# UNDERSTANDING TELEPHONES

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## Everybody has one, but what makes it work?

Although telephones and telephone company practices may vary dramatically from one locality to another, the basic principles underlying the way they work remain unchanged.

Every telephone consists of three separate subassemblies, each capable of independent operation. These assemblies are the speech network, the dialing mechanism, and the ringer or bell. Together, these parts - as well as any additional devices such as modems, dialers, and answering machines - are attached to the phone line.

### The phone line

A telephone is usually connected to the telephone exchange by about three miles (4.83 km) of a twisted pair of No.22 (AWG) or 0.5 mm copper wires, known by your phone company as "the loop". Although copper is a good conductor, it does have resistance. The resistance of No.22 AWG wire is 16.46 Ohms per thousand feet at 77 degrees F (25 degrees C). In the United States, wire resistance is measured in Ohms per thousand feet; telephone companies describe loop length in kilofeet (thousands of feet). In other parts of the world, wire resistance is usually expressed as Ohms per kilometer.

Because telephone apparatus is generally considered to be current driven, all phone measurements refer to current consumption, not voltage. The length of the wire connecting the subscriber to the telephone exchange affects the total amount of current that can be drawn by anything attached at the subscriber's end of the line.

In the United States, the voltage applied to the line to drive the telephone is 48 VDC; some countries use 50 VDC. Note that telephones are peculiar in that the signal line is also the power supply line. The voltage is supplied by lead acid cells, thus assuring a hum-free supply and complete independence from the electric company, which may be especially useful during power outages.

At the telephone exchange the DC voltage and audio signal are separated by directing the audio signal through 2 uF capacitors and blocking the audio from the power supply with a 5-

**Henry choke in each line. Usually these two chokes are the coil windings of a relay that switches your phone line at the exchange; in the United States, this relay is known as the "A" relay (see fig.1). The resistance of each of these chokes is 200 Ohms.**

**We can find out how well a phone line is operating by using Ohm's law and an ammeter. The DC resistance of any device attached to the phone line is often quoted in telephone company specifications as 200 Ohms; this will vary in practice from between 150 to 1,000 Ohms. You can measure the DC resistance of your phone with an Ohmmeter. Note this is DC resistance, not impedance.**

**Using these figures you can estimate the distance between your telephone and the telephone exchange. In the United States, the telephone company guarantees you no lower current than 20 mA - or what is known to your phone company as a "long loop." A "short loop" will draw 50 to 70 mA, and an average loop, about 35 mA. Some countries will consider their maximum loop as low as 12 mA. In practice, United States telephones are usually capable of working at currents as low as 14 mA. Some exchanges will consider your phone in use and feed dial tone down the line with currents as low as 8 mA, even though the telephone may not be able to operate.**

**Although the telephone company has supplied plenty of nice clean DC direct to your home, don't assume you have a free battery for your own circuits. The telephone company wants the DC resistance of your line to be about 10 megOhms when there's no apparatus in use ("on hook," in telephone company jargon); you can draw no more than 5 microamperes while the phone is in that state. When the phone is in use, or "off hook," you can draw current, but you will need that current to power your phone, any current you might draw for other purposes would tend to lower the signal level.**

**The phone line has an impedance composed of distributed resistance, capacitance, and inductance. The impedance will vary according to the length of the loop, the type of insulation of the wire, and whether the wire is aerial cable, buried cable, or bare parallel wires strung on telephone poles. For calculation and specification purposes, the impedance is normally assumed to be 600 to 900 Ohms. If the instrument attached to the phone line should be of the wrong impedance, you would get a mismatch, or what telephone company personnel refer to as "return loss." (Radio Amateurs will recognize return loss as SWR.) A mismatch on telephone lines results in echo and whistling, which the phone company calls "singing" and owners of very cheap telephones may have come to expect. A mismatched device can, by the way, be matched to the phone line by placing resistors in parallel or series with the line to bring the impedance of the device to within the desired limits. This will cause some signal loss, of course, but will make the device usable.**

A phone line is balanced feed, with each side equally balanced to ground. Any imbalance will introduce hum and noise to the phone line and increase susceptibility to RFI.

The balance of the phone line is known to your telephone company as "longitudinal balance." If both impedance match and balance to ground are kept in mind, any device attached to the phone line will perform well, just as the correct matching of transmission lines and devices will ensure good performance in radio practice.

