The Telephone Example

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1 Introduction

In the 20th century, the telephone system has evolved from a simple method of transmitting voice signals over short distances to a complex global network capable of transmitting voice, images, and data. The telephone has become a ubiquitous component of modern life, allowing instantaneous access to and communication with almost any point on the globe.

The technologies that implement the telephone system span many subdisciplines communications contributes to the overall system design and to the transmission of voice and data signals over wires, fiber optic cables, and microwave links. The subdiscipline of signal processing contributes to compression, sampling, and analog-to-digital and digital-to-analog conversion. The design, fabrication, and miniaturization of the circuits necessary to implement the telephone system is the domain of solid state electronics. Digital design and computer science contribute to the control of every aspect of the phone system.

This document serves three purposes. The first purpose is to provide an accessible, reasonably non-technical description of the telephone system. The second is to provide understandable, physically meaningful examples and exercises for concepts central to electrical engineering and, more particularly, linear circuit analysis. The third is to integrate concepts that will be covered in ECE 301, EEE 302, and EEE 303.

This document is structured as follows. First, we present a simplified description of the earliest phone systems. This description serves to introduce the fundamental concepts associated with the telephone system. Then, we present an overview of the modern telephone system. We then present a conceptual description of the important operations involved in the completion of a telephone call. Finally, we briefly discuss the concept of a complex hardware/software system.

2 The Early Phone System

A schematic of an early telephone system is shown in Figure 1. Each telephone is connected by two wires to a *central office*. The function of the central office is to make connections between

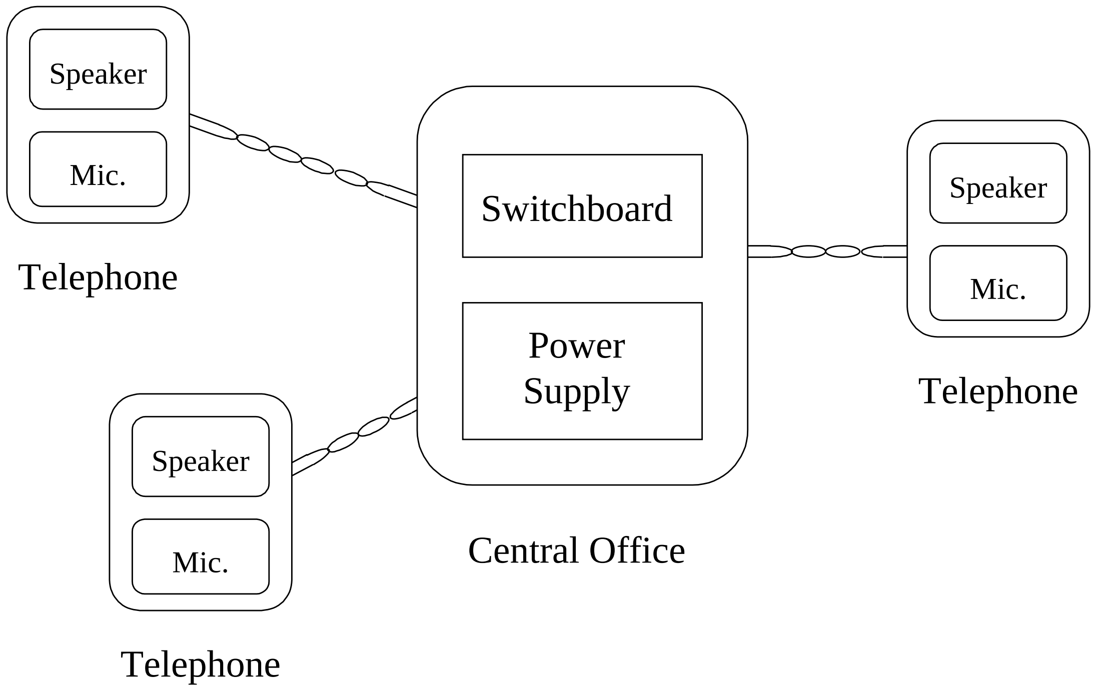

Figure 1: A schematic representation of an early phone system.

phones via a switchboard and to provide the power necessary to operate the phones.

