SYSTEM ARCHITECTURE
ADVANCED SYSTEM ARCHITECTURE
BATEMAN
Chapter2: Data transmission fundamentals

2013/Fall-Winter Term
Monday 12:50

Room# 1-322 or 5F Meeting Room

Instructor: Fire Tom Wada, Professor

Chapter2: Data transmission fundamentals

2.1 Factor affecting system design

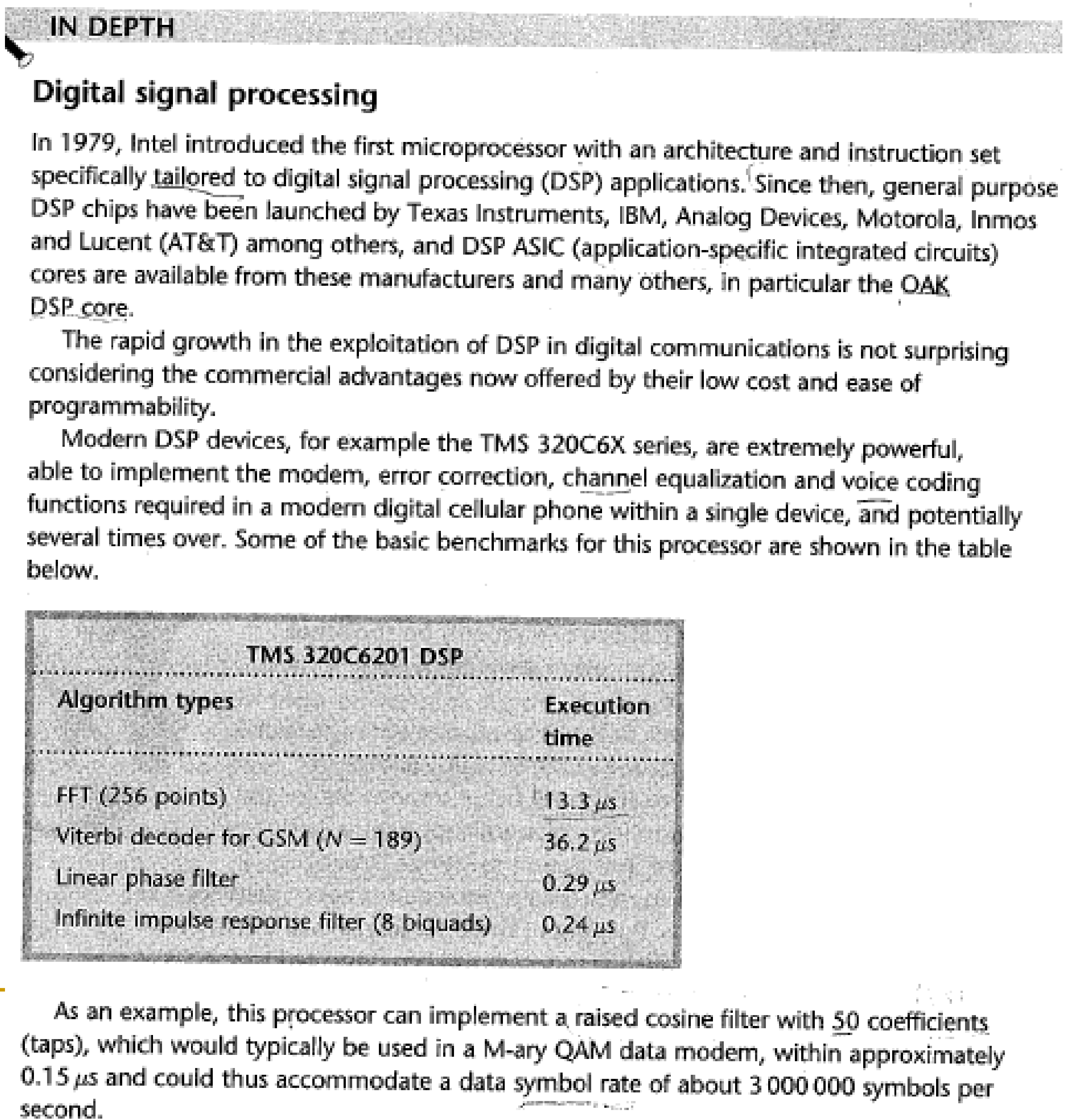
2.2 Data transmission fundamentals

2.3 Multi-level signaling (M-ary signalling)

2.4 Calculation of channel capacity

2.1 Factor affecting system design

1. Hardware and Software availability
   - Key is Digital Signal Processing



IN DEPTH

Digital signal processing

In 1979, Intel introduced the first microprocessor with an architecture and instruction set specifically tailored to digital signal processing (DSP) applications. Since then, general purpose DSP chips have been launched by Texas Instruments, IBM, Analog Devices, Motorola, Inmos and Lucent (AT&T) among others, and DSP ASIC (application-specific integrated circuits) cores are available from these manufacturers and many others, in particular the OAK DSP core.

The rapid growth in the exploitation of DSP in digital communications is not surprising considering the commercial advantages now offered by their low cost and ease of programmability.

Modern DSP devices, for example the TMS 320C6X series, are extremely powerful, able to implement the modem, error correction, channel equalization and voice coding functions required in a modern digital cellular phone within a single device, and potentially several times over. Some of the basic benchmarks for this processor are shown in the table below.

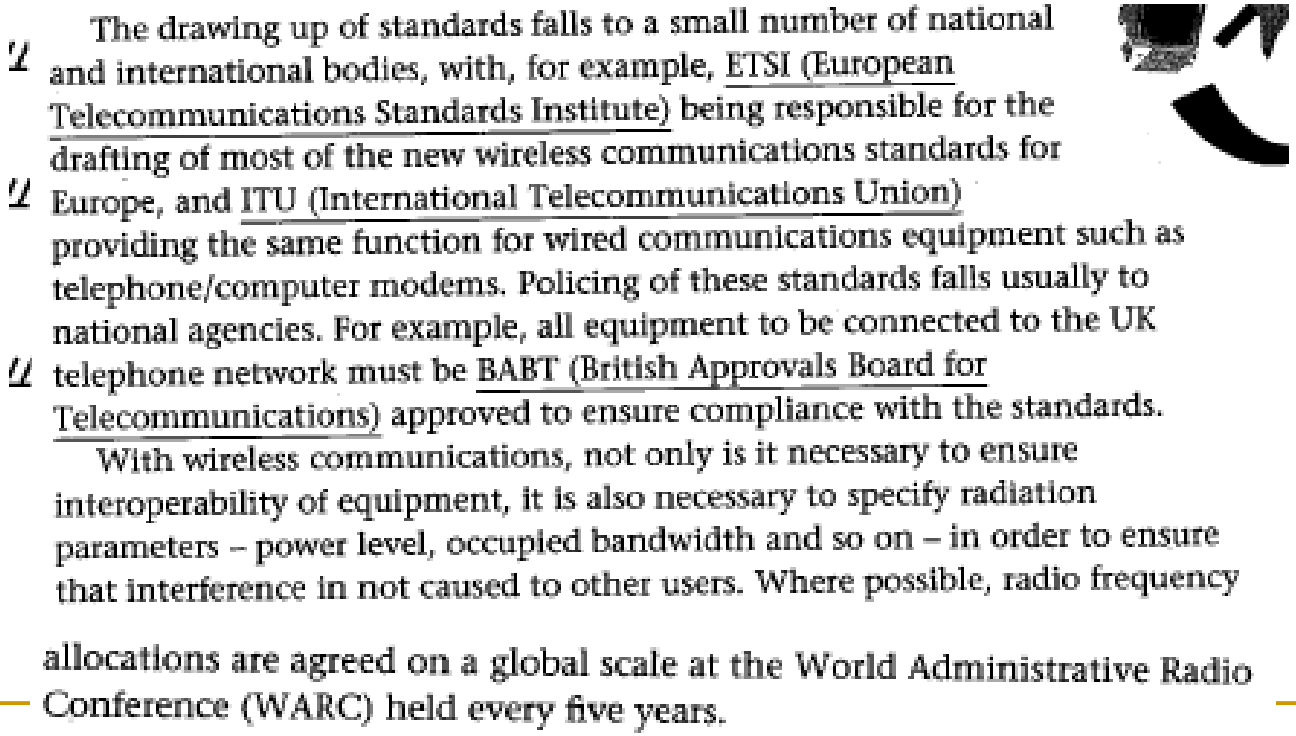
TMS 320C6201 DSP

Algorithm types	Execution time
FFT (256 points)	13.3 μs
Viterbi decoder for GSM ($N = 189$)	36.2 μs
Linear phase filter	0.29 μs
Infinite impulse response filter (8 biquads)	0.24 μs

As an example, this processor can implement a raised cosine filter with 50 coefficients (taps), which would typically be used in a M-ary QAM data modem, within approximately 0.15 μs and could thus accommodate a data symbol rate of about 3 000 000 symbols per second.

2.1 Factor affecting system design

2. Power consumption
3. Component Size
4. Government regulations and standards



The drawing up of standards falls to a small number of national and international bodies, with, for example, ETSI (European Telecommunications Standards Institute) being responsible for the drafting of most of the new wireless communications standards for Europe, and ITU (International Telecommunications Union) providing the same function for wired communications equipment such as telephone/computer modems. Policing of these standards falls usually to national agencies. For example, all equipment to be connected to the UK telephone network must be BABT (British Approvals Board for Telecommunications) approved to ensure compliance with the standards.

With wireless communications, not only is it necessary to ensure interoperability of equipment, it is also necessary to specify radiation parameters – power level, occupied bandwidth and so on – in order to ensure that interference in not caused to other users. Where possible, radio frequency allocations are agreed on a global scale at the World Administrative Radio Conference (WARC) held every five years.

2.1 Factor affecting system design

5. Commercial realities

Commercial realities

The reality of the communications market-place is that cost and appearance mean more to the consumer than the technology inside. Mobile phones sell on their style and talk time, rather than their receiver sensitivity or BER performance. This is an important lesson for engineers to grasp, for although some mobile phones are much better technically than others, all are simply assumed by the customer to work properly, and achieving technical excellence may not lead to excellent sales.

It is a difficult and challenging task to design a product that meets user expectations and needs without *over-engineering or under-engineering*, and all the cost, timescale and reliability issues that follow. It is hoped that this book will provide a good grasp of the design choices available to the digital communications engineer, from which a correctly engineered product can be achieved.

