDMA) in theory as follows.

A.

In FDMA, the total allocated bandwidth B_t can be divided by M channels. The radio capacity m in (12) is

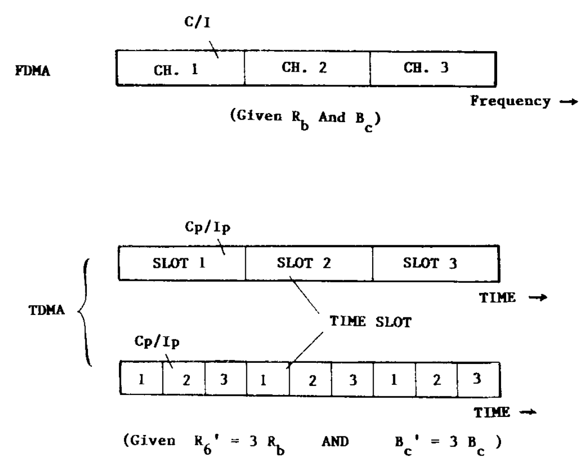

Fig. 5. Multiple access schemes, FDMA versus TDMA.

$$m = \frac{B_t}{\frac{B_t}{M}\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_s}} = \frac{M}{\sqrt{\frac{2}{3}\left(\frac{C}{I}\right)_s}}. \tag{30}$$

A three-channel FDMA with $B_t = 30$ kHz and $M = 3$ is illustrated in Fig. 5. Now both the carrier and the interference can be expressed, respectively, as

$$C = E_b \cdot R_b \tag{31}$$

and

$$I = I_0 \cdot B_c \tag{32}$$

where R_b is the transmission rate, E_b is the energy per bit, and I_0 is the interference (power) per hertz. For comparing the spectrum efficiency between FDMA and TDMA in a simple manner, we may use 10-kHz FDMA channels and 30-kHz TDMA channels. Let the notations used in (31) and (32) represent the parameters for a 10 kHz FM channel. The following notations are for the 30-kHz TDMA channels.

$$C' = E_b \cdot R_b' \tag{33}$$

$$I' = I_0 \cdot B_c'. \tag{34}$$

Note that E_b and I_0 are the same for both channel bandwidths.

B.

For easier understanding in TDMA, we may also have to show the calculation of radio capacity from the example depicted in Fig. 5. The radio capacities between the following two multiple access schemes need to be compared:

1) (M = three channels, B_c = 10 kHz, and R_b = 10 kbps)
2) TDMA (S = three time slots, B_c' = 30 kHz, and R_b' = 30 kbps).

The received carrier-to-interference ratio C_p/I_p at a TDMA 30-kHz channel is only measured in its 333 ms time in a second.[1] It can be equivalent to the C/I of a 10-kHz FDMA channel as

$$C_p = \frac{10 \text{ Kb} \cdot E_b}{\frac{1}{3} \text{ s}} = 3 \text{ (10 kbps) } E_b = 3R_bE_b = 3C \quad (35)$$

and

$$I_p = I_0 \frac{10 \text{ K cycles}}{\frac{1}{3} \text{ s}} = I_0 \cdot B_c' = I' = 3I. \quad (36)$$

The carrier-to-interference ratio $(C/I)_p$ in 333 ms of a second is the same as the (C/I) of an FDMA 10-kHz channel.

$$\frac{C_p}{I_p} = \frac{C'}{I'} = \frac{C}{I}. \quad (37)$$

Substituting (37) into (30) indicates that FDMA and TDMA have the same radio capacity, and therefore, the same spectrum efficiency. However, the power of a TDMA signal has to be three times (or 5 dB) higher than that of a FDMA signal. If a TDMA signal has k time slots and a bandwidth of kB_c, where B_c is the FDMA channel bandwidth, then the required power for TDMA is

$$C_p = C' = 10 \log k + C \quad \text{(in dB)}. \quad (38)$$

It means that the required power of a TDMA is 10 log k higher than that of a FDMA signal.

IX. Summary and Conclusion

A general radio capacity equation for cellular system was derived. It involves two parameters; channel bandwidth and the required carrier-to-interference ratio. Its dimension is number of channels per cell. The spectrum efficiency can be measured from the radio capacity formula. The radio capacity can be also represented in various units with additional given information. Using the radio capacity, we have proved that splitting analog channels does not increase the spectrum efficiency.

The concept of spectrum efficiency in cellular is also described. Use of digital cellular channels shows a higher spectral efficient than use of analog cellular channels. A simple evaluation method of spectrum efficiency is introduced in judging different digital systems. The similar nature of channel capacity and radio capacity has been mentioned. From radio capacity, we may conclude that maintaining the same voice quality reduces the channel bandwidth by half, increases $(C/I)_s$ four times, or increases the energy per bit eight times.

[1] A three time-slot TDMA system means that three slots serve three different users. The number of time slots in one second can be a number of multiples of three. However, the total time spent for each user in one second is always 333 ms.

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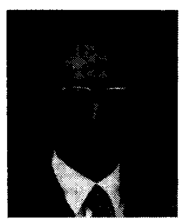

William C. Y. Lee (M'64–SM'80–F'82) received the B.Sc. degree from the Chinese Naval Academy, Taiwan, and the M.S. and Ph.D. degrees from The Ohio State University, Columbus, in 1954, 1960, and 1963, respectively.

From 1959 to 1963 he was a Research Assistant at the Electroscience Laboratory, The Ohio State University. He was associated with Bell Laboratories from 1964 to 1979 where he was concerned with the study of wave propagation and systems, millimeter and optical wave propagation, switching systems, and satellite communications. He developed a UHF propagation model for use in planning the Bell System's new Advanced Mobile Phone Service and was a pioneer in mobile radio communication studies. He applied the field component diversity scheme over mobile radio communication links. While working in satellite communications, he discovered a method of calculating the rain rate statistics which would affect the signal attenuation at 10 GHz and above. He successfully designed a 4 × 4 element printed circuit antenna for tryout use. He studied and set a 3-mm-wave link between the Empire State Building and Pan American Building in New York City, experimentally using the newly developed IMPATT diode. He also studied the scanning spot beam concept for satellite communication using the adaptive array scheme. From April 1979 until April 1985 he worked for ITT Defense Communications Division and was involved with advanced programs for wiring military communications systems. He developed several simulation programs for the multipath fading medium and applied them to ground mobile communication systems. In 1982 he was Manager of the Advanced Development Department, responsible for the pursuit of new technologies for future communication systems. He developed an artificial intelligence application in the networking area and filed a patent application before leaving ITT. He joined PacTel Mobile Companies in 1985, where he is engaged in the improvement of system performance and capacity.