The essential elements of the early telephone were a microphone and a speaker. The microphone converted a sound signal (time variations in pressure) into a time-varying electrical current. Early microphones were constructed using a canister with one side constructed of a flexible diaphram; the canister was filled with carbon granules. The electrical resistance between two wires attached to the canister varied proportionally to the displacement of the diaphragm. The speaker converted a time-varying electrical current into a sound signal. Speakers were typically constructed from an electromagnet and a paramagnetic diaphram. The electromagnet was a coil of wire; changes in the current flowing through the coil changed the force on the diaphram, which in turn changed the diaphram's displacement. Variations in the diaphram's displacement were transmitted to the surrounding air as sound waves.

Figure 2 shows an electrical schematic of a circuit consisting of two telephones; each phone contains a microphone and a speaker. The microphone resistor is represented schematically by the zigzag line; the arrow pointing to the middle of the zigzag line represents the variability of the resistance provided by the diaphram. The speaker coil is represented schematically by the curly line.

Early phone systems required a direct electrical connection between the two telephones involved in a phone call. In the earliest telephone systems, this connection was made physically

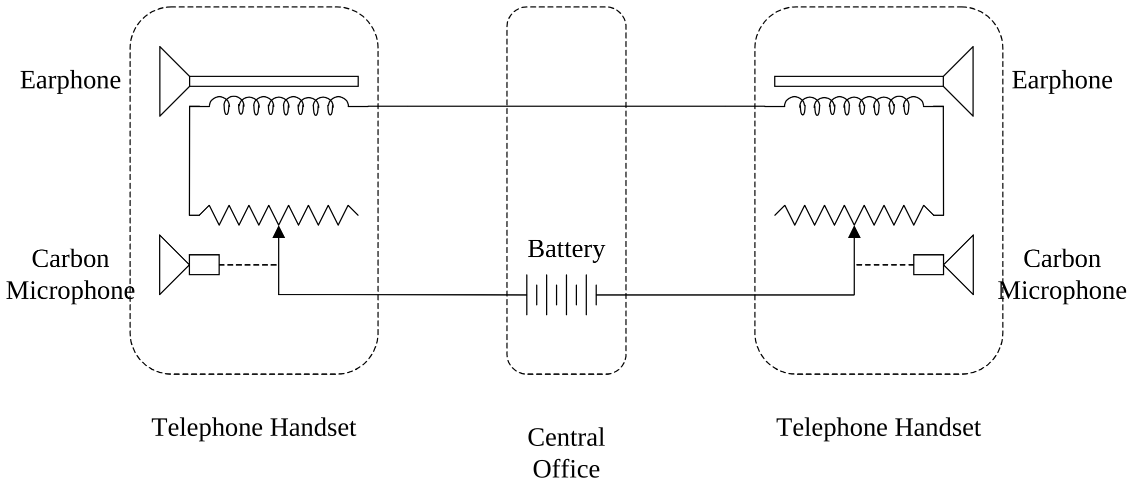

Figure 2: A simple telephone connection illustrating the series connection of telephones and a battery at the central office.

by an operator at a plug switchboard. In later telephone systems, this connection was made by automated electrical switching equipment.

The connection between two telephones formed a loop through which current flowed (called a local current loop). In this loop were the speakers and microphones for each handset as well as a battery at the central office. This configuration is illustrated in Figure 2. All of the elements in this loop are in *series*; the same current flows through each element. When a caller speaks into their microphone, the sound wave causes variations in the resistance of the microphone. These variations in resistance in turn cause variations in the current flowing around the loop. The current variations are converted to sound signals by *both* speakers. Thus, the series arrangement of elements means that both parties to the call can talk and listen simultaneously to the other party. The ability to talk and listen simultaneously is called *full duplex*. If only one party to the call can talk at a time, the call is *half duplex*.