Chapter2: Data transmission fundamentals

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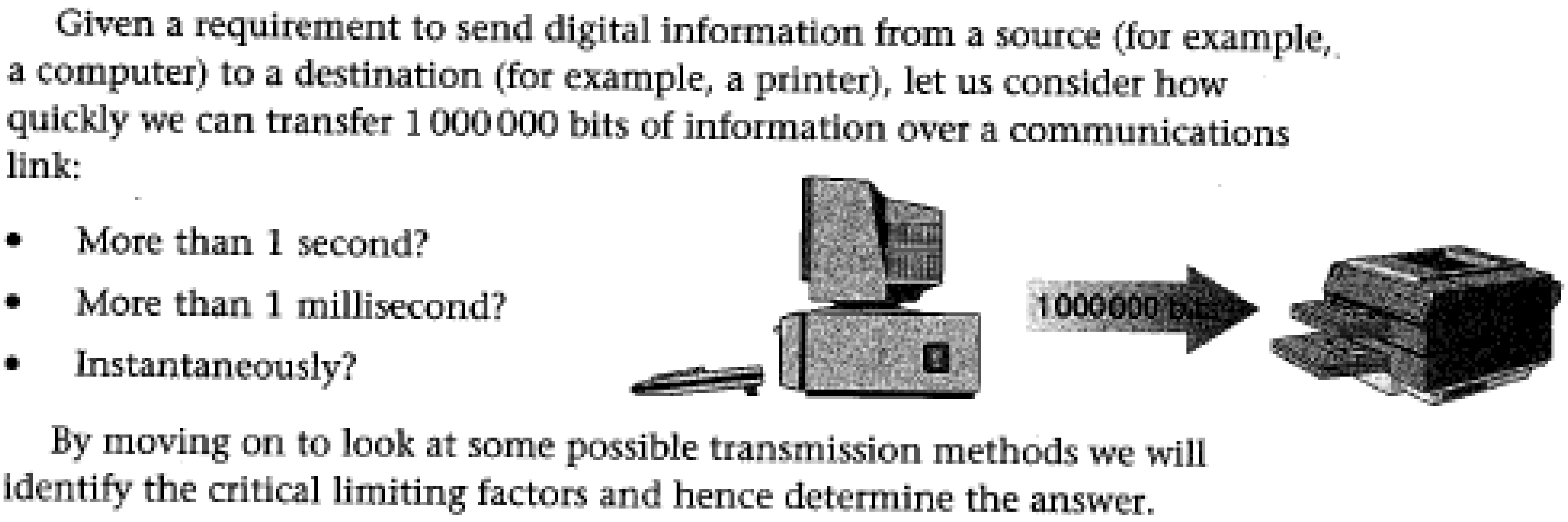
2.4 Calculation of channel capacity

How quickly can information flow?



Given a requirement to send digital information from a source (for example, a computer) to a destination (for example, a printer), let us consider how quickly we can transfer 1 000 000 bits of information over a communications link:

- More than 1 second?
- More than 1 millisecond?
- Instantaneously?

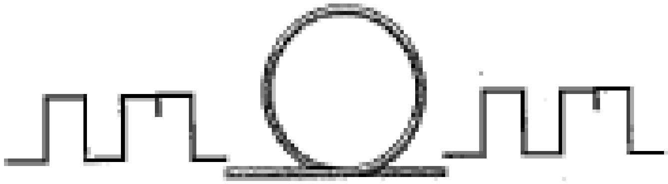
By moving on to look at some possible transmission methods we will identify the critical limiting factors and hence determine the answer.

- Methods of communication
  1. Binary signaling
  2. Multi-level signaling
  3. Multi-level symbol operation

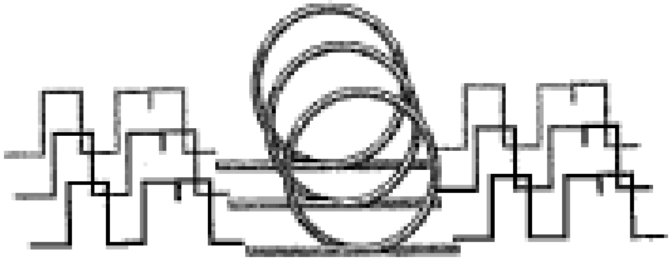
Binary signaling

Binary signalling

- **Binary signalling using a single cable**
  Here the transmission rate is determined by how fast the voltage (or other symbol type) can be varied on the channel, before the frequency content (as predicted by the Fourier series expansion (see Section 1.1)) is so high that the inevitable filtering of the channel attenuates and hence distorts too much of the signal. In other words, it is limited by the *bandwidth* of the link.



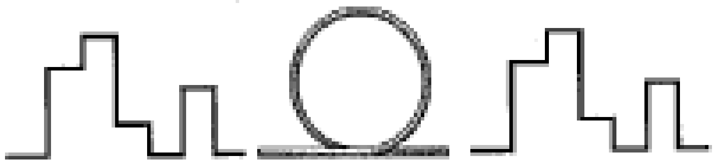
- **Binary signalling using many parallel cables**
  By using multiple cables, the throughput over the link can be increased in proportion to the number of cables (channels) used. Alternatively, the throughput can be maintained at that of the single binary link, allowing lower bandwidth (probably lower cost) links to be substituted.



Multi-level signaling

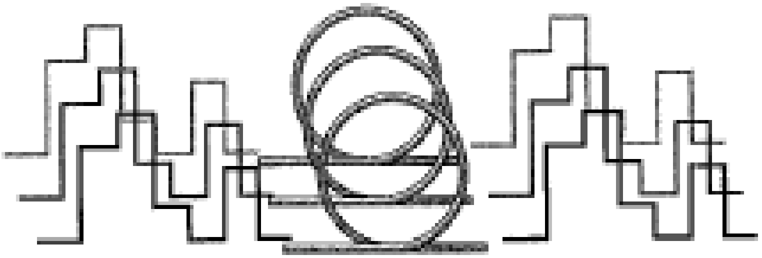
Multi-level signalling

- **Multi-level signalling using a single cable**
  There is no reason why data transmission should be limited to a binary (two symbol state) format over a channel, and in theory, it should be possible to use any number of voltage levels or symbol types.

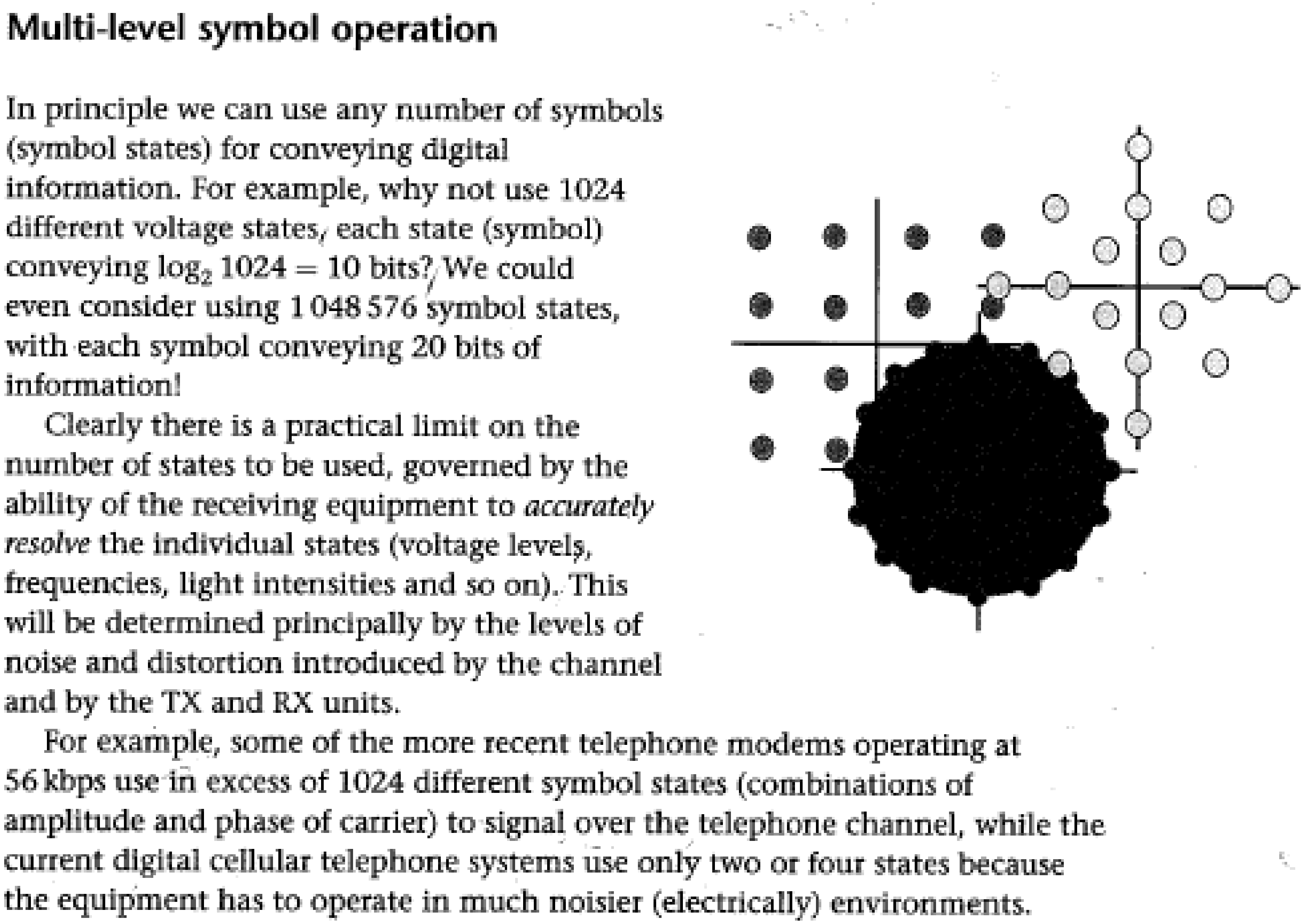


For example, using four voltage levels means that we can uniquely encode two bits into each of the four levels (00 = level A, 01 = level B, 10 = level C, 11 = level D). This means that every time we change the symbol state, two bits of information are conveyed compared with only one for the binary system. Hence, we can send information *twice as fast* for a given bandwidth of link, or use a link with *half the bandwidth* and maintain equivalent transmission rate.

- **Multi-level signalling using multiple cables**
  It is of course possible to use multi-level signalling (often termed *M-ary signalling*) over parallel channels if so desired, with the consequent increase in throughput or opportunity to reduce the bandwidth on each channel as required.



