Communications Unravelled

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Introduction

This guide aims to act as an introduction to communications technology in general, and to provide essential background explanations for studying communications engineering. I'm aiming to introduce the mind-set and ways of thinking that are usually assumed in most other texts, so that you'll get to grips with the subject quickly.

It's good to talk...

So said Bob Hoskins in that infamous BT advert. Communications is (obviously) all about talking- whether it's you calling your Auntie Marjorie in Australia, or your computer talking to other computers on the Internet. Communications engineering has grown up around the basic need of people to talk to each other over distances further than they can shout, and encompasses cabled and wireless systems, broadcasting, computer networking and uses a wide range of techniques, drawing on the worlds of both analogue and digital electronics. But it does have its foibles, and most of these are historical, so read the next section!

A History Lesson

Electrical communications began in earnest with Oersteds discovery that current flowing in a coil of wire could deflect a compass. His circuit, consisting of a battery, switch and a coil wrapped around a pocket compass, could be described as the first electric *telegraph*. By putting the switch in one location, and the compass elsewhere, you could send messages in some sort of code along the wire. Linking the transmitter (switch) and receiver (compass) were two wires – the first *transmission line*. The new technology of *telegraphy* had begun.
Very early commercial telegraphs were little more than this. Some had multiple wires running between transmitter and receiver, and several needles that would deflect to show the letter of the alphabet being transmitted. This used lots of wire- easily the highest cost of the system, and so it was inevitable that a system devised by Samuel Morse would be a winner. Morse came up with the idea of a *line code*, a system converting data into a form that was easily transmitted. Morse code, as his invention became known, turns letters and numbers into short and long pulses ("dots" and "dashes"), which could then be sent down a simple two-wire line using a switch.
With Morse code, the telegraph system began to take off dramatically. Cables were laid between cities (usually along railway lines- railway companies needed telegraphy to control trains) and then between countries. Morse operators became highly skilled, able to transmit and receive very rapidly. Telegraphy brought out some basic principles that are still around today- the use of a two-wire transmission line; line coding; early transmission-line theory and the use of repeater stations to boost signals over long distances.
Some time later, Heinrich Hertz (after whom the SI unit of frequency is named) discovered the principles of radio, which had been foretold many years earlier by James Maxwell (of the famous EM wave equations). Hertz found that a large spark generated by capacitor discharge

could induce a small spark in a wire loop with an air gap. He transmitted over a few metres in his lab.
However, it was the Italian engineer Marconi who made *wireless telegraphy* (or radio) a realistic proposition. He discovered the principle of an antenna-and-earth system, where a wire attached to one side of the spark gap is raised up in the air, whilst one on the other side is connected to the Earth. He also found that radio waves propagate better over water (sending the first cross-channel radio message, and the first transatlantic one), and developed techniques for improving Hertz's (very) basic receiver. But wireless telegraphy's drawback was *bandwidth*. A spark generates "white noise", with components at all frequencies. Thus, you couldn't have two transmissions at the same time- they interfere. Oliver Lodge discovered the idea of *tuning*- using a capacitor and inductor as a *bandpass filter* to only transmit on a certain band of frequencies- and having an identical circuit in the receiver to only "listen" to those frequencies. This is the first concept of *multiplexing*- in this case a *frequency division multiplex*- to allow multiple users to use a single communications channel.

Meanwhile, Alexander Bell worked on the early principles of telephony. Thomas Edison had already made sound recordings using a mechanical phonograph, and Bell discovered the mechanism for converting sound to electricity and vice versa. He built microphones and loudspeakers (the first *analogue transducers*), but he had no means to amplify the signal. His first audio systems relied on very sensitive microphones and speakers. But it was possible to turn Bell's prototypes into a commercial system, and the development of the telephone, and thus the whole of audio-frequency electronics became more and more advanced. Early telephone systems had very poor sound quality, and it was necessary to shout loudly into the microphone in order to make yourself heard at the other end of the line.
Telephony gave communications a lot of new ideas. Transducer technology improved, and the principle of impedance matching was discovered, which made sure that you got maximum signal-level at the receiver. Also, a number of things became standardised:

- 600 ohms as the characteristic impedance of an audio line (now used very approximately!)
- 775mV rms as 0dBu (actually 1mW into 600Ω), which is the maximum amplitude of a signal on a phone line- hence "line level"
- 48V as the DC supply voltage for telecomms equipment (this is also about the highest voltage that won't give you a fatal electric shock, unless you're really unlucky…)
- the jack plug and patchbay
- the principle of balanced-line transmission over twisted-pair cable
- the use of transformers to convert between balanced and unbalanced transmission, and to isolate circuits
- the idea of running DC and audio signals along the same circuit
- the use of a "hybrid" circuit to combine both halves of the conversation onto the same pair of wires