All of the signals in the early phone system were *analog* signals. An analog signal is one that can be represented as a continuous function of time.

3 The Modern Telephone System

Superficially, the modern telephone system appears to a caller to operate much the same as the early system. However, there are substantial and very significant differences:

- The early telephone system provided (what is know today as) POTS-"plain old telephone service"; POTS consists of completing calls and voice transmission. The modern telephone

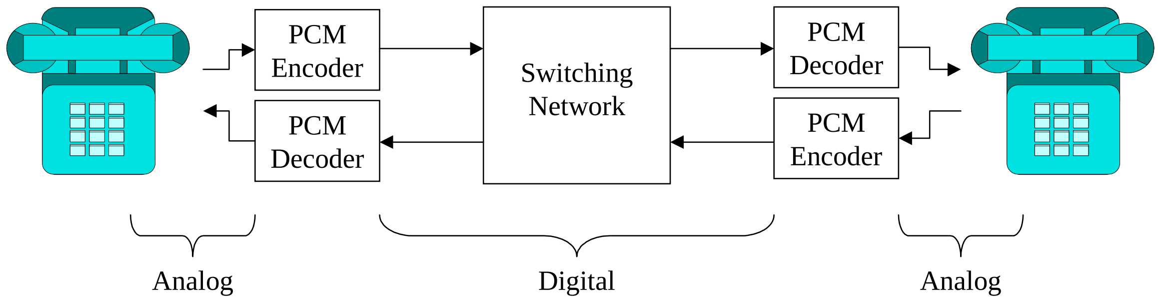

Figure 3: A person-to-person connection in the modern telephone system.

system provides POTS as well as a host of other services including data and video transmission and sophisticated billing and feature capabilities.

- In the early system, calls were routed manually. In the modern system, calls are routed automatically under software control.

- In the early system, speech signals were represented by analog voltage or current signals. In most of the modern system, speech signals are represented digitally.

In this section, we describe some aspects of the operation of the modern telephone system. First, we describe the signal processing involved in a simple person to person call. This signal processing includes sampling and quantization of analog waveforms to obtain digital data. Second, we describe briefly the telephone system architecture.

Figure 3 shows a schematic representation of the configuration of the the telephone system in the process of conducting a person-to-person call. Each person in the call uses a telephone (actually called a *handset* in the telephone industry). Each handset is connected (typically using a wall phone jack) to the wiring of the telephone system. Each phone requires a pair of wires. The wires are in turn connected to a remote terminal (located up to several miles away from the building containing the handset) that contains a PCM encoder and a PCM decoder for each handset to which it is connected. The PCM encoders and decoders are in turn connected to a switching network. This switching network encompasses all of the phone system equipment used to route the data necessary for the person-to-person call between the two handsets.

In the following, we present some details associated with this person-to-person call. We first discuss the difference between analog and digital signals, and then describe the function of the PCM encoder and decoder which convert analog signals to digital and digital signals to analog. We then discuss briefly the structure and operation of the switching network.

The speech signals transmitted in a person-to-person call are represented either as analog signals or digitally; Figure 3 indicates where in the telephone system the signals are analog and where they are digital. An analog signal is a continuous function of time. Figure 4 shows an analog signal. A digital signal is represented as a sequence of 1's and 0's.

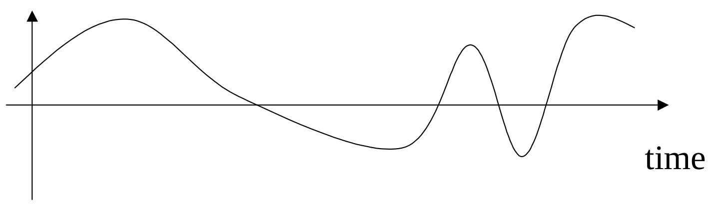

Figure 4: An analog signal.