Multi-level symbol operation



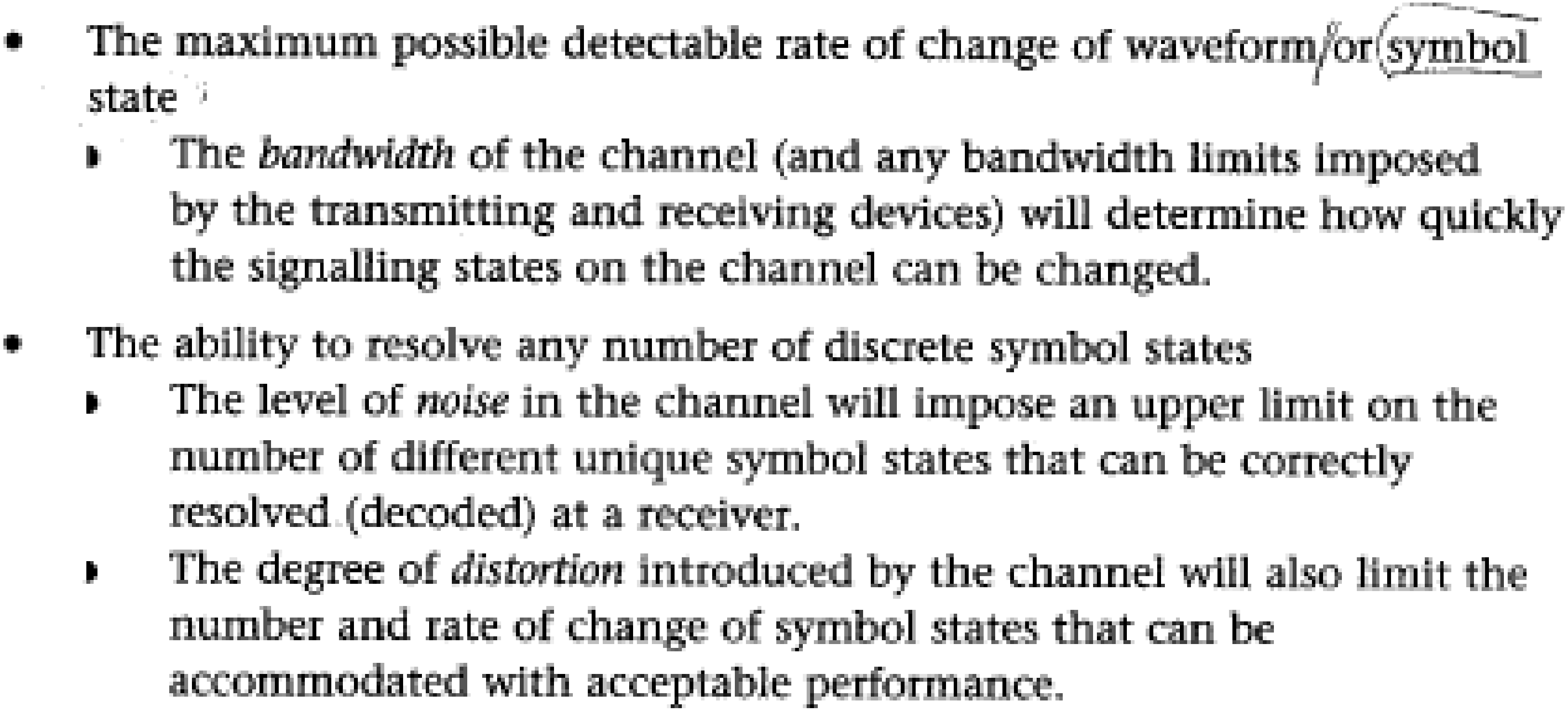
Multi-level symbol operation

In principle we can use any number of symbols (symbol states) for conveying digital information. For example, why not use 1024 different voltage states, each state (symbol) conveying $\log_2 1024 = 10$ bits? We could even consider using 1 048 576 symbol states, with each symbol conveying 20 bits of information!

Clearly there is a practical limit on the number of states to be used, governed by the ability of the receiving equipment to *accurately resolve* the individual states (voltage levels, frequencies, light intensities and so on). This will be determined principally by the levels of noise and distortion introduced by the channel and by the TX and RX units.

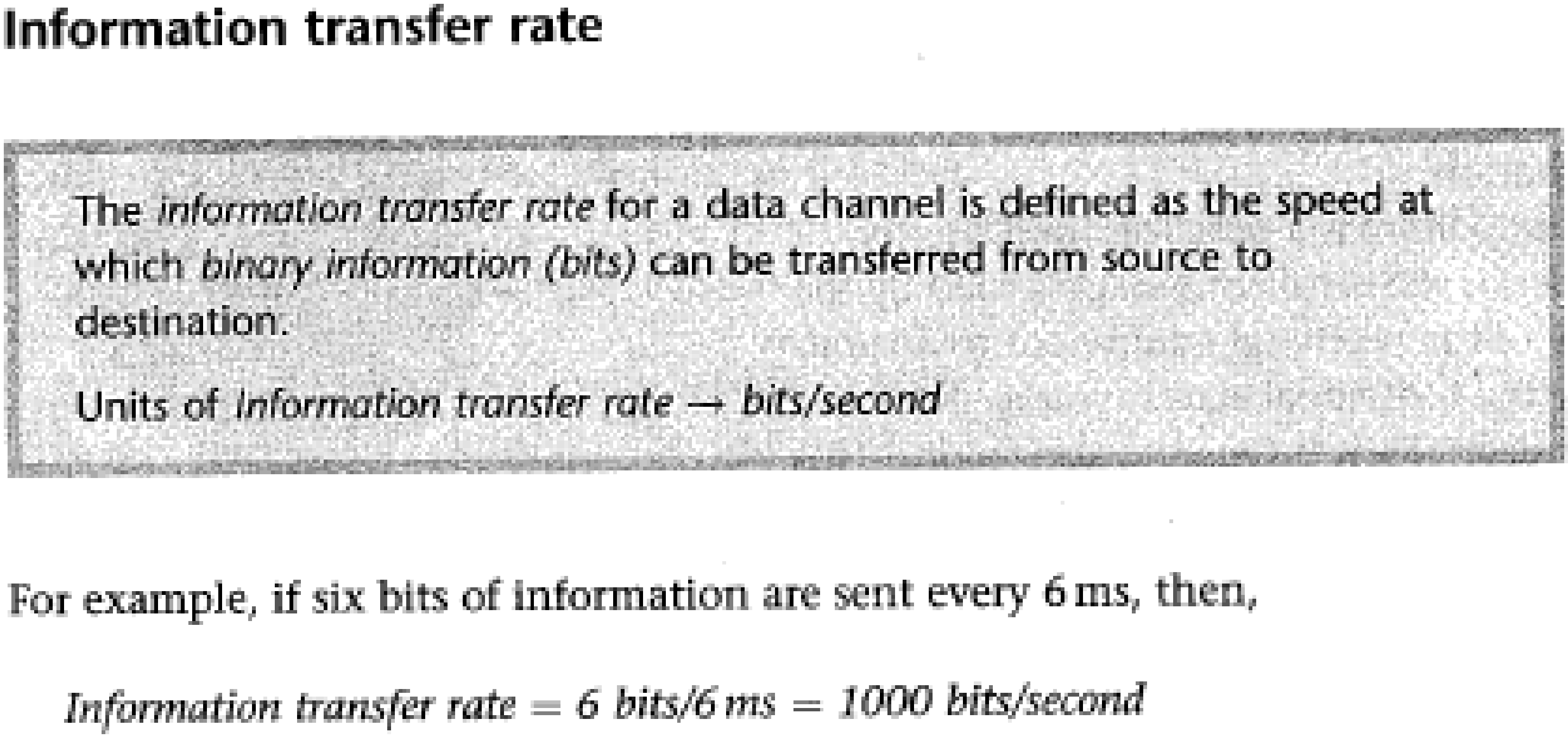
For example, some of the more recent telephone modems operating at 56 kbps use in excess of 1024 different symbol states (combinations of amplitude and phase of carrier) to signal over the telephone channel, while the current digital cellular telephone systems use only two or four states because the equipment has to operate in much noisier (electrically) environments.

How quickly can information flow? - TWO FACTORS-



- The maximum possible detectable rate of change of waveform/or symbol state
  - The *bandwidth* of the channel (and any bandwidth limits imposed by the transmitting and receiving devices) will determine how quickly the signalling states on the channel can be changed.
- The ability to resolve any number of discrete symbol states
  - The level of *noise* in the channel will impose an upper limit on the number of different unique symbol states that can be correctly resolved (decoded) at a receiver.
  - The degree of *distortion* introduced by the channel will also limit the number and rate of change of symbol states that can be accommodated with acceptable performance.

Some technical terms (1)



Information transfer rate

The *information transfer rate* for a data channel is defined as the speed at which *binary information (bits)* can be transferred from source to destination.

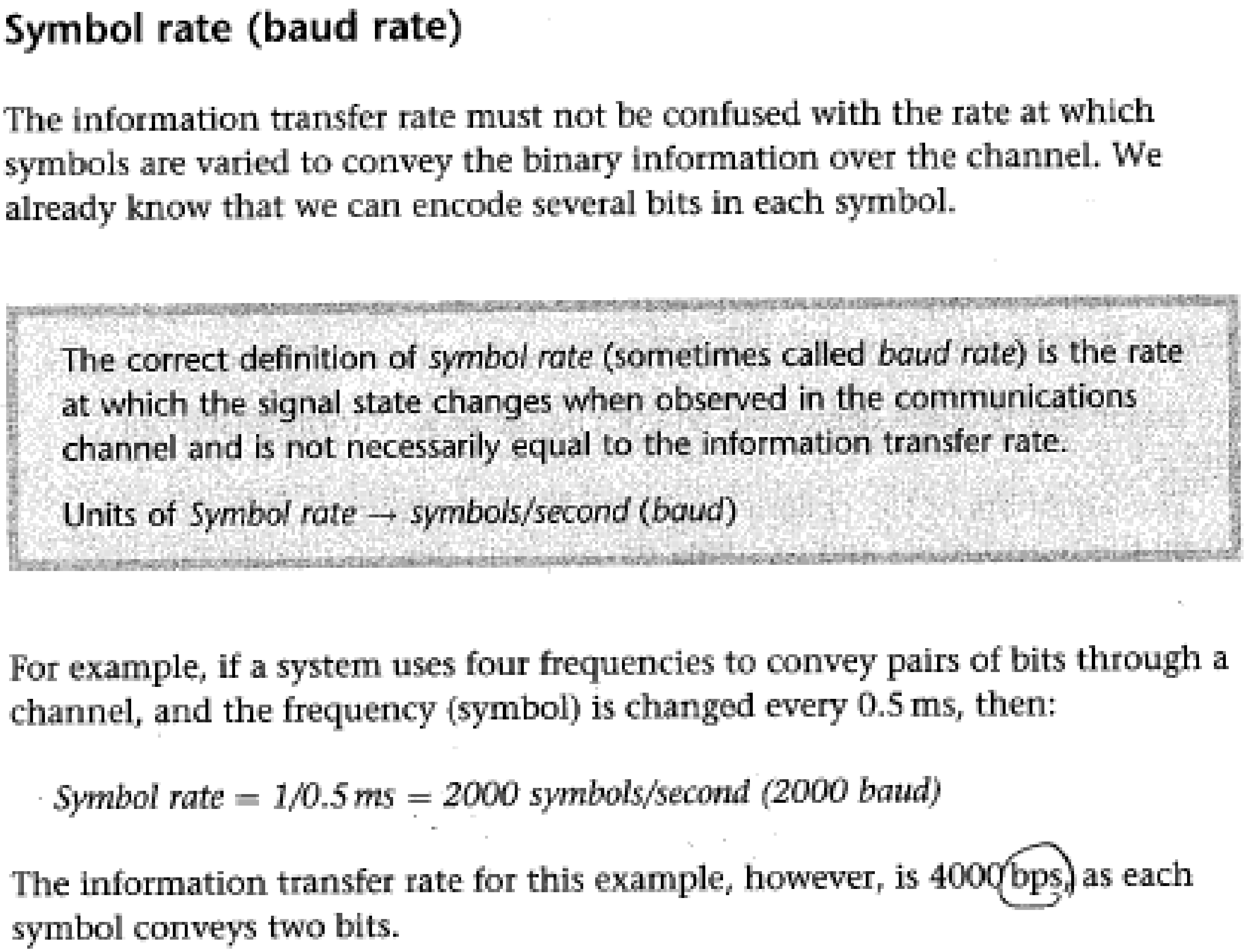
Units of *information transfer rate* → *bits/second*

For example, if six bits of information are sent every 6 ms, then,

Information transfer rate = 6 bits/6 ms = 1000 bits/second

1000 bps

Some technical terms (2)



Symbol rate (baud rate)

The information transfer rate must not be confused with the rate at which symbols are varied to convey the binary information over the channel. We already know that we can encode several bits in each symbol.