Wireless audio transmission had to wait for Lee DeForest's miraculous invention, the triode valve before it was possible. The valve (or tube, as it's known in the USA) finally made it possible to amplify a signal- it's a (somewhat non-ideal) voltage amplifier. With the valve, the whole field of *signal processing* could begin. Amplifiers also radically improved telephony, allowing longer-distance calls and higher sound quality. Oscillators were also possible, and it was the development of a radio-frequency sine wave oscillator that freed radio from the requirement for a spark. Wireless telegraphy was able to be highly tuneable, with hundreds of transmitters being able to share the airwaves without interfering. This led to the first frequency planning arrangements, and the issuing of radio licences and callsigns.

It was also possible to create the first wireless audio transmissions- a valve oscillator could be turned into an *amplitude modulator* by varying the valve's acceleration voltage in sympathy with the audio signal. The signal could be received on a *crystal set*- a radio receiver consisting of an antenna, a tuned circuit and a diode (originally made from a piece of a particular crystal and a very fine wire) which required no power. This led to the beginnings of radio broadcasting, which borrowed most of the audio concepts and standards from telephony, whilst taking radio-frequency ideas from existing wireless telegraphy. Even to this day, the BBC use telephone-style audio patchbays- the design hasn't changed since the Corporation began. In fact, in the very early days of the BBC, there were no audio mixers, so the junctions between programmes were marked by a few minutes silence whilst the patchbays were re-plugged!

AM radio broadcasting (taking place on what we now call long and medium wave) gave a lot to the world of radio, including antenna theory, tuning circuits, demodulation circuits, the heterodyne principle and the use of coaxial cable for radio-frequency signals.

Also, telephony started to become more advanced. The old operators were replaced with Strowger's Automatic Telephone Exchange (developed by an undertaker in Kansas City who thought the operators were in the pay of his rival!) which consisted of big mechanical switching systems, driven by pulses sent down the line by the dial on the callers' telephone. This was one of the first widely used digital communications systems (not counting Morse!). Telephony also borrowed the ideas of multiplexing from radio, using frequency division multiplex to carry multiple conversations between exchanges over a single higher-quality cable. Network theory started to appear, to improve and automate the process of routing long-distance calls between exchanges. Exchanges were originally linked directly to adjacent exchanges, with the operators patching callers between exchanges with jack plugs. The first transcontinental telephone calls in America required 30 minutes notice to make all the connections *en route*. You might remember the distinction between local and trunk calls that existed until the early 1990s in Britain- to make a local call to another nearby exchange you needed a prefix code (from my home to Portsmouth you would dial 91 in front of the number). To call elsewhere, you used the Subscriber Trunk Dialling (STD) code (for Portsmouth, this was 0705) which routed your call through the national Trunk network, which was more expensive! It was possible (knowing all the numbers) to make a local-rate call across the country, by dialling the local exchange codes along the route in sequence!

By the time of the Second World War, AM radio broadcasting was commonplace, telephony and telegraphy were widely available (run by the General Post Office) and television was just beginning. Electronics had diverged from electrics, and was exclusively devoted to valve circuits, primarily analogue in nature. Any digital-type switching was done with electromechanical relays. The war brought a lot of developments in communications- scrambling systems, the idea of *frequency hopping* (swapping frequency regularly during transmission) and the development of the cavity magnetron, which produces microwaves.
In the 1950s, the transistor was developed, and later the portable "transistor" radio. Television (at this time black-and-white) became widespread, being transmitted in the VHF band, at between 50 and 300 MHz.
The 1960s brought an explosion in electronics and communication technologies. The telephone system brought in *pulse code modulation* (PCM) to increase the quality of its trunk circuits- this is a straightforward digital system carrying analogue data. Radio started to move to using *frequency modulation* to carry higher quality signals, and the first broadcasts were made in *stereophonic sound*. Television became colour, increased in

resolution and was moved up into the UHF band at around 900 MHz. The first satellite communications allowed TV to be transmitted across the Atlantic, and reduced the requirement to lay cables across oceans.

The 1970s brought computers onto the scene in earnest, with *modems* being used to allow them to communicate over the phone line. The RS232C standard for serial communications between computers was specified in 1969. The first dedicated computer networks also appeared, the most popular being *Ethernet*, which borrowed extensively from radio technology.