If you live in the United States, the two phone wires connected to your telephone should be red and green. (In other parts of the world they may be different colors.) The red wire is negative and the green wire is positive. Your telephone company calls the green wire "Tip" and the red wire "Ring". (In other parts of the world, these wires may be called "A" and "B".) Most installations have another pair of wires, yellow and black. These wires can be used for many different purposes, if they are used at all. Some party lines use the yellow wire as a ground; sometimes there's 6.8 VAC on this pair to light the dials of Princess type phones. If you have two separate phone lines (not extensions) in your home, you will find the yellow and black pair carrying a second telephone line. In this case, black is "Tip" and yellow is "Ring."

The above description applies to a standard line with a DC connection between your end of the line and the telephone exchange. Most phone lines in the world are of this type, known as a "metallic line." In a metallic line, there may or may not be inductance devices placed in the line to alter the frequency response of the line; the devices used to do this are called "loading coils." (Note: if they impair the operation of your modem, your telephone company can remove them.) Other types of lines are party lines, which may be metallic lines but require special telephones to allow the telephone company to differentiate between subscribers. Very long lines may have amplifiers, sometimes called "loop extenders" on them. Some telephone companies use a system called "subscriber carrier," which is basically an RF system in which your telephone signal is heterodyned up to around 100 Khz and then sent along another subscriber's "twisted pair."

If you have questions about your telephone line, you can call your telephone company; depending on the company and who you can reach, you may be able to obtain a wealth of information.

## The Speech Network

The speech network - also known as the "hybrid" or the "two wire/four wire network" - takes the incoming signal and feeds it to the earpiece and takes the microphone output and feeds it down the line. The standard network used all over the world is an LC device with a carbon microphone; some newer phones use discrete transistors or ICs.

One of the advantages of an LC network is that it has no semiconductors, is not voltage sensitive, and will work continuously as the voltage across the line is reduced. Many transistorized phones stop working as the voltage approaches 3 to 4 Volts.

When a telephone is taken off the hook, the line voltage drops from 48 Volts to between 9 and 3 Volts, depending on the length of the loop. If another telephone in parallel is taken off the hook, the current consumption of the line will remain the same and the voltage across the terminals of both telephones will drop. Bell Telephone specifications state that three telephones should work in parallel on a 20 mA loop; transistorized phones tend not to pass this test, although some manufacturers use ICs that will pass. Although some European telephone companies claim that phones working in parallel is "technically impossible," and discourage attempts to make them work that way, some of their telephones will work in parallel.

While low levels of audio may be difficult to hear, overly loud audio can be painful. Consequently, a well designed telephone will automatically adjust its transmit and receive levels to allow for the attenuation - or lack of it - caused by the length of the loop. This adjustment is called "loop compensation." In the United States, telephone manufacturers achieve this compensation with silicon carbide varistors that consume any excess current from a short loop (see fig. 2). Although some telephones using ICs have built-in loop compensation, many do not; the latter have been designed to provide adequate volume on the average loop, which means that they provide low volume on long loops, and are too loud on short loops. Various countries have different specifications for transmit and receive levels; some European countries require a higher transmit level than is standard in the United States so a domestically-manufactured telephone may suffer from low transmit level if used on European lines without modification.

Because a telephone is a duplex device, both transmitting and receiving on the same pair of wires, the speech network must ensure that not too much of the caller's voice is fed back into his or her receiver. This function, called "sidetone," is achieved by phasing the signal so that some cancellation occurs in the speech network before the signal is fed to the receiver. Callers faced with no sidetone at all will consider the phone "dead." Too little sidetone will convince callers that they're not being heard and cause them to shout, "I can hear you. Can you hear ME?" Too much sidetone causes callers to lower their voices and not be heard well at the other end of the line.

A telephone on a short loop with no loop compensation will appear to have too much sidetone, and callers will lower their voices. In this case, the percentage of sidetone is the same, but as the overall level is higher the sidetone level will also be higher.

**The Dial**

There are two types of dials in use around the world. The most common one is called pulse, loop disconnect, or rotary; the oldest form of dialing, it's been with us since the 1920's. The other dialing method, more modern and much loved by Radio Amateurs is called Touch-tone, Dual Tone Multi-Frequency (DTMF) or Multi-Frequency (MF) in Europe. In the U.S. MF means single tones used for system control.