The correct definition of *symbol rate* (sometimes called *baud rate*) is the rate at which the signal state changes when observed in the communications channel and is not necessarily equal to the information transfer rate.

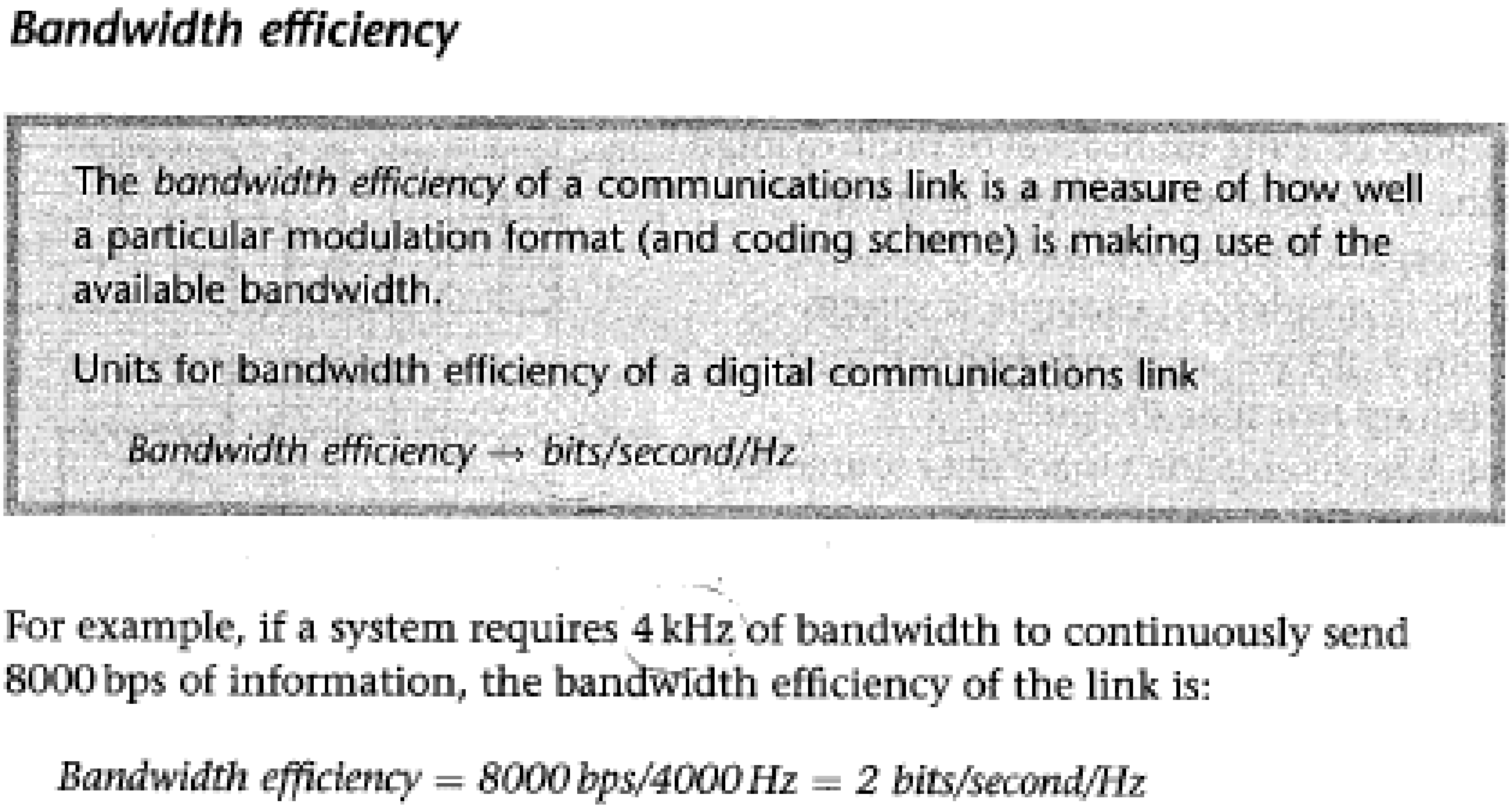
Units of *Symbol rate* → *symbols/second* (*baud*)

For example, if a system uses four frequencies to convey pairs of bits through a channel, and the frequency (symbol) is changed every 0.5 ms, then:

Symbol rate = *1/0.5 ms* = *2000 symbols/second (2000 baud)*

The information transfer rate for this example, however, is 4000 bps as each symbol conveys two bits.

Some technical terms (3)



Bandwidth efficiency

The *bandwidth efficiency* of a communications link is a measure of how well a particular modulation format (and coding scheme) is making use of the available bandwidth.

Units for bandwidth efficiency of a digital communications link

Bandwidth efficiency → bits/second/Hz

For example, if a system requires 4 kHz of bandwidth to continuously send 8000 bps of information, the bandwidth efficiency of the link is:

Bandwidth efficiency = 8000 bps/4000 Hz = 2 bits/second/Hz

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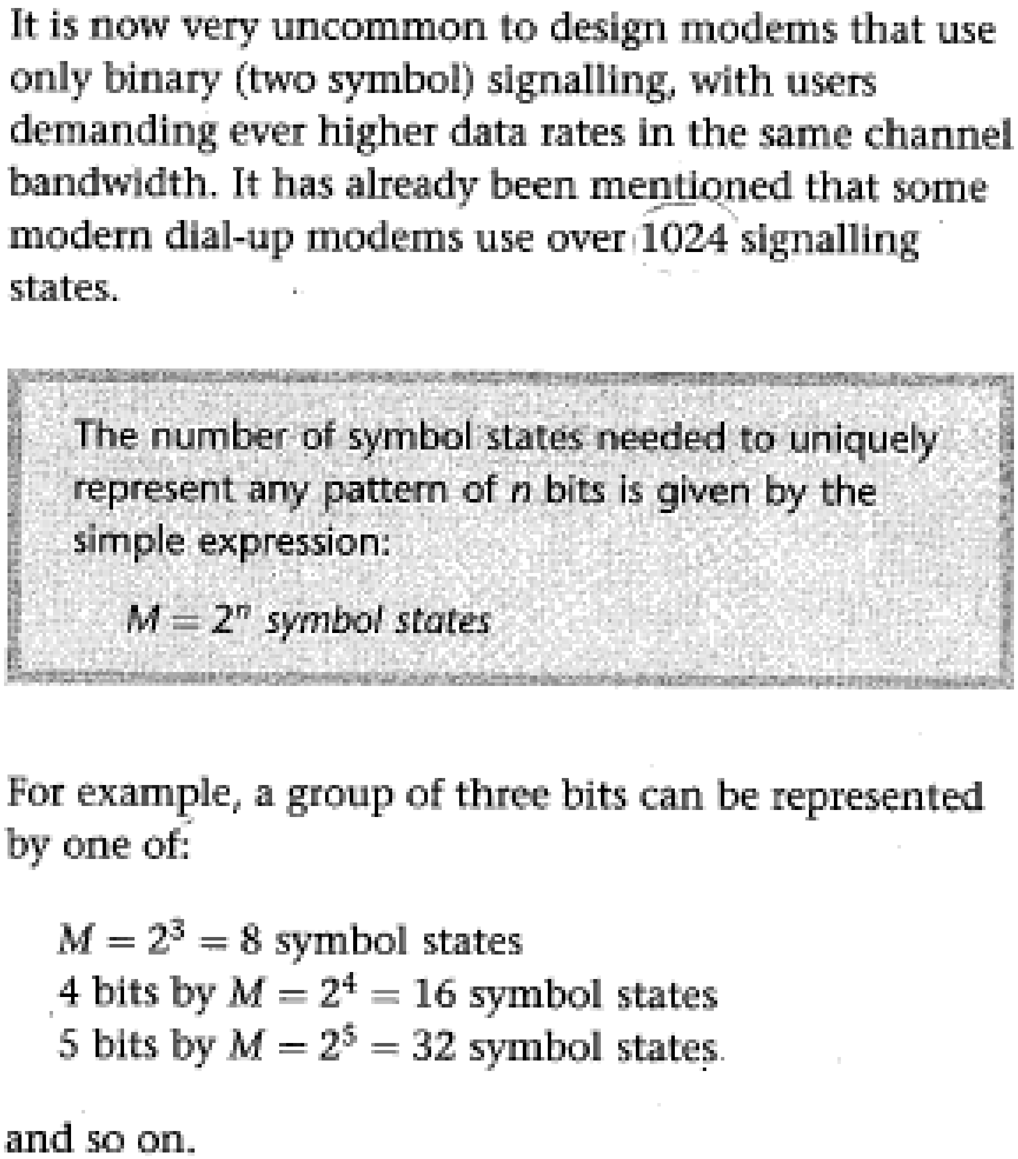
The relation between bit and symbol



It is now very uncommon to design modems that use only binary (two symbol) signalling, with users demanding ever higher data rates in the same channel bandwidth. It has already been mentioned that some modern dial-up modems use over 1024 signalling states.

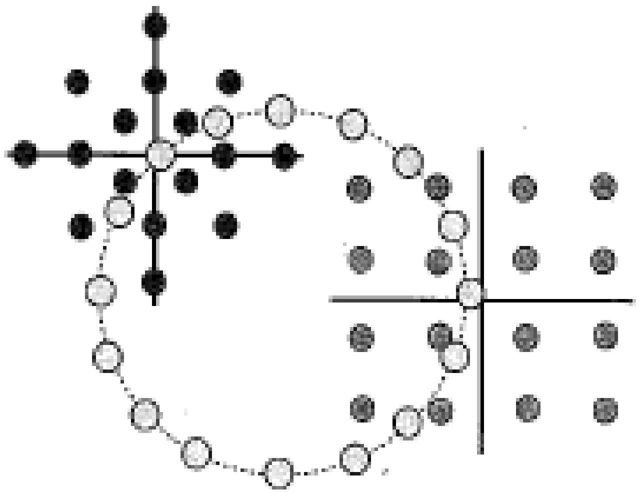
The number of symbol states needed to uniquely represent any pattern of *n* bits is given by the simple expression:

$$M = 2^n \text{ symbol states}$$

For example, a group of three bits can be represented by one of:

$M = 2^3 = 8$ symbol states
4 bits by $M = 2^4 = 16$ symbol states
5 bits by $M = 2^5 = 32$ symbol states

and so on.

