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https://computer.rip - me@computer.rip - fax: +1 (505) 926-5492

2023-05-07 electrical characteristics of telephone lines

Let's take a break from our boring topic of regional history to focus instead on an even more boring topic: implementation details of telephone lines.

The conventional "copper pair" analog telephone line is fading away. The FCC has begun to authorize abandonment of copper outside plant in major markets, and telcos are applying to perform such abandonment in more and more areas. The replacement is IP, part of the overall trend of "over the top" delivery, meaning that all communications utilities can be delivered by the use of IP as a common denominator.

This type of service is usually branded as "digital voice." Historically this seems to have come about to evade VoIP's bad reputation; in the early days of Vonage and the charmingly sketchy, back-of-magazine-ad Magic Jack, VoIP products often delivered subpar service. Today, I think "digital voice" has mostly just become part of price differentiation for carrier-offered VoIP, since independent VoIP services tend to cost considerably less. Still, there is some logic to differentiating digital voice and VoIP: because digital voice service is offered by the operator of the underlying IP network, it benefits from QoS measures that general internet traffic doesn't. On consumer internet connections, especially slower ones, digital voice is still likely to be more reliable than VoIP due to QoS policy.

Ultimately the move to digital voice is probably a good thing, as the abandonment of copper plant will kill off DSL in urban markets and make way for faster offerings---from telcos, usually PON. I'll take the opportunity to eulogize the conventional copper pair, though, by going in to a bit of detail about how it actually worked.

To start, a large disclaimer: the details of the telephone network have varied over time as technology and the industry evolved. Details often varied from manufacturer to manufacturer, and because Western Electric had a practical monopoly on the manufacturing of telephone instruments for many decades, it's pretty much the case that the "standards" for telephone lines in the US were "whatever Western Electric did," which varied over time. There were some independent organizations that promulgated telephone standards (such as the railroads which had their own extensive telephone plants), but they were almost always completely deferential to the Bell System. Independent telephone companies initially *had* to use different conventions than Bell because much of the Bell telephone system was under patent; after the expiration of these patents they mostly shifted to doing whatever Western Electric did to benefit from the ready availability of compatible equipment.

After divestiture, Western Electric's de facto standards-making power was vested to Bellcore, later Telcordia, today iconectiv, which after the end of AT&T monopoly was owned by defense contractor SAIC and is owned today by AT&T's erstwhile competitor

Ericsson. iconectiv continues to promulgate some of the standards used in the telephone industry today, through contracts awarded by the FCC.

This is all to explain that the telephone system is actually surprisingly poorly standardized in the United States. You might expect some hefty ISO specification for analog telephone lines, but there isn't really one outside of equipment specifications published by manufacturers. Many international markets have much more detailed engineering specifications from independent bodies, but they're usually based directly on Western Electric's practices. To make things more confusing, it's not unusual for international telephone standards to either be based on older US practices that are now rare in the US, or to have standardized on "in practice" properties of the US system instead of nominal values, or to have mixed conventions from Western Electric with conventions from European telephone manufacturers like Ericsson. All of these standards end up being *mostly the same,* but with a dizzying number of slight differences.

Today, the FCC imposes requirements on telephone lines as part of its regulatory oversight of telcos. The FCC's requirements are basically to "keep doing whatever Western Electric did," and are often surprisingly loose. Phones are really very robust, and the basic design of the system is over 100 years old. Local loops are routinely in poor condition which throws things out of spec anyway, and then subscribers use all kinds of weird phones that are not always that well designed (the history of regulation of telephone instruments could fill its own post). It's actually fairly intentional that the electrical specifications in the system are all soft targets.

For the purpose of this article I am mostly going to describe the state of a fairly modern local loop, such as one connected to a 5ESS or DMS-100 digital switch. But I will definitely not describe either of these switches totally accurately. I'm trying to give the right general idea without getting too bogged down in the details like the last few paragraphs. I'll take the topic of electrical specifications (potential and current on telephone lines) as a chance to give some examples of the variation you see in practice.