Pulse dialing is traditionally accomplished with a rotary dial, which is a speed governed wheel with a cam that opens and closes a switch in series with your phone and the line. It works by actually disconnecting or "hanging up" the telephone at specific intervals. The United States standard is one disconnect per digit, so if you dial a "1," your telephone is "disconnected" once. Dial a seven and you'll be "disconnected" seven times; dial a zero, and you'll "hang up " ten times. Some countries invert the system so "1" causes ten "disconnects" and 0, one disconnect. Some add a digit so that dialing a 5 would cause six disconnects and 0, eleven disconnects. There are even some systems in which dialing 0 results in one disconnect, and all other digits are plus one, making a 5 cause six disconnects and 9, ten disconnects.

Although most exchanges are quite happy with rates of 6 to 15 Pulses Per Second (PPS), the phone company accepted standard is 8 to 10 PPS. Some modern digital exchanges, free of the mechanical inertia problems of older systems, will accept a PPS rate as high as 20.

Besides the PPS rate, the dialing pulses have a make/break ratio, usually described as a percentage, but sometimes as a straight ratio. The North American standard is 60/40 percent; most of Europe accepts a standard of 63/37 percent. This is the pulse measured at the telephone, not at the exchange, where it's somewhat different, having traveled through the phone line with its distributed resistance, capacitance, and inductance. In practice, the make/break ratio does not seem to affect the performance of the dial when attached to a normal loop. Bear in mind that each pulse is a switch connect and disconnect across a complex impedance, so the switching transient often reaches 300 Volts. Try not to have your fingers across the line when dialing.

Most pulse dialing phones produced today use a CMOS IC and a keyboard. Instead of pushing your finger round in circles, then removing your finger and waiting for the dial to return before dialing the next digit, you punch the button as fast as you want. The IC stores the number and pulses it out at the correct rate with the correct make/break ratio and the switching is done with a high-voltage switching transistor. Because the IC has already stored the dialed number in order to pulse it out at the correct rate, it's a simple matter for telephone designers to keep the memory "alive" and allow the telephone to store, recall, and redial the Last Number Dialed (LND). This feature enables you to redial by picking up the handset and pushing just one button.

Because pulse dialing entails rapid connection and disconnection of the phone line, you can "dial" a telephone that has lost its dial, by hitting the hook-switch rapidly. It requires some practice to do this with consistent success, but it can be done. A more sophisticated approach is to place a Morse key in series with the line, wire it as normally closed and send strings of dots corresponding to the digits you wish to dial.

Touch tone, the most modern form of dialing, is fast and less prone to error than pulse dialing. Compared to pulse, its major advantage is that its audio band signals can travel down phone lines further than pulse, which can travel only as far as your local exchange. Touch-tone can therefore send signals around the world via the telephone lines, and can be used to control phone answering machines and computers. Pulse dialing is to touch-tone as FSK or AFSK RTTY is to Switched Carrier RTTY, where mark and space are sent by the presence or absence of DC or unmodulated RF carrier. Most Radio Amateurs are familiar with DTMF for controlling repeaters and for accessing remote and auto phone patches.

Bell Labs developed DTMF in order to have a dialing system that could travel across microwave links and work rapidly with computer controlled exchanges. Each transmitted digit consists of two separate audio tones that are mixed together (see fig.3). The four vertical columns on the keypad are known as the high group and the four horizontal rows as the low group; the digit 8 is composed of 1336 Hz and 852 Hz. The level of each tone is within 3 dB of the other, (the telephone company calls this "Twist"). A complete touch-tone pad has 16 digits, as opposed to ten on a pulse dial. Besides the numerals 0 to 9, a DTMF "dial" has *, #, A, B, C, and D. Although the letters are not normally found on consumer telephones, the IC in the phone is capable of generating them.

The * sign is usually called "star" or "asterisk." The # sign, often referred to as the "pound sign." is actually called an octothorpe. Although many phone users have never used these digits - they are not, after all, ordinarily used in dialing phone numbers - they are used for control purposes, phone answering machines, bringing up remote bases, electronic banking, and repeater control. The one use of the octothorpe that may be familiar occurs in dialing international calls from phones in the United States. After dialing the complete number, dialing the octothorpe lets the exchange know you've finished dialing. It can now begin routing your call; without the octothorpe, it would wait and "time out" before switching your call.

When DTMF dials first came out they had complicated cams and switches for selecting the digits and used a transistor oscillator with an LC tuning network to generate the tones. Modern dials use a matrix switch and a CMOS IC that synthesizes the tones from a 3.57MHz (TV color burst) crystal. This oscillator runs only during dialing, so it doesn't normally produce QRM.

