ELEX 4340 : Data Communications
2015 Fall Session

Introduction to Data Communication

This lecture introduces some basic terminology, describes a model for communication systems and networks and describes some characteristics of data.
After this lecture you should be able to: define the terms introduced this lecture; compute information, entropy, bit, symbol, bit error and frame error rates; compute throughput; convert between characters, Unicode code points and their UTF-8 encodings; convert numbers between different number bases and bit and byte orders.

Model of a Communication System

A model for a communication system includes the following[1]:

- information source - generates the information
- transmitter - converts the information into an electrical signal that can be transmitted over the channel
- channel - distorts the signal and adds noise
- receiver - attempts to recover the information that was transmitted
- data destination - accepts the information (sometimes called a data "sink")

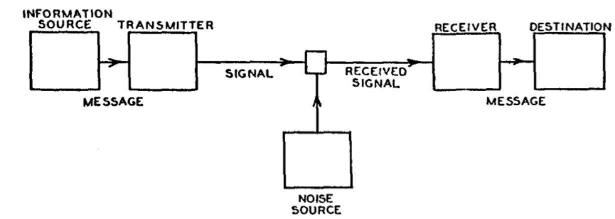
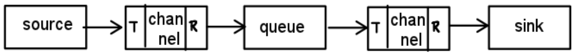


Fig. 1—Schematic diagram of a general communication system.

In many cases information travels over a network consisting of multiple channels and their associated transmitters and receivers. In some cases the information is stored ("queued") before being forwarded over the next channel.



In this course we will study the implementation of digital communication systems and networks.

Exercise 1: For each of the following communication systems identify the source, sink and the channel(s) involved: a laptop's connection to an external hard drive; a cell phone call; watching a YouTube video. Which of these involve networks? Come up with your own examples of communication systems and identify these components.

Digital Communication vs Data Communications

Digital communication systems communicate information that is in the form of digits, almost always binary digits or "bits".

Digital communication systems include those used to transmit digitized speech or video waveforms as well more abstract information such as text, images, or computer software (often called "data").

However, today the terms "data communications" and "digital communications" are often used interchangeably because the same networks are used to carry all types of digital information.

Characteristics of Data Sources, Channels and Sinks

Information Rate

We can model sources as generating one of a limited number of messages. We define the information that is transmitted by a message that occurs with a probability P as:

$$I = -\log_2(P) \quad \text{bits}$$

The information rate (also known as the "entropy") of a source in units of bits per message can be com-

[1] The diagram is from Claude Shannon's fundamental paper, "A Mathematical Theory of Communication," *The Bell System Technical Journal*, Vol. 27, pp. 379–423, 623–656, July, October, 1948.

puted as the average information generated by the source:

$$H = \sum_i (-\log_2(P_i) \times P_i) \quad \text{bits/message}$$

Exercise 2: A source generates four different messages. The first three have probabilities 0.125, 0.125, 0.25. What is the probability of the fourth message? How much information is transmitted by each message? What is the entropy of the source? What is the average information rate if 100 messages are generated every second? What if there were four equally-likely messages?

We will see later in the course that there is a limit, called the "capacity," (C) for the information rate that can be transmitted over a given channel.

Data Rates

The rate at which the source generates the data that is sent over the channel, the "data rate", is also specified in bits per second (bps or b/s).

Unfortunately, particularly in consumer-facing data communications applications, the same acronym is often used for "bytes per second". To avoid confusion it's best to spell out the units if the meaning is not clear from the context.

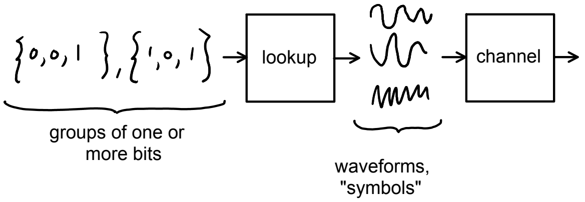
Some people use the convention that a capital 'B' indicates bytes and a lower-case 'b' indicates bits, but you should not assume this convention is universally understood.

In this course "bps" will always mean "bits per second". This convention is used in almost all technical documents (equipment specifications, interoperability standards, data sheets, etc).

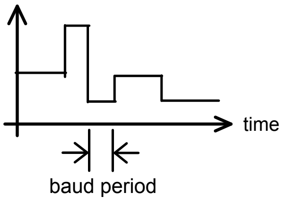
Computer storage is often measured in units with prefixes that are powers of 2 (e.g. kilo means 2^{10} or 1024 rather than 10^3). Communication system data rates always use units that are powers of 10 (e.g. 1 kb/s is 1000 b/s).

Symbol Rate

A waveform is a voltage or current that varies with time. The transmitter converts the data to a signal, a waveform that carries information, for transmission over the channel. Often the transmitter uses a number of bits to select from one of several possible waveforms, or "symbols", to transmit. The rate at which these waveforms are transmitted is called the "symbol rate". The symbol rate is equal to or lower than the bit rate(*why?*).



One possible set of signaling waveforms is voltages of different levels. The maximum rate at which these levels can change is called the "baud rate". The baud rate can be lower or higher than the bit rate depending on the design of the transmitter.