First, let's talk about the very general architecture of an analog local loop.

Somewhere in town there is a telephone exchange, and somewhere in your house there is a telephone. The local loop is fundamentally two long copper wires that go directly from your phone to the exchange. This distance varies greatly. It's advantageous to keep it under a few miles (mostly for DSL), but in rural areas especially it can be far longer.

There's a little more detail to what goes on at the two ends of the line. In your house, you have one or more telephones that you use to make and receive calls. In the parlance of the industry, these are often referred to as "instruments" or "subscriber terminals" depending on the era and organization. Historically, instruments were considered part of the telephone system proper and were property of your telco. Today, you are allowed to purchase and use your own telephones. This comes with some downsides. Along with the phone being your property (and thus your problem), the telephone wiring inside of your home is your property (/problem).

The telephone wiring in your house runs from jack to jack. In the United States, all of the telephone jacks in a home are connected in parallel. This is one of the differences you will find if you look in other countries: because of exact details of the electrical design of the exchange and the phones, and where different components are placed, some countries such as the UK require slightly more complex household wiring than just putting all jacks in parallel. But in the US, that's all we do.

If you crack open a wall and look at your household telephone wiring, you will almost certainly find a surprising number of wires. Not two, but four. This, of course, corresponds with the four pins on a modular telephone jack. Your telephone only uses two wires (one pair), but dating back to the '60s it has been a widespread convention to wire homes for two separate telephone lines. It doesn't cost much more, but it gives the telco the opportunity to upsell you to a second line. This convention is reflected not only in the wiring but, as I mentioned, the connector.

The connector used for modern telephones is often called RJ-11, although that term is not exactly correct in a pedantic way that rarely matters. It's a little more correct, when speaking of the connector itself, to call it a 6P4C modular connector. 6P4C means six positions, four contacts---it could have six pins, but only four of the pins are actually populated. Two are for one phone line, two are for the other. If you actually have two phone lines fitted to your house, you will find that the single-line phones common in homes always use the same pair, so you'll either need an adapter cable or some jacks wired the other way around to use two lines. If you've ever lived in a house with two phone jacks right next to each other, it's likely that one of them is wired with the pairs reversed (or only has one pair at all) so that a standard single line phone can be used on the second line.

The phone wiring in your house joins your phones in parallel with a device formally called a Network Interface Device (NID), but often referred to as the demarc or demarcation point. This is because the NID is not just a technical object but an administrative concept: it is the border between your property and the telco's property. Inside of the NID there is usually a short phone cable (connected to your house wiring) plugged directly into a jack (connected to the telco's wiring). If your phone ever malfunctions, the telco will likely ask you to take it directly to the NID, unplug your household wiring, and plug your phone straight into the jack. If the problem goes away, it is somewhere in your household wiring, and therefore not the telephone company's problem. This is their preferred outcome, and you will be told to use your non-functioning phone to call an electrician.

The NID may be located in different places depending on the details of your house, when it was built, and when telephone service was installed. Most commonly it is somewhere outside of the house mounted on an exterior wall or skirting, often somewhere near the electrical service entry. There are plenty of exceptions, and especially in older houses the NID may be in the basement or crawl space. In some cases, mostly mobile and manufactured homes, the NID may actually be mounted to the telephone pole at the street or your property line, and the overhead or underground connection to your house is also your problem.

From the NID, the telephone line makes way to the exchange. In most cases today this will be as part of a telephone cable. A telephone cable is an assembly of many telephone pairs bundled into one sleeve, and they're either run along utility poles (lower than the electrical lines for isolation) or underground. Either way, your telephone line will be connected to the cable inside of a splice closure. For overhead wiring, splice closure are usually black plastic cylinders hung alongside the cable. For underground wiring, they're usually gray-green pedestals sticking out of the ground. Either one provides space for the many pairs in a cable to be spliced together, some to another cable but some to a drop line that runs to your house.