Standard DTMF dials will produce a tone as long as a key is depressed. No matter how long you press, the tone will be decoded as the appropriate digit. The shortest duration in which a digit can be sent and decoded is about 100 milliseconds (ms). It's pretty difficult to dial by hand at such a speed, but automatic dialers can do it. A twelve-digit long distance number can be dialed by an automatic dialer in a little more than a second - about as long as it takes a pulse dial to send a single 0 digit.

The output level of DTMF tones from your telephone should be between 0 and -12 dBm. In telephones, 0 dB is 1 miliwatt over 600 Ohms. So 0 dB is 0.775 Volts. Because your telephone is considered a 600 Ohm load, placing a voltmeter across the line will enable you to measure the level of your tones.

## The Ringer

Simply speaking this is a device that alerts you to an incoming call. It may be a bell, light, or warbling tone. The telephone company sends a ringing signal which is an AC waveform. Although the common frequency used in the United States is 20 HZ, it can be any frequency between 15 and 68 Hz. Most of the world uses frequencies between 20 and 40 Hz. The voltage at the subscribers end depends upon loop length and number of ringers attached to the line; it could be between 40 and 150 Volts. Note that ringing voltage can be hazardous; when you're working on a phone line, be sure at least one telephone on the line is off the hook (in use); if any are not, take high voltage precautions. The telephone company may or may not remove the 48 VDC during ringing; as far as you're concerned, this is not important. Don't take chances.

The ringing cadence - the timing of ringing to pause - varies from company to company. In the United States the cadence is normally 2 seconds of ringing to 4 seconds of pause. An unanswered phone in the United States will keep ringing until the caller hangs up. But in some countries, the ringing will "time out" if the call is not answered.

The most common ringing device is the gong ringer, a solenoid coil with a clapper that strikes either a single or double bell. A gong ringer is the loudest signaling device that is solely phone-line powered.

Modern telephones tend to use warbling ringers, which are usually ICs powered by the rectified ringing signal. The audio transducer is either a piezoceramic disk or a small loudspeaker via a transformer.

Ringers are isolated from the DC of the phone line by a capacitor. Gong ringers in the United States use a 0.47 uF capacitor. Warbling ringers in the United States generally use a 1.0 uF capacitor. Telephone companies in other parts of the world use capacitors between 0.2 and 2.0 uF. The paper capacitors of the past have been replaced almost exclusively with capacitors made of Mylar film. Their voltage rating is always 250 Volts.

The capacitor and ringer coil, or Zeners in a warbling ringer, constitute a resonant circuit. When your phone is hung up ("on hook") the ringer is across the line; if you have turned off the ringer you have merely silenced the transducer, not removed the circuit from the line.

When the telephone company uses the ringer to test the line, it sends a low-voltage, low frequency signal down the line (usually 2 Volts at 10 Hz) to test for continuity. The company keeps records of the expected signals on your line. This is how it can tell you have added equipment to your line. If your telephone has had its ringer disconnected, the telephone company cannot detect its presence on the line.

Because there is only a certain amount of current available to drive ringers, if you keep adding ringers to your phone line you will reach a point at which either all ringers will cease to ring, some will cease to ring, or some ringers will ring weakly. In the United States the phone company will guarantee to ring five normal ringers. A normal ringer is defined as a standard gong ringer as supplied in a phone company standard desk telephone. Value given to this ringer is Ringer Equivalence Number (REN) 1. If you look at the FCC registration label of your telephone, modem, or other device to be connected to the phone line, you'll see the REN number. It can be as high as 3.2, which means that device consumes the equivalent power of 3.2 standard ringers, or 0.0, which means it consumes no current when subjected to a ringing signal. If you have problems with ringing, total up your RENs; if the total is greater than 5, disconnect ringers until your REN is at 5 or below.

Other countries have various ways of expressing REN, and some systems will handle no more than three of their standard ringers. But whatever the system, if you add extra equipment and the phones stop ringing, or the phone answering machine won't pick up calls, the solution is disconnect ringers until the problem is resolved. Warbling ringers tend to draw less current than gong ringers, so changing from gong ringers to warbling ringers may help you spread the sound better.