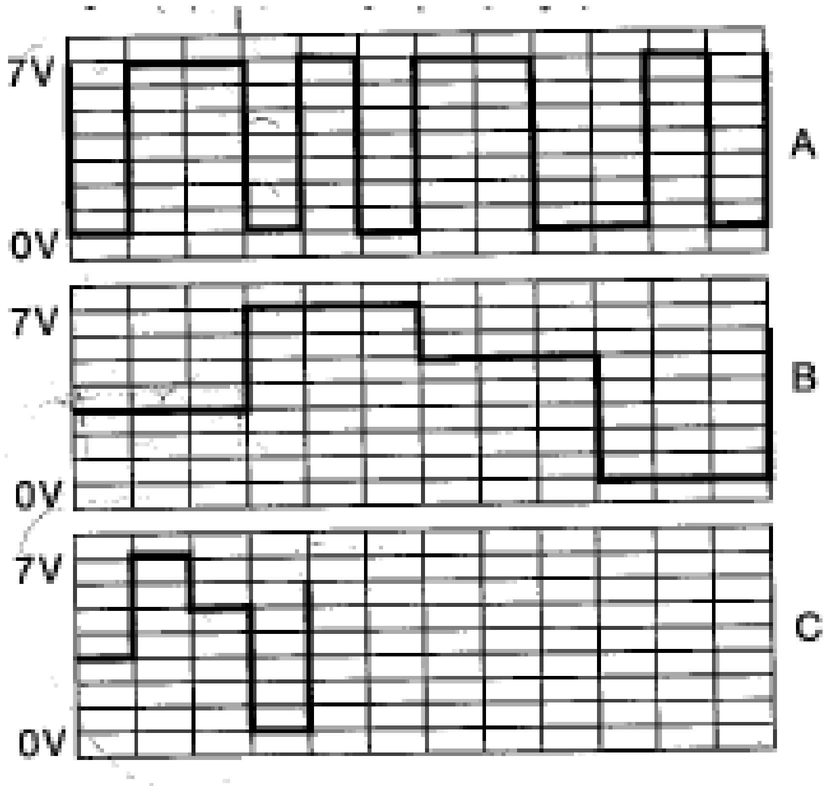


8-ary signaling

The purpose of using multi-level or multi-symbol signalling is to allow the designer to trade channel capacity with bandwidth and noise immunity. Consider, for example, a system employing eight voltage states rather than a simple binary two-state design.

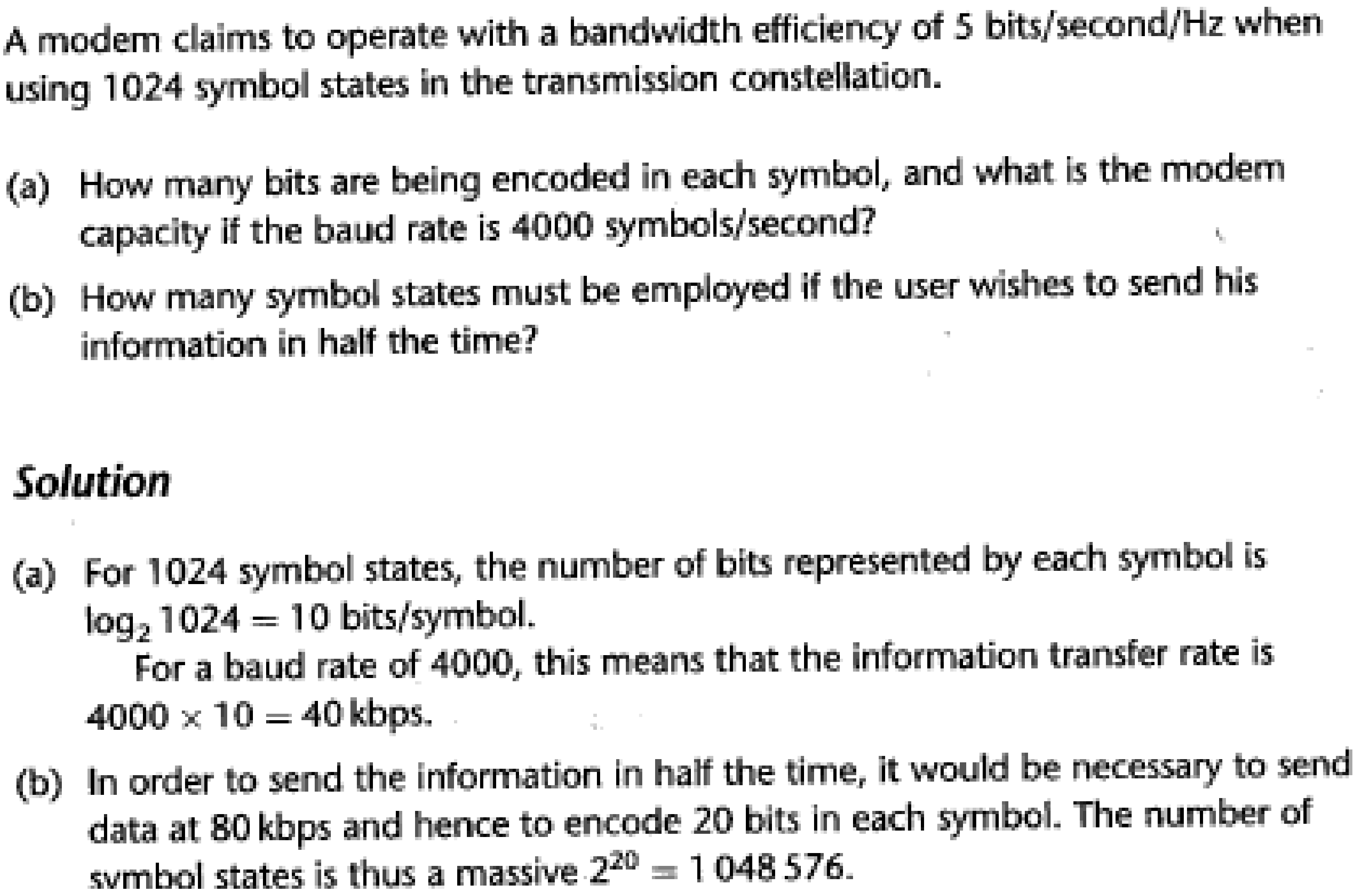
Trace A represents the binary data source to be encoded into the 8-ary signal.

Trace B is the encoded signal with the *information rate* kept the same for both binary and 8-ary systems. The result is that the rate at which the voltage state is varied on the channel is reduced by a factor of three. This translates directly into a threefold reduction in bandwidth required to support communication.



Finally, trace C shows an 8-ary signal which has the same *symbol rate* as the binary source and hence requires the same bandwidth, but the information rate has been increased threefold.

EXAMPLE 2.1



A modem claims to operate with a bandwidth efficiency of 5 bits/second/Hz when using 1024 symbol states in the transmission constellation.

(a) How many bits are being encoded in each symbol, and what is the modem capacity if the baud rate is 4000 symbols/second?

(b) How many symbol states must be employed if the user wishes to send his information in half the time?

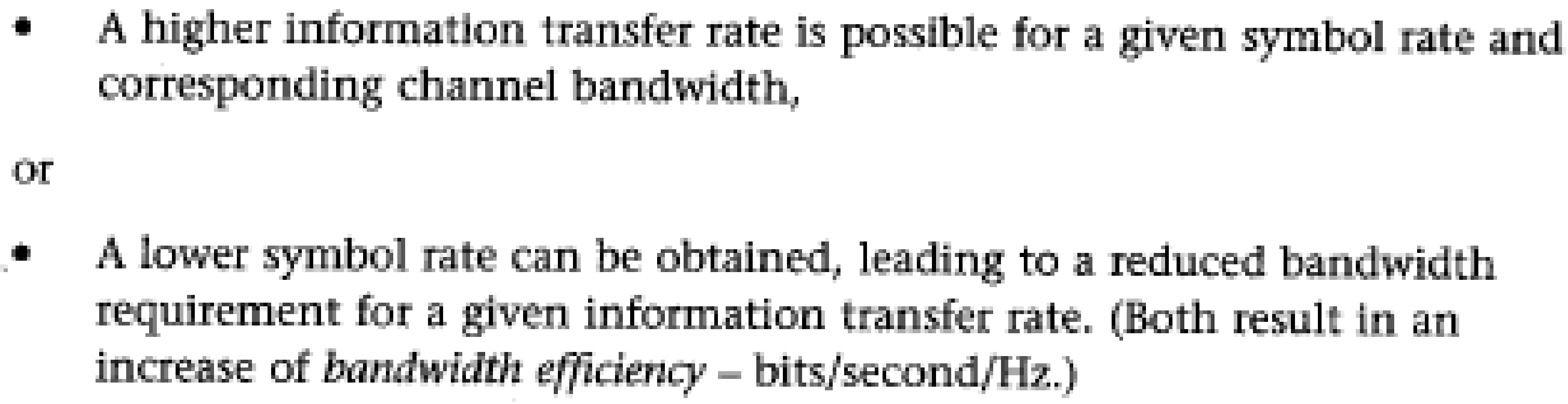
Solution

(a) For 1024 symbol states, the number of bits represented by each symbol is $\log_2 1024 = 10$ bits/symbol.

For a baud rate of 4000, this means that the information transfer rate is $4000 \times 10 = 40$ kbps.

(b) In order to send the information in half the time, it would be necessary to send data at 80 kbps and hence to encode 20 bits in each symbol. The number of symbol states is thus a massive $2^{20} = 1\,048\,576$.

Advantages of M-ary signaling

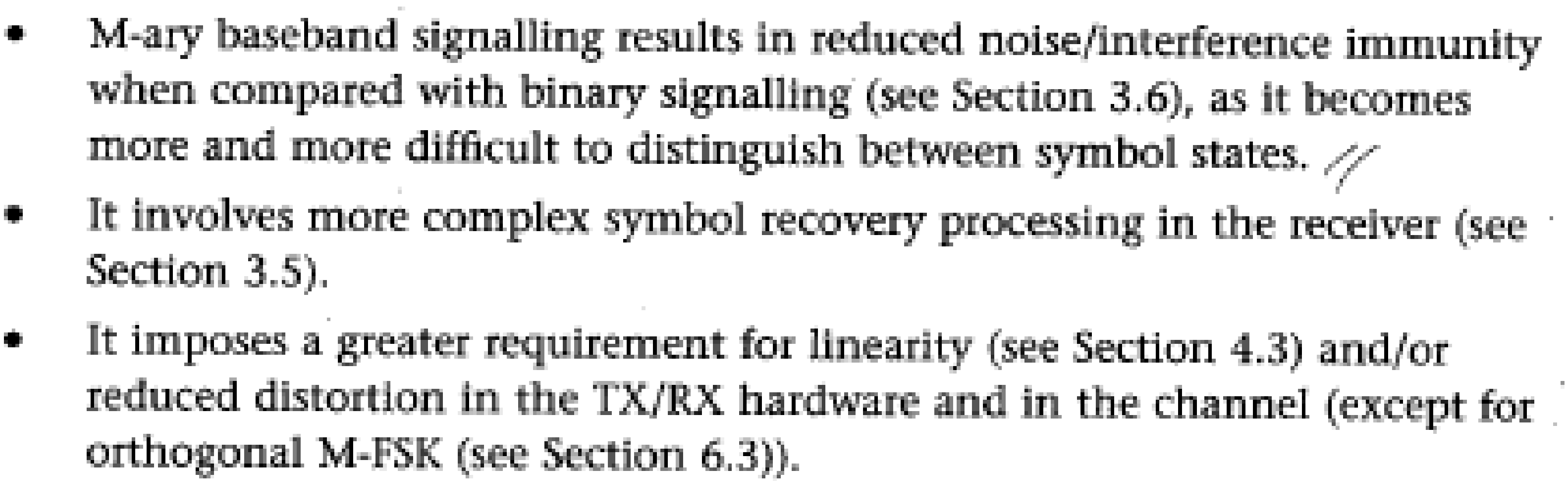


- A higher information transfer rate is possible for a given symbol rate and corresponding channel bandwidth,

or

- A lower symbol rate can be obtained, leading to a reduced bandwidth requirement for a given information transfer rate. (Both result in an increase of *bandwidth efficiency* – bits/second/Hz.)