Most of the time, the cable does not run directly to the exchange. This is not exactly modern practice, but a common convention is to have two levels of "feeder" cables. The F1 cable is a very large cable that runs from the telephone exchange to a neighborhood. There, the F1 cable is spliced onto multiple smaller F2 cables that run along neighborhood streets.

The splice between F1 and F2 cables, and in general any splice between multiple cables, is usually done in a larger splice cabinet. Historically splice cabinets were sometimes mounted up utility poles, but this made them more difficult to safely work on so this arrangement is pretty much gone to history. Instead, modern splice cabinets are larger ground-level pedestals, usually a good 4-8 feet wide with large double doors.

There are several advantages to these splice points. First, they are obviously necessary for the original installation of the telephone infrastructure. Second, splice closure and cabinets are intentionally made for easy modification. This gives the telco a lot of flexibility in fixing problems. The world of local telephone loops is a dirty one, full of dirt and rain. Despite precautions, water has a way of working its way into telephone cables and can cause corrosion which makes pairs unreliable. When you complain, and the NID test shows the problem is on the telco side, they will likely just resplice your home telephone service onto a different pair back to the exchange. This swap from one pair to the other avoids the problem, which is a whole lot easier than fixing it. Actually fixing problems inside of telephone cables is a whole lot of work, and with subscriber numbers dwindling in cities there are usually lots of unused pairs so it's easy to swap them out.

In some areas, your local loop may not actually go directly to an exchange. It might go to something like a remote line concentrator, or a serving area cabinet, or a loop extender. These are all variations on the idea of putting some of the exchange-side equipment in a big curb cabinet, closer to your house. These arrangements are most common in suburban areas where local loop lengths are long and subscriber density is fairly high. I'll mostly ignore this, but know that some of the parts of the telephone switch may actually be in a curb cabinet in your case. These curb cabinets usually function as remote components of the switch and connect back by ISDN or fiber.

Once your telephone loop makes it from your phone, through your house wiring, down a drop cable, through an F2 cable, and then through an F1 cable, it arrives at the telephone exchange. There it often passes through an area called the cable vault, usually an underground space in or adjacent to the basement where cables enter the building, seeping water is drained, and pairs come out of the armored cable jacket. Everything before this point has been "outside plant," and is the realm of outside plant engineers. Now, we have entered the sanctum of the inside plant, and a different department of the company.

From the basement, pairs go to the main frame, basically a really big splice cabinet inside of the telephone exchange. The main frame allows exchange technicians to connect pairs to the switch as they please. If an outside plant technician has fixed your telephone problem by resplicing your house to a different pair, they will submit a ticket (originally a paper slip) to have the exchange technicians perform the same remapping on the main frame. Originally, if you stopped paying your bill, a ticket would be generated for an exchange technician to un-splice your phone line at the main frame. Today, both of these are often done digitally instead by leaving pairs connected to the switch's line cards and reconfiguring the line card mapping.

Which takes us to your local loop's next stop: the actual switch. The many local loops that a class-5 or exchange switch serves terminate (in the case of modern electronic switch) at what are called "line cards." The line card is responsible for managing all of the electrical aspects of a small set of local loops connected to it. Depending on the type of switch, the line card may perform ADC and DAC to convert your analog local loop to digital signaling for further handling by digital means. Or, it may connect your local loop to a device called a hybrid transformer that separates your call into two pairs (one for audio each direction) for further handling in analog form.

And that is your local loop. It's called a loop because the two wires, connected at one end by the switch and at the other end by your phone, allow current to flow all the way around. "Current loop" is the term in electrical engineering for this type of arrangement, and it's such a common means of conveying information by electrical signals that it's often only implied.