Exercise 3: One system encodes each bit using two pulses of opposite polarity (H-L for 0 and L-H for 1). A second system encodes bits using one pulse per bit (H for 0 and L for 1). A third system encodes two bits per pulse by using four different pulse levels (-3V for 00, -1V for 01, +1V for 10 and +3V for 11). Assuming each system transmits at 1000 bits per second, what are the baud rates in each case? How many different symbols are used by each system? What are the symbol rates?

Error Rates

The bit error rate (BER, P_e) is the average fraction of bits that are received incorrectly.

When these bits are grouped into "frames" we are often interested in the average fraction of the frames that contain one or more errors. This is known as the FER (Frame Error Rate). Sometimes frames include additional bits that allow us to detect most, but not all, errors. We often want the UEP (Undetected Error Probability) to be very small.

Exercise 4: You receive 1 million frames, each of which contains 100 bits. By comparing the received frames to the transmitted ones you find that 56 frames had errors. Of these, 40 frames had one bit in error, 15 had two bit errors and one had three errors. What was the FER? The BER?

Throughput

In addition to the data rate at the transmitter, we are often interested in the average data rate at the destination. This is called the “throughput”. The average rate at which data arrives at the destination can be different than the instantaneous rate at which the transmitter sends data to the channel because:

- the channel may have to be shared between different users
- the transmitter may add (and the receiver remove) “overhead” bits for addressing, error detection, etc
- incorrectly received data may have to be retransmitted
- there may be gaps between frames

Exercise 5: A system transmits data at an (instantaneous) rate of 1 Mb/s in frames of 256 bytes. 200 of these bytes are data and the rest are overhead. The time available for transmission over the channel is shared equally between four users. A 200 μs gap must be left between each packet. What throughput does each user see? Now assume 10% of the frames are lost due to errors. What is the new throughput per user?

Compression

Sometimes data is not completely random and we can make use of the redundancy to reduce the amount of data that needs to be transmitted. Both lossless and lossy compression are examples of “source coding”.

Lossless. Some types of data contains redundancy such as sequences of bits or bytes that occur more often than others. This type of data can be compressed before transmission and then decompressed at the receiver without loss of information. An example of this “lossless” compression is the ‘zip’ compression used for computer files.

Another way of defining the information rate is that it is the theoretical minimum data rate, assuming the best possible lossless compression has been applied. Lossless compression cannot reduce the information rate of the source but it can can reduce the bit rate that needs to be transmitted over the channel.

Lossy. Data representing speech and video can often be compressed with little degradation because humans cannot perceive certain details of sounds and images. These details can be removed resulting in lower data rates. Examples of these “lossy” compression techniques include “MP3” for compressing audio and MPEG-4 for video.

Data Rate Variability

One characteristic of a data source is whether the rate at which the data is generated is:

- constant - “Isochronous” sources generate data at a constant bit rate (CBR) and are typical of regularly sampled waveforms such as (uncompressed) audio or video sources.
- variable - Variable bit rate (VBR) sources are typical of compressed speech and video because different parts of the speech or video signal have different amounts of redundancy and can be compressed to different bit rates.
- bursty - Bursty data sources generate large amounts of information at instants of time in-between pauses where no information is generated. This is typical of systems involving human interaction such as web surfing.

Exercise 6: Plot some sample data rate versus time curves for these three types of sources. What characteristics of a video source might result in a variable bit rate when it is compressed? (*Hint: what types of redundancy are there in video?*).

Tolerance To Impairments

Data sinks vary in their tolerance to channel impairments such as errors, delay and variability of delay (delay “jitter”).

For example, computer data transmission systems usually require very low undetected error rates (e.g. one undetected error in decades) but can often tolerate high delay and delay variability (seconds). On the other hand telephone systems can tolerate loss of a small percentage of the speech waveform but become difficult to use if delays exceed a significant fraction of a second.

Exercise 7: For each of the following communication systems identify the tolerance it is likely to have to errors and delay:

Table 3-6. UTF-8 Bit Distribution

Scalar Value	First Byte	Second Byte	Third Byte	Fourth Byte
00000000 0xxxxxxx	0xxxxxxx			
00000yyy yyxxxxxx	110yyyyy	10xxxxxx		
zzzzyyyy yyxxxxxx	1110zzzz	10yyyyyy	10xxxxxx	
000uuuuu zzzzyyyy yyxxxxxx	11110uuu	10uuzzzz	10yyyyyy	10xxxxxx

a phone call between two people, "texting", downloading a computer program, streaming a video over a computer network. What do you think might be the maximum tolerable delay for each?

Words, Bit and Byte Order

The bits generated by a data source are usually organized into "words". Words of 8 bits are called bytes (or "octets" in some standards documents). Words of 4 bits are often called nibbles (or nybbles). Words composed of other multiples of 8 bits (16, 32, 48 and 64 bits) are also common.

It is important that the communication system preserve the order of the bits and bytes between the source and sink.