Frequency response is the second criterion by which a ringer is described. In the United States most gong ringers are electromechanically resonant. They are usually resonant at 20 and 30 Hz (+&- 3 Hz). The FCC refers to this as A so a normal gong ringer is described as REN 1.0A. The other common frequency response is known as type B. Type B ringers will respond to signals between 15.3 and 68.0 Hz. Warbling ringers are all type B and some United States gong ringers are type B. Outside the United States, gong ringers appear to be non-frequency selective, or type B.

Because a ringer is supposed to respond to AC waveforms, it will tend to respond to transients (such as switching transients) when the phone is hung up, or when the rotary dial is used on an extension phone. This is called "bell tap" in the United States; in other countries, it's often called "bell tinkle." While European and Asian phones tend to bell tap, or tinkle, United States ringers that bell tap are considered defective. The bell tap is designed out of gong ringers and fine tuned with bias springs. Warbling ringers for use in the United States are designed not to respond to short transients; this is usually accomplished by rectifying the AC and filtering it before it powers the IC, then not switching on the output stage unless the voltage lasts long enough to charge a second capacitor.

End of text. Figures Follow

Fig 1. The Phone Line

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       A RELAY
       200 Ohms   Telephone    . Subscriber
       -------    Exchange     .
       -------                 .  TIP +
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 |       5 H    |              .
 |              |              .
+|              |              .
---             |              .    No 22 AWG wire
--- 48V DC      |              .    up to 10 Miles Long
 -              |              .
---    A RELAY  |              .
-|     200 Ohms |              .
 |     -------  |              .
 |     -------  |              . RING -
 -----~~~~~~~~--|---------o------------o
         5 H    |         |    .
 Audio      2uF |     2uF |    .
 coupling 250V ---  250V ---
 Capacitors    ---       ---
                |         |
 o----- \--------         |
                          |
      A RELAY Contacts    |
                          |
 o----- \------------------
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**Fig 2. Telephone Speech Network.**

Simplified U.S. Standard "425B". Component Values may vary between manufacturers. Connections for Dials, Ringers etc. not shown.

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                       . |                  .|
     Sidetone balancing. |  0.047uF 250V    .|
     impedance & loop  . |    | |           .|
     compensation. >>> . o----| |-------o   .|
                       . |    | |       |   .|
                       . |              |   .|
                       . |    |<| VR2   |   .|
                       . o----| |-------o---.|
                       . |    |>|          |.|
                       . |                 |.|
                       . |   68 Ohms       |.|
                       . o---\/\/\/-----|  |.|
                       ..|..............|..|.|
                         |              |  | |
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                         -----)||(------|---------o (GN)
                             1)||(5     |  | |    |
               Loop           )||(      |  | |    |
     TIP       Compensation  2)||(6     |  | |    |
     o------ \------o---------)||(------o  | | RX O
            .       | (RR)   . ||       |  | |    |
            .       |          || 1.5uF |  | |    |
            .       \ 180      ||      --- | |    |
            .       / Ohms     ||      --- | |----o (R)
            .       \          || 250V  |  |      |
            .       |          ||       |  |      |
            .  VR1 ---       . || .     |  |      |
            .      ^ ^    ----)||(------o---   TX O
            .      ---    |  3)||(7              |
            .       |     |   )||(               |
      RING  .       | (C) |  4)||(8       22 Ohms |
     o----- \-------o---------)||(---o----/\/\/---o (B)
                          |          |
            ^             |          |
        Hookswitch        ------------
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Fig. 3.   Standard DTMF pad and Frequencies

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(Low     _____     _____     _____     _____
 Group)|     |   |     |   |     |   |     |
697Hz >|  1  |   |  2  |   |  3  |   |  A  |
       |_____|   |_____|   |_____|   |_____|


         _____     _____     _____     _____
       |     |   |     |   |     |   |     |
770Hz >|  4  |   |  5  |   |  6  |   |  B  |
       |_____|   |_____|   |_____|   |_____|


         _____     _____     _____     _____
       |     |   |     |   |     |   |     |
825Hz >|  7  |   |  8  |   |  9  |   |  C  |
       |_____|   |_____|   |_____|   |_____|


         _____     _____     _____     _____
       |     |   |     |   |     |   |     |
941Hz >|  *  |   |  0  |   |  #  |   |  D  |
       |_____|   |_____|   |_____|   |_____|

         ^         ^         ^         ^
       1209Hz    1336Hz    1477Hz    1633Hz
                  (High Group)
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END