For there to be current through the loop, though, someone has to put some potential onto the line. Historically, phones were expected to provide power, but this practice had become obsolete by the end of WWII. In modern phone systems the loop power is provided by the switch. In the case of phones providing power, the phone contained a battery which was occasionally replaced by the telco. In the case of switch-provided power, AC-DC rectification was an imperfect art and there was a need for a backup capability in any case, and so the telephone switch would get its loop power from a very large battery. Because of this history, the normal potential on your phone line is known as battery power. People will sometimes shorten this to say that the switch "provides battery," especially in situations like test equipment or military field phones where it isn't always obvious which end battery power will come from. As another bit of telephone terminology, a telephone line with battery applied is sometimes called "wet," while one without battery applied is called "dry."

Battery power in the United States nominally comes from a series of lead-acid batteries producing a nominal 48v. In practice, there is some considerable variation. In older phone switches, a float charger was continually connected to the batteries and so held the battery voltage higher (around 52-54v) whenever the exchange had utility power available. Likely because of this, some countries such as Japan actually standardized 50v or 52v as the nominal off-hook potential. In newer equipment, battery voltage often comes not from batteries at all but from a regulated switch-mode power supply (that runs either off of external AC power or a battery bank of a potentially different voltage). It may therefore be exactly 48v, but some of these power supplies are actually regulated to 50v to match the typical behavior of older equipment. It really just depends on the device, and most telephones will function acceptably with well below 48v off-hook.

For historic reasons, telephone switches are mostly frame-positive. This means that battery voltage is often described as -48v. The difference doesn't really matter that much on the telephone end, but can be confusing if you are looking at documents that use different conventions. Owing to the 1/4" jacks originally used for telephone exchanges, the two wires in a telephone pair are called "tip" and "ring." Compared to ground, "tip" should be about 0v while "ring" should be about -48v. This "ring" is not to be confused with ringing power, to be discussed later. It's just the naming convention for the wires. Some phones, especially rotary types, will function fine with the polarity backwards. Most newer phones won't.

This talk of voltages, so far, has all been assuming that the phone is on hook. When a phone is on hook, the "hookswitch" disconnects the two sides of the local loop from each other, leaving an open circuit. The voltage across the phone thus settles at whatever voltage is applied by the switch. There are two conditions under which this voltage changes significantly.

First, when the phone is off-hook and you receive a call, the exchange needs some way to ring your phone. An age-old method of ringing phones is a magnetic solenoid (arranged so that its core will strike bells when it moves) with the line passing through it. The coil provides a very high resistance and so passes little current under normal off-hook conditions. When the switch wants your phone to ring, it applies a much higher voltage, and alternates it. In fact, this AC voltage is superimposed on the normal DC battery voltage, and is known as "ringing power" or "ringing voltage." Ringing voltage is AC at

20Hz by wide agreement (this works well for the simple mechanical solenoid ringers), but the potential has varied over time and by manufacturer. It also just tended to vary based on equipment condition, since it was originally produced by electromechanical means such as a motor-generator. 90v is fairly typical, but up to 110v AC is acceptable.

The fact that a telephone line can carry 110v AC is a surprise to many, and should discourage licking loose phone wiring, but from a fire safety perspective it's reassuring to know that the current of the ringing power is rather limited. The details of how it's limited, and to what level, depend on the telephone switch in use, but the current-limiting at the switch allows telephone lines to be handled as class 2 or power-limited for purposes of the electrical code.

The astute reader might notice an interesting problem here. Multiple telephones may be connected in parallel, but ringing voltage provides only limited power. If you have enough phones, will there not be enough ringing power?

Yes.

The implementation of this problem is sort of an odd thing. Federal standards created the concept of a "ringer equivalence number" or REN. When the REN was developed, the standard telephone instrument from Western Electric was the model 500, and other Western Electric phones for PSTN use were made to match the 500. So, a REN is defined as the impedance and resistance imposed by a single Western Electric model 500. Local loops are expected to provide enough ringing power for up to 5 REN. In practice, this is rarely a concern today. Few modern phones use the power-intensive electromechanical ringer of the 500, and if you look at the literature that came with a digital phone like a DECT cordless set you will likely find that it is specified as 0.1 REN. You can have a lot of modern phones before you run into problems.