Disadvantages of M-ary signaling



- M-ary baseband signalling results in reduced noise/interference immunity when compared with binary signalling (see Section 3.6), as it becomes more and more difficult to distinguish between symbol states.
- It involves more complex symbol recovery processing in the receiver (see Section 3.5).
- It imposes a greater requirement for linearity (see Section 4.3) and/or reduced distortion in the TX/RX hardware and in the channel (except for orthogonal M-FSK (see Section 6.3)).

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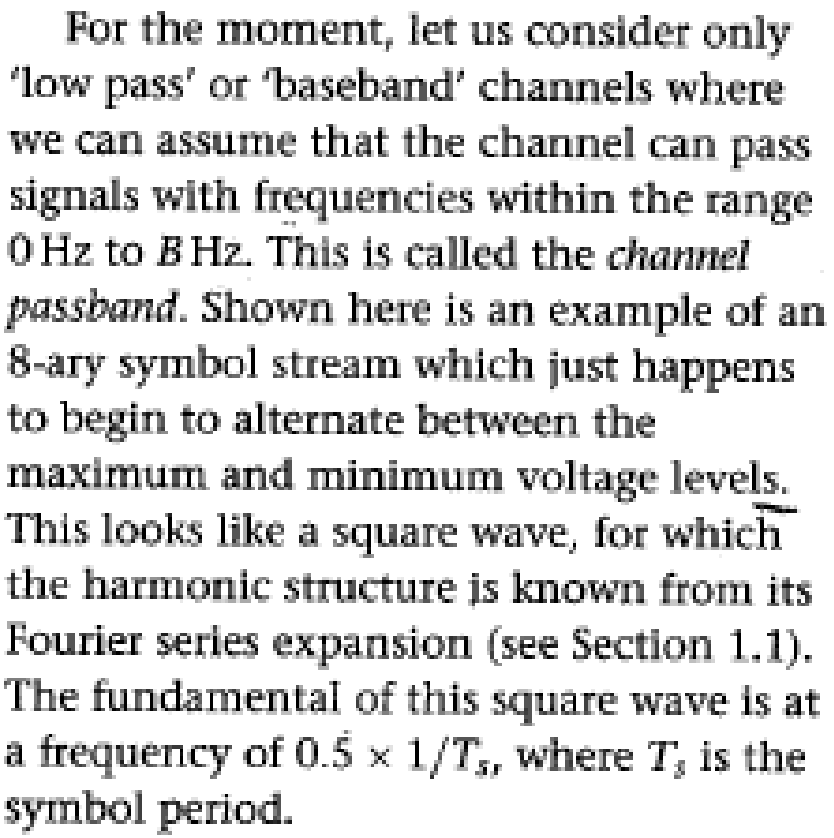
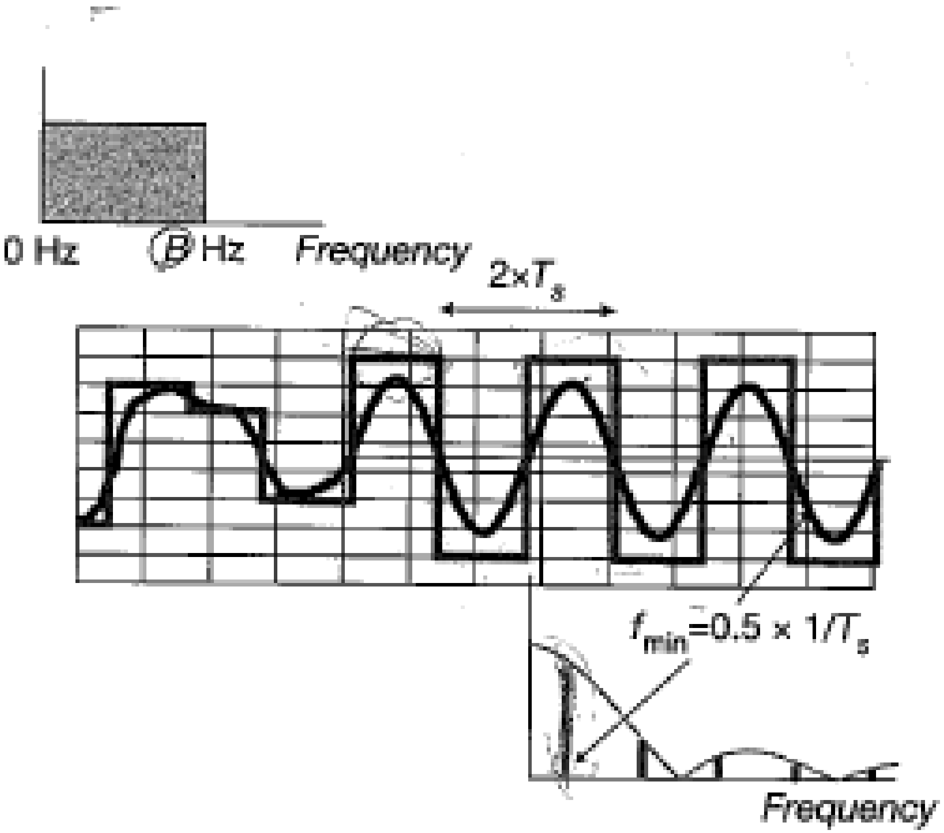
If we can use only 0 to B[Hz] BW.



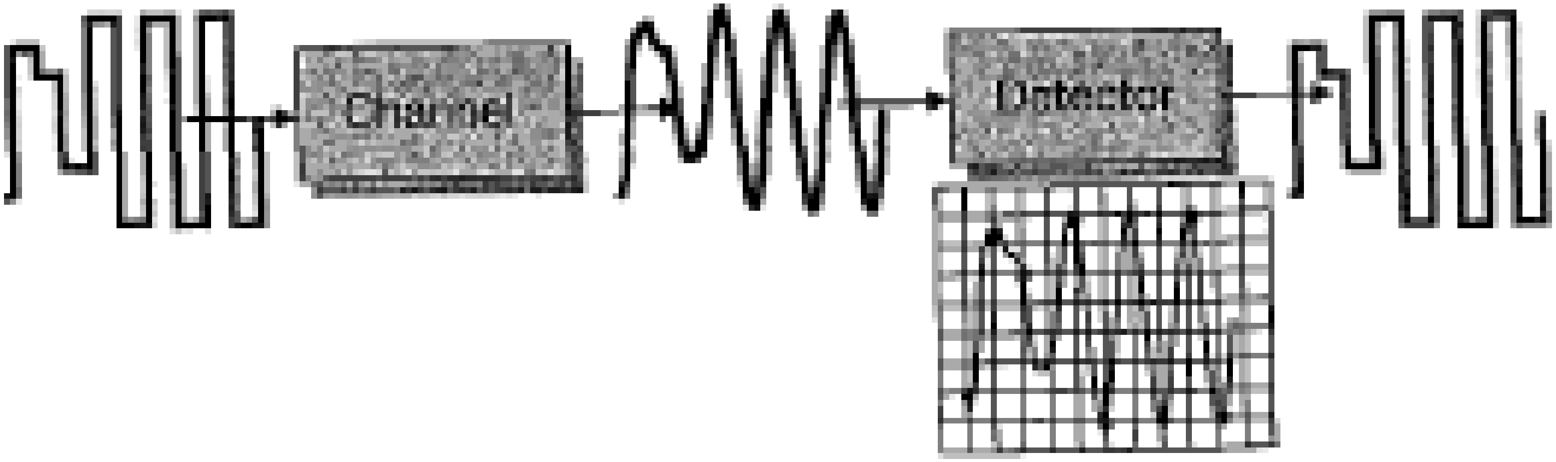
For the moment, let us consider only 'low pass' or 'baseband' channels where we can assume that the channel can pass signals with frequencies within the range 0 Hz to B Hz. This is called the *channel passband*. Shown here is an example of an 8-ary symbol stream which just happens to begin to alternate between the maximum and minimum voltage levels. This looks like a square wave, for which the harmonic structure is known from its Fourier series expansion (see Section 1.1). The fundamental of this square wave is at a frequency of $0.5 \times 1/T_s$, where T_s is the symbol period.



8-ary pulse is distorted!

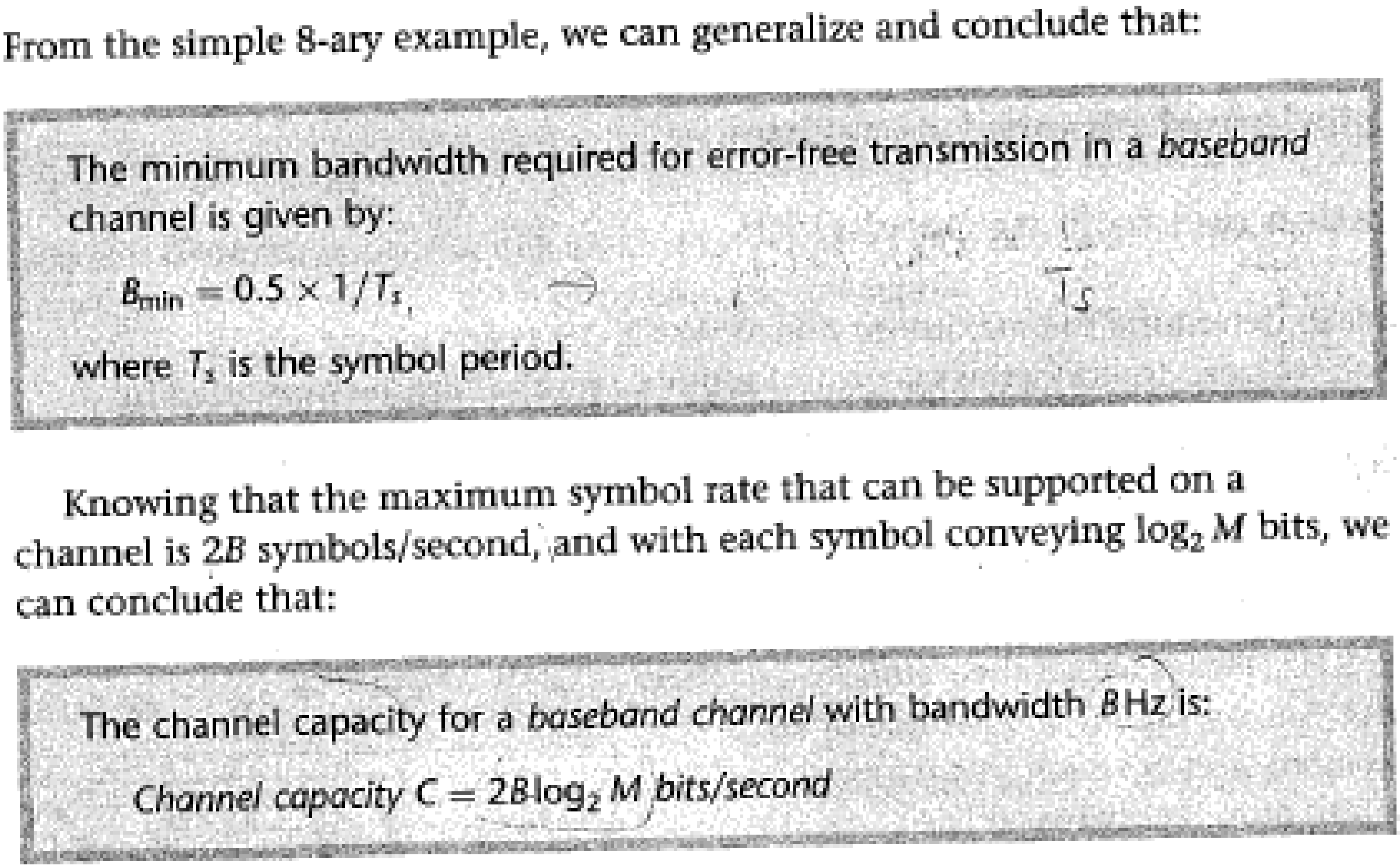
Min B = 0.5X1/Ts

Detector has to recover!