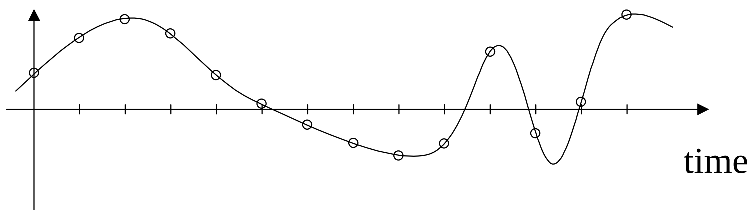

Figure 5: Sampling an analog signal.

In the modern telephone system, digital signals are used wherever possible because digital signals have several advantages over analog signals. One advantage is in long-distance transmission of signals. Noise and distortion degrade a signal when it is transmitted over long distances; a digital signal can be "cleaned up", restoring the original signal, while an analog signal cannot be completely restored. Thus, *repeaters* (systems that clean up and amplify the signal) can be used to transmit digital signals over long distances. Another advantage of digital signals over analog signals is that many different types of information, including speech, video, and data, can be mixed into a single digital signal. Also, digital hardware is typically less expensive than analog hardware. Finally, digital signals can be processed directly by computers; since the switching network in Figure 3 is implemented with computers, digital signals are the most effective format.

In Figure 3, the PCM encoder and decoder convert between analog and digital signals. PCM stands for pulse code modulation. A PCM encoder converts an analog signal into a digital signal with a particular format. A PCM decoder converts the digital signal back into an analog signal.

3.1 The PCM Encoder

A PCM encoder uses three operations to convert an analog signal into a digital signal. These operations are sampling, quantization, and encoding.

Sampling is the process of obtaining the value of an analog signal at equally spaced points in time, as illustrated in Figure 5. Each value is called a *sample*.

Quantization is the process of quantizing each sample (which in principle could be any real number) into one of a finite number of values. Quantization is performed by a device called

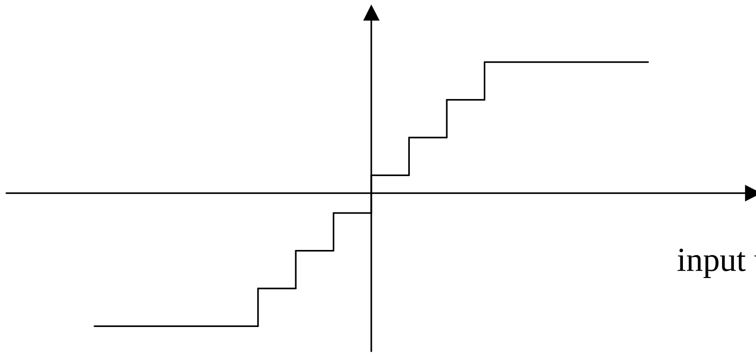

Figure 6: The input/output relationship of an example quantizer.

a quantizer that has an input and an output that is a function of the input. The mathematical relationship between the input and output of an example quantizer is show in Figure 6. Note that any possible input voltage is mapped to one of eight possible output voltages.

Encoding is the process of assigning a specific bit pattern to each possible output level of the quantizer. For example, the lowest output voltage of the quantizer in Figure 6 might be assigned the bit pattern 000, the next lowest output voltage might be assigned 001, and so on. In general, 2^n quantizer output levels can be encoded using n bits.

3.2 The PCM Decoder

The PCM decoder "undoes" the work of the PCM encoder-it converts from digital bit patterns to analog voltages. Each n-bit pattern, corresponding to a given sample of the analog waveform, is converted into a corresponding voltage. For example, if the quantizer in Figure 6 is used, then a bit pattern of 000 would be converted into the lowest output voltage of the quantizer; a bit pattern of 001 would be converted into the next lowest voltage, and so on. Figure 7 shows the output of a PCM decoder for an example input. The "stair-step" nature of the signal is a consequence of the finite number of quantization values of the quantizer. This stair-step signal is an approximation to the original speech signal.