Ringing current only applies when there is an incoming call and the phone is on hook. When you take the phone off hook, the hookswitch connects the two sides of your local loop together via the phone's "voice circuit." This prompts the switch to stop applying ringing current. Once the voice circuit is connected, the voltage across your phone drops considerably. Power is now flowing and so Ohm's law has taken control. Local loops are long and made of small-gauge wire; just the resistance of the telephone line itself is often over a thousand ohms.

Besides the wiring itself, there are two other notable components the loop current must pass through. First, there is some resistance imposed by the switch. The details of this resistance depend on the exact switch in use but the most common situation is that the phone line passes through a coil in a "line relay" assembly as long as your phone is off hook. This relay informs the switch logic of the state of your telephone line. The resistance imposed by the line relay varies by switch, and on many switches it's adjustable, at least in two or three steps. This allows an exchange technician to make an adjustment if your loop is very short or very long, to keep the loop current more in a normal range. 600 ohms is fairly typical for line relays.

The third important component is the voice circuit of your phone itself, which also varies by phone but is also typically around 200 ohms. Because the phone is in fact powered by the loop current, there is a certain requirement for enough power for the phone to operate. AT&T specified that the maximum local loop resistance should be 2400 ohm. At 2400 ohm and 48v battery power, the loop current will be 20mA. 20mA was about the lower bound at which the voice circuit in typical Western Electric models (such as the 500) performed acceptably. Modern electronic phones are often workable at lower currents (and thus higher loop resistance), but audio quality will become worse.

Too high of loop current can also be a problem. There isn't a widely accepted upper limit that I know of, but it was known by the '60s at least that high loop currents due to low resistance loops (usually found when the subscriber lived close to the telephone exchange) caused higher temperatures in the line relay which could result in early failure of the line card. This is one of the reasons line cards often provide an adjustment, so that short loops can have a higher line relay resistance to reduce the current. Modern line cards often monitor the current on a loop and raise a trouble ticket if it is abnormally low or high. Either one tends to indicate that there is a problem somewhere in the line. Modern line cards also provide better over current protection and will usually automatically disconnect battery power (and raise a trouble ticket) if the current goes significantly above normal. This is why you can't get greedy if you are trying to charge your laptop on Ma Bell's dollar. Older equipment may have just used a fuse, so at least newer systems have the forgiveness of auto-reset a few seconds after laptop-charging mistakes.

Under off-hook conditions, with loop current flowing, the voltage across your telephone will be much lower. 3-5v is pretty typical, but the value will vary with voice modulation as you use the phone and isn't very important.

It's important to emphasize that nothing in this system is very well regulated. Well, with modern equipment the battery voltage is often precisely regulated, but that's more a natural consequence of switch-mode power supplies than any aspect of the design of the telephone system. Battery voltage is 48v in the same sense that automotive electronics are 12 or 24v, in practice it's often higher. Loop current is limited but fairly loosely. The acceptable range is pretty wide in either case.

To put some more solid numbers on it, here are some specs taken from the manual for a PABX. They seem pretty typical, except the upper limit for off-hook voltage which seems unusually low. Many sources say 4-9v. Note the two different ringing voltage specifications, these are to accommodate two different national standards.

- On-hook voltage: 40-50 V DC
- Off-hook voltage: 4 to 6 V DC
- Ringing: 90-100 V AC 20Hz or 60-90 V AC 25Hz.
- Loop current: 25-40 mA (up to 80 mA in "unusual circumstances")

And for flavor, numbers I took from the spec sheet of a different business telephony product:

- On-hook voltage: -54v to 40v DC
- Off-hook voltage: -20v to -5v DC
- Current: 23-35 mA

Note the different voltage convention, and that all the numbers are, well, similar, but different. That's just how it is!