Min B = 0.5X1/Ts

Channel capacity



From the simple 8-ary example, we can generalize and conclude that:

The minimum bandwidth required for error-free transmission in a *baseband* channel is given by:

$$B_{\min} = 0.5 \times 1/T_s, \quad \rightarrow \quad T_s$$

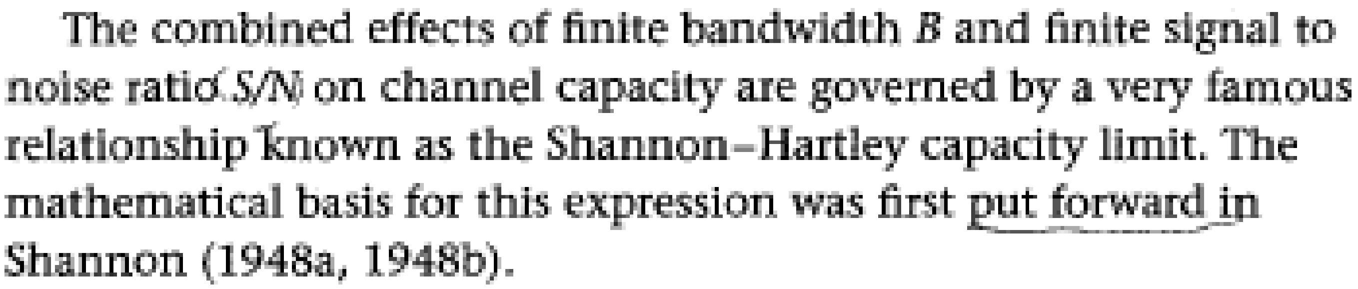
where T_s is the symbol period.

Knowing that the maximum symbol rate that can be supported on a channel is $2B$ symbols/second, and with each symbol conveying $\log_2 M$ bits, we can conclude that:

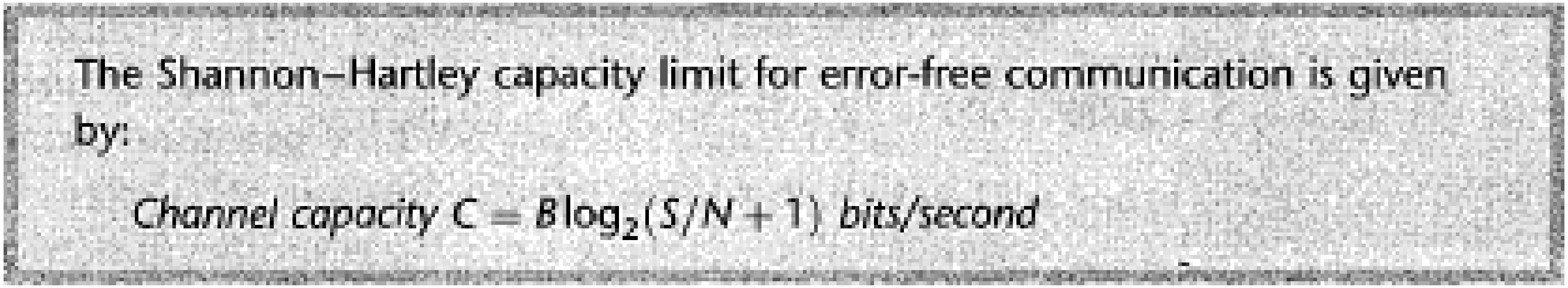
The channel capacity for a *baseband channel* with bandwidth B Hz is:

Channel capacity $C = 2B\log_2 M$ *bits/second*

Shannon’s Law



The combined effects of finite bandwidth *B* and finite signal to noise ratio *S/N* on channel capacity are governed by a very famous relationship known as the Shannon–Hartley capacity limit. The mathematical basis for this expression was first put forward in Shannon (1948a, 1948b).

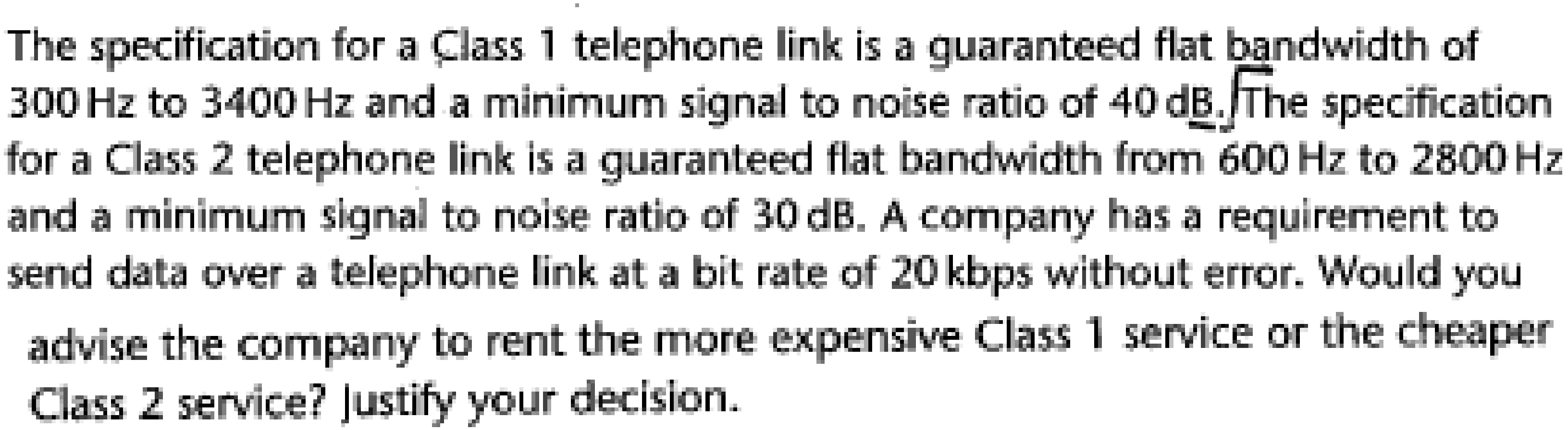


The Shannon–Hartley capacity limit for error-free communication is given by:

Channel capacity $C = B\log_2(S/N + 1)$ *bits/second*

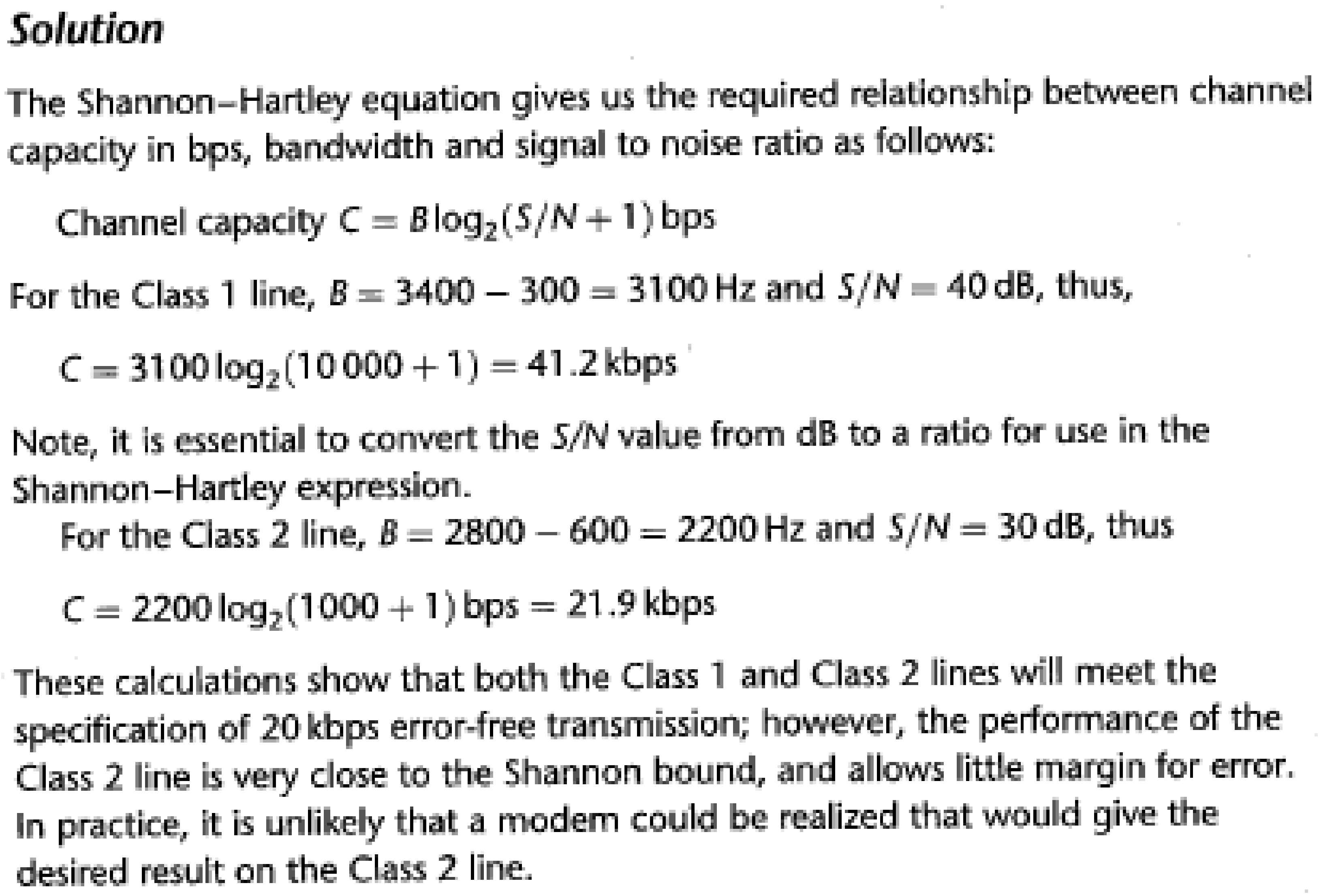
S = Signal Power
N = Noise Power
S/N = Signal to Noise Power ratio

EXAMPLE 2.2



The specification for a Class 1 telephone link is a guaranteed flat bandwidth of 300 Hz to 3400 Hz and a minimum signal to noise ratio of 40 dB. The specification for a Class 2 telephone link is a guaranteed flat bandwidth from 600 Hz to 2800 Hz and a minimum signal to noise ratio of 30 dB. A company has a requirement to send data over a telephone link at a bit rate of 20 kbps without error. Would you advise the company to rent the more expensive Class 1 service or the cheaper Class 2 service? Justify your decision.