If the bits in a word represent a binary number they can be ordered from "most significant bit" (MSB) to "least significant bit" (LSB). This is sometimes called "big endian" order. The reverse order is called "little endian".

Often the bits (in either bit order) are part of bytes which themselves are concatenated to form words. The bytes in each word can also be ordered MSB(yte) first (big-endian) or LSB(yte) first (little endian).

Most Internet protocols use big-endian bit and byte order which is sometimes called "network order". In network order the bits and bytes are transmitted in the order they are written.

Exercise 8: Convert the decimal number 525 to a 16-bit (two-byte) binary number. Write the sequence of bits that would be transmitted if both the bytes and bits were transmitted in little-endian order. Write the sequence of bits that would be transmitted in "network order".

Notation

When collections of bits are interpreted as numbers they can be written using digits from various bases.

The most common notation is hexadecimal because it allows 8-bit values (bytes) to be written using two hexadecimal digits. Hexadecimal digits are 0 to 9 and A through F (representing values from 10 through 15). Typically a special prefix of non-numeric character(s) is used to indicate that the number is written in binary, octal or hexadecimal notation. Typical prefixes for hexadecimal notation include "$", "#", "0x", and "0H".

Exercise 9: Write the 16-bit number above in hexadecimal notation.

Character Codes

Data often represent printable characters or "glyphs".

A standard, called Unicode, has been developed to assign a unique number (called a "code point") to over 100,000 of the characters used by over 100 different languages and scripts. Unicode is used by most modern operating systems and most Internet applications.

Exercise 10: How many bits would be required to uniquely identify 100,000 different characters? (Hint: $2^{16} = 65536$).

The first 127 characters of Unicode correspond to an earlier character encoding called ASCII (American Standard Code for Information Interchange).

16 bits is not sufficient for representing all of the Unicode characters and even if it were, it would double the size of typical text files and web pages that primarily use ASCII characters. UTF-8 (Unicode Transformation Format - 8 bits) was developed as a way to

represent typical Unicode documents in an efficient way. The UTF-8 encoding is the same as the ASCII encoding for the first 127 characters. This makes existing ASCII files compatible with software that expects UTF-8 encoded Unicode.

Other Unicode characters require between 2 and 4 bytes according to the rules summarized in Table 3-6 of the Unicode standard shown above. To encode a code point, convert it to a binary number and find the first row in the table that can represent the number. Then copy the bits indicated by x, y, z and u from the binary number into the corresponding locations in the bits in the bytes values.

ASCII also includes some non-printable control codes (values 0 to 31) that will be discussed later in the course.

The table below shows the ASCII table as given in version 6.2 of the Unicode standard. The columns are labelled with the most significant (first) hex digit and the rows with the least-significant (second) hex digit of the numerical value of each character.

Exercise 11: Find the ASCII codes for the *characters* '525'. Write out the first 16 bits of the sequence that would be transmitted assuming each character is encoded using 8 bits per character and little-endian bit order. *Hint: the character code for a digit is 0x30 plus the value of the digit.*

Exercise 12: The Chinese character for "Rice" (the grain) is "米" with Unicode value (code point) U+7C73. What is the UTF-8 encoding for this character?

Exercise 13: Highlight or underline each term where it is defined in these lecture notes.

C0 Controls and Basic Latin

	000	001	002	003	004	005	006	007
0	NUL 0000	DLE 0010	SP 0020	0 0030	@ 0040	P 0050	` 0060	p 0070
1	SOH 0001	DC1 0011	! 0021	1 0031	A 0041	Q 0051	a 0061	q 0071
2	STX 0002	DC2 0012	" 0022	2 0032	B 0042	R 0052	b 0062	r 0072
3	ETX 0003	DC3 0013	# 0023	3 0033	C 0043	S 0053	c 0063	s 0073
4	EOT 0004	DC4 0014	$ 0024	4 0034	D 0044	T 0054	d 0064	t 0074
5	ENQ 0005	NAK 0015	% 0025	5 0035	E 0045	U 0055	e 0065	u 0075
6	ACK 0006	SYN 0016	& 0026	6 0036	F 0046	V 0056	f 0066	v 0076
7	BEL 0007	ETB 0017	' 0027	7 0037	G 0047	W 0057	g 0067	w 0077
8	BS 0008	CAN 0018	(0028	8 0038	H 0048	X 0058	h 0068	x 0078
9	HT 0009	EM 0019	) 0029	9 0039	I 0049	Y 0059	i 0069	y 0079
A	LF 000A	SUB 001A	* 002A	: 003A	J 004A	Z 005A	j 006A	z 007A
B	VT 000B	ESC 001B	+ 002B	; 003B	K 004B	[005B	k 006B	{ 007B
C	FF 000C	FS 001C	, 002C	< 003C	L 004C	\ 005C	l 006C	| 007C
D	CR 000D	GS 001D	- 002D	= 003D	M 004D	] 005D	m 006D	} 007D
E	SO 000E	RS 001E	. 002E	> 003E	N 004E	^ 005E	n 006E	~ 007E
F	SI 000F	US 001F	/ 002F	? 003F	O 004F	_ 005F	o 006F	DEL 007F