More recently, satellites have brought multichannel TV to our homes, the telephone networks have replaced copper wire with optical fibres, and more and more communications is carried out digitally, giving a more robust transmission. The increasingly ubiquitous mobile phone makes use of all sorts of techniques, from RF modulation techniques through to advanced digital signal processing and error correction systems. The system covers all branches of electronics, analogue, digital, low and high frequency, not to mention control and software. Don’t be led into the trap that “digital” doesn’t require an understanding of “analogue”!

Time versus frequency

This is one of the fundamental concepts that needs to be grasped before you can understand communications- the relationship between the time and frequency domains. Time is a concept that most of us are happy with, although people can find frequency rather weird to begin with.

Drawing graphs of signal voltage or current against time is known as *time domain analysis*, and this is what oscilloscopes do. A ‘scope will show you the behaviour of a signal over time. Analogue ‘scopes are best used with periodic signals, whilst the digital storage kind can capture one-off waveforms. Once you have a repetitive waveform, you can describe it in terms of its period- the time between repetitions.

Digital electronics is almost exclusively analysed in the time domain. Most audio-frequency signals are also drawn in terms of time.

Frequency is the reciprocal of time, mathematically. Instead of measuring the time between repetitions of the waveform, you measure the number of times the waveform repeats within one second. This sounds fairly simple, but it radically alters your viewpoint. Fourier’s theories tell us that the sinusoidal waveform is the basic building block of all signals. It’s possible to make (synthesise) any periodic waveform from a series of sine waves added together, all with different amplitudes, frequencies and relative phases. The Fourier Transform allows non-periodic waveforms and transients to be described in terms of frequency- this is rather more complex, but the basis of it is that a sharp transient (such as a perfectly square step with infinitesimal rise-time) is made up of an infinitely large number of component frequencies. Or to put it another way, perfect sine waves have zero bandwidth, whilst a perfectly square step has infinite bandwidth. Bandwidth is, of course, the range of frequencies occupied by your signal.

The easiest way to understand frequency domain analysis and bandwidth is to play with a *spectrum analyser*. This lab instrument usually uses digital processing to perform the Fourier Transform on an incoming waveform, displaying a voltage-against-frequency graph on the screen. On the frequency domain graph, many principles become clear:

- *superposition & frequency division multiplexing*- different signals at different frequencies can all coexist on a single cable or other communication channel

- *filtering*- you can separate signals at different frequencies using a filter circuit, which amplifies or attenuates signals depending on their frequencies.
- *signal-to-noise ratio* – the graph shows the peaks at the signal frequencies, with respect to the noise appearing on the channel at all frequencies.

Physicists say that you never really understand a new theory, you just get used to it, and this is often the case with the time versus frequency debate. Experienced analogue and communications engineers often talk in terms of frequency without realising other people don't understand. You'll just have to get used to it- although working in the field helps a lot!

Bandwidth is often the most talked-about frequency term. It's nearly always the source of compromises in communications systems. I worked in spectrum planning for short period, where the construction of TV and radio transmitters was regulated. In British TV transmissions, there are 48 channels available, each of which has a bandwidth of 8 MHz. Into that bandwidth, the RF researchers can fit a variety of different signals:

- one analogue TV channel, carrying both mono and NICAM stereo sound.
- between 4 and 8 digital TV channels with stereo sound (a 25 Mb/s MPEG-2 data stream) at a moderate level of robustness aimed at domestic receivers.
- one highly robust digital TV channel with stereo sound (8 Mb/s MPEG-2) which can be received without interference on TV sets in vehicles travelling at speed.

As you can see, there's a trade-off between data rate, bandwidth and robustness. Of course, you've then got issues of data compression and error correction on top of this. Bandwidth is (nearly always) a fixed factor- in radio, your bandwidth is controlled by law (the Radiocommunications Agency administers it) and in cable systems the bandwidth depends on what cables and equipment you buy. Because buying extra bandwidth tends to be expensive or impossible, a lot of communications engineering is about getting as much data as possible out of the bandwidth available. Whilst this is fine in a low-noise environment (such as optical fibre), the noisy world of radio is reliant on all sorts of systems for reducing noise. Try listening to short wave radio and you'll find that you have to do most of the noise-reduction yourself!

I hope that I've explained some of the mysteries of communications, and that you'll come to enjoy the subject in the way that I did when I first worked in the field.