EXAMPLE 2.2(2)



Solution

The Shannon–Hartley equation gives us the required relationship between channel capacity in bps, bandwidth and signal to noise ratio as follows:

$$\text{Channel capacity } C = B\log_2(S/N + 1) \text{ bps}$$

For the Class 1 line, $B = 3400 - 300 = 3100$ Hz and $S/N = 40$ dB, thus,

$$C = 3100\log_2(10\,000 + 1) = 41.2 \text{ kbps}$$

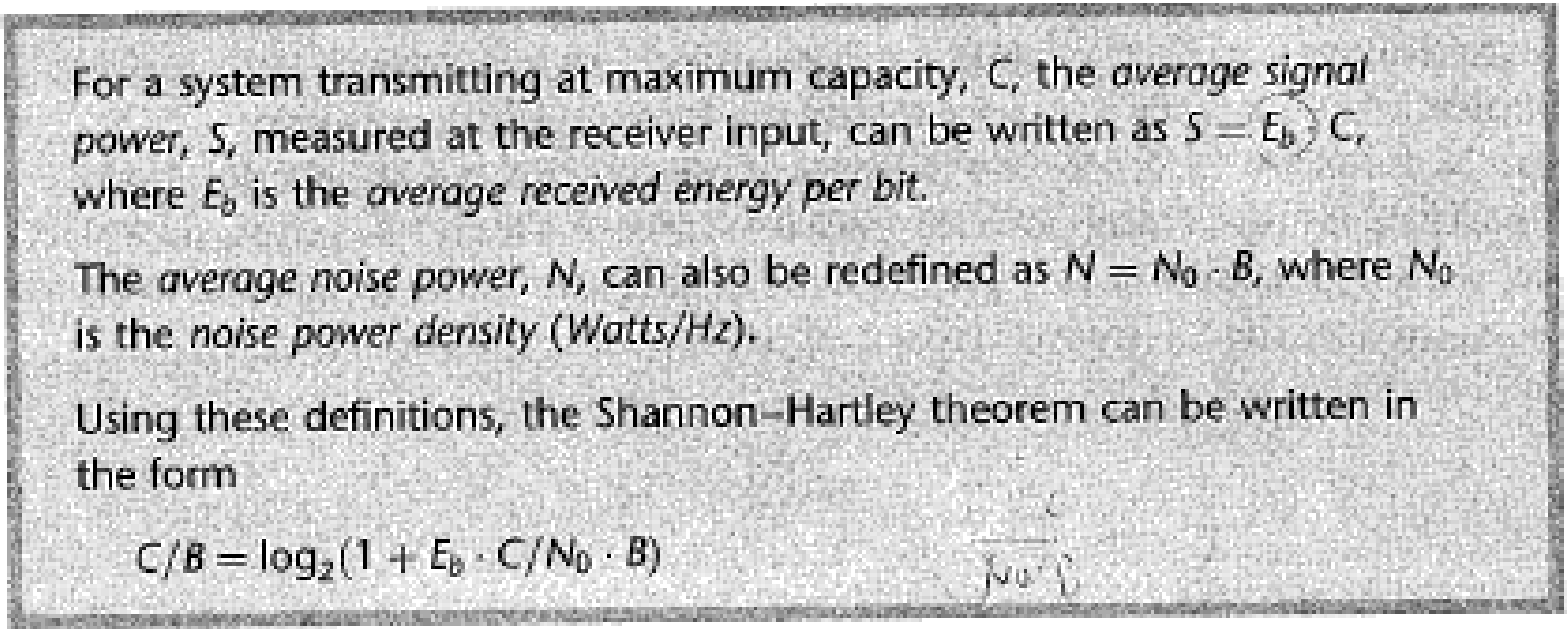
Note, it is essential to convert the S/N value from dB to a ratio for use in the Shannon–Hartley expression.

For the Class 2 line, $B = 2800 - 600 = 2200$ Hz and $S/N = 30$ dB, thus

$$C = 2200\log_2(1000 + 1) \text{ bps} = 21.9 \text{ kbps}$$

These calculations show that both the Class 1 and Class 2 lines will meet the specification of 20 kbps error-free transmission; however, the performance of the Class 2 line is very close to the Shannon bound, and allows little margin for error. In practice, it is unlikely that a modem could be realized that would give the desired result on the Class 2 line.

Bandwidth Efficiency (C/B [bit/sec/Hz])



For a system transmitting at maximum capacity, C, the *average signal power*, S, measured at the receiver input, can be written as $S = E_b \cdot C$, where E_b is the *average received energy per bit*.

The *average noise power*, N, can also be redefined as $N = N_0 \cdot B$, where N_0 is the *noise power density* (Watts/Hz).

Using these definitions, the Shannon–Hartley theorem can be written in the form

$$C/B = \log_2(1 + E_b \cdot C/N_0 \cdot B)$$

$\frac{C}{N_0 \cdot [illegible]}$

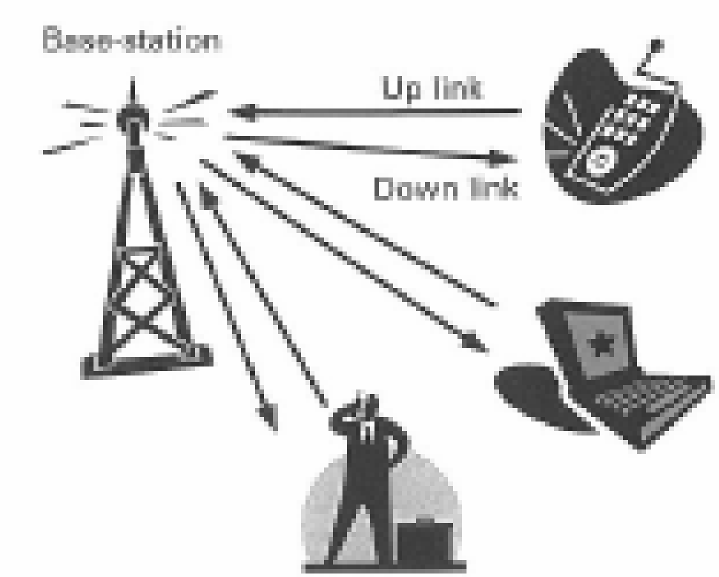
$$\frac{C}{B} = log_2\left(1 + \frac{E_b \cdot C}{N_0 \cdot B}\right)$$

$$\frac{E_b}{N_0} = Power\ efficiency$$

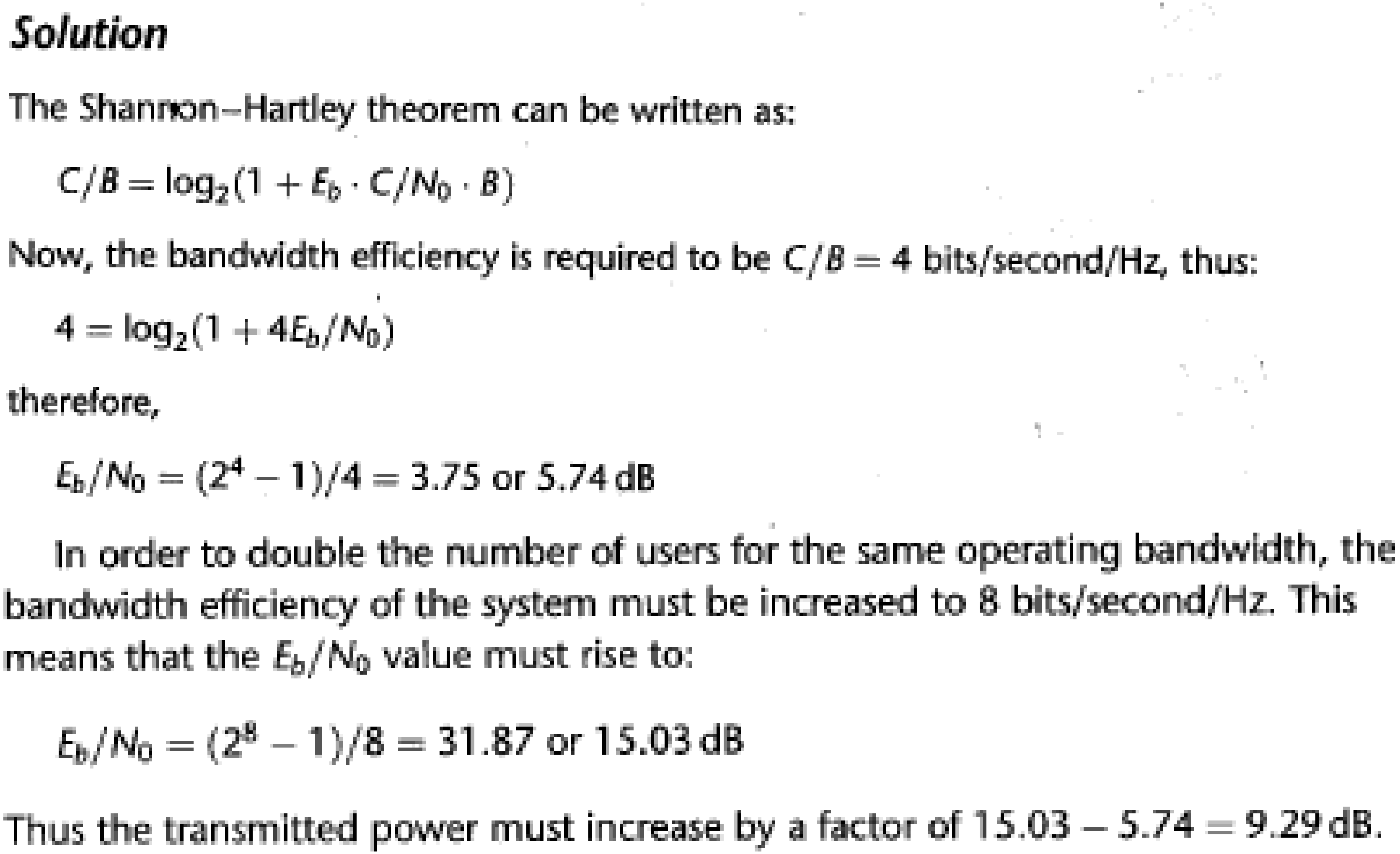
EXAMPLE 2.3

A digital cellular telephone system is required to work at a bandwidth efficiency of 4 bits/second/Hz in order to accommodate sufficient users to make it profitable. What is the minimum E_b/N_0 ratio that must be planned for in order to ensure that users on the edge of the coverage area receive error-free communication?

If the operator wishes to double the number of users on his existing network, how much more power must the base-station and handsets radiate in order to maintain coverage and error-free communication?



EXAMPLE 2.3(2)



Solution

The Shannon–Hartley theorem can be written as:

$$C/B = \log_2(1 + E_b \cdot C/N_0 \cdot B)$$

Now, the bandwidth efficiency is required to be $C/B = 4$ bits/second/Hz, thus:

$$4 = \log_2(1 + 4E_b/N_0)$$

therefore,

$$E_b/N_0 = (2^4 - 1)/4 = 3.75 \text{ or } 5.74\,\text{dB}$$

In order to double the number of users for the same operating bandwidth, the bandwidth efficiency of the system must be increased to 8 bits/second/Hz. This means that the E_b/N_0 value must rise to:

$$E_b/N_0 = (2^8 - 1)/8 = 31.87 \text{ or } 15.03\,\text{dB}$$

Thus the transmitted power must increase by a factor of $15.03 - 5.74 = 9.29$ dB.

Need two presenter

- Each presenter shall chose two problems from 2.1 to 2.13.
- Show your answer at the beginning of next lecture. Each has 5 minutes.
- Next lecture will be 11/18 (mon)