3.3 The Switching Network

We now turn our attention to the switching network-that portion of the phone system that connects one caller to another. We begin by defining several components of the network. We then show a portion of the network and describe the components of this network.

Figure 8 shows a portion of the telephone switching network. A house or a business connected

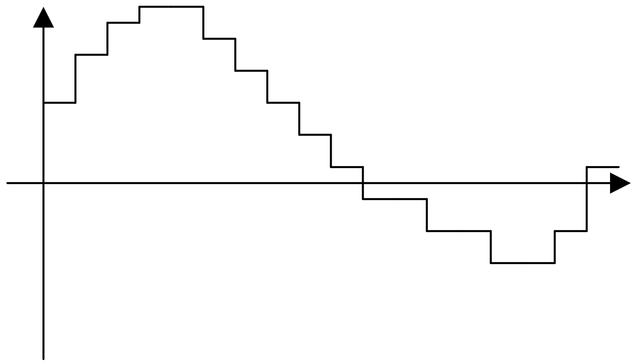

Figure 7: Output of a PCM decoder.

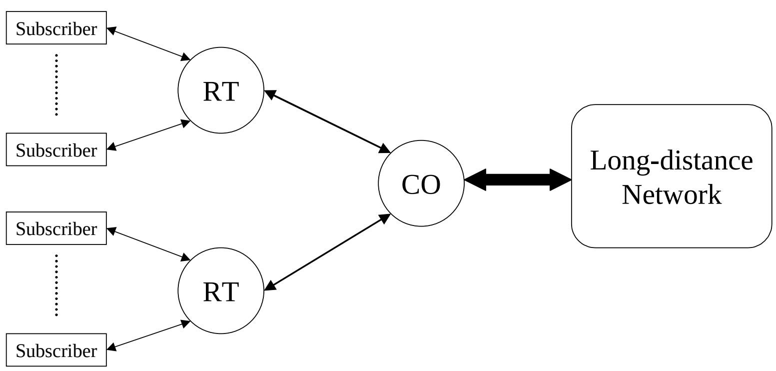

Figure 8: A portion of the telephone switching network.

to the network is called a *subscriber*. Typically, subscriber connections to the network are made with twisted-pair wires. The RT is a *remote terminal*. The remote terminal is located at most a few miles distant from the subscribers to which it is connected. The PCM encoder and decoder that convert between analog and digital signals are typically housed within the remote terminal. The CO is a *central office*. The central office is connected to several remote terminals as well as to one or more long-distance networks.

The primary functions of the remote terminal are to do conversion between analog and digital signals and to *multiplex* the signals from many subscriber calls into a single signal that is transmitted to the central office. As previously described, the conversion between analog and digital signals is performed by PCM encoders and decoders. The multiplexing operation is time-division multiplexing, in which many digital signals with a reasonably low bit-rate are combined into a single digital signal with a much higher bit-rate.

The central office performs most of the functions that we associate with the phone system. At the beginning of a telephone call, computers at the central office interpret the dialed number and, if the call is local (ie. to another subscriber connected to this central office), set up a data connection between the caller and the called handset. If the call is not local, the central office communicates with other central offices via the long-distance network to set up the data connection. The central office also keeps track of billing information. Many extra features, such as call forwarding, call waiting, and voice mail, are also implemented by the central office.

4 Complex Hardware/Software Systems

The modern telephone system is an excellent example of a complex hardware/software system. Almost all operations of the system, including completion and routing of calls, billing, and supporting extra features, are performed by computers under software control. The software running these computers is frequently updated to implement new features and improve system performance and reliability.

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   Strongly Agree Agree Neutral Disagree Strongly Disagree

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