DC signaling in the traditional long-distance telephone network–SX, CX, and DX

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PREFACE

In the traditional long-distance ("toll") telephone network, before the introduction of multiplex ("carrier") transmission systems, intercity circuits were carried by individual metallic conductor pairs. And even after the introduction of multiplex systems, for a while shorter intercity circuits were often carried that way.

These circuits of course carried voice signals in both directions. But they also needed to carry in each direction a two-state "signaling channel", needed so the circuit could participate in the operations needed to set up and administer a connection. These signaling channels operated with DC voltages sent over the conductor pairs.

Three principal schemes were used, identified (in order of the sequence of their introduction) by the designations "SX" (for "simplex"), "CX" ("composite"), and "DX" ("duplex").

This article describes the need for signaling channels and the principles of these three schemes. The origin and basic principles of the "E&M led" signaling interface are described. Pertinent background is given.

1 THE TOLL NETWORK

1.1 Trunks and circuits

The traditional long distance telephone network (generally spoken of in the business as the "toll" network) was dependent on trunks that linked together the various switching points in the network (originally all using manual switchboards). I will speak of these overall as "intercity trunks." Each *trunk* was carried by a *circuit*.

Prior to the introduction of multiplex ("carrier") transmission systems, in the most basic situation each of these circuits was carried by a distinct pair of conductors, either on an open-wire pole line or in a cable.

1.2 Supervisory signaling

1.2.1 *Introduction*

Each of these circuits of course was expected to carry voice signals. But in addition, they needed to carry various sorts of *signaling*, needed so that the circuit could participate in the process of setting up, and then administering, a long-distance connection.

The type of signaling in which we will here be interested is called *supervisory signaling* (the basis for that term will be seen shortly). In the form that eventually became the norm, this required a two-state *signaling channel* in each direction as part of the overall circuit capability. The most prominent uses of those two signaling channels are as follows.

1. In the "rearward" direction of an established connection: the two states told whether the called station was off-hook or on-hook. This was needed so that the long-distance switchboard operator at the originating end of the connection could:

a. Determine if and when the called telephone had answered.

b. Determine when the called telephone had been "hung up" (in order to end the call).

2. In the "forward" direction of a connection being established, the signaling channel was used so that when the operator at the "originating" end plugged a cord into a trunk, that would be conveyed (over the forward signaling channel of the circuit) to bring up a lamp indicator at the far end switchboard, notifying the operator there that a call was "coming over" that trunk and that she should attend to it (spoken of as the "seizure" of the trunk).

1.2.2 *The term "supervisory signaling"*

The term "supervisory signaling" came from usage 1, above. It was said that one of the duties of the originating switchboard operator was to "supervise" the connection, that is, to administer it. An important piece of information needed to fulfill that duty was whether each of the other telephones involved was "off-hook" or "on-hook.

Thus we can see why the rearward signing channel of a toll circuit was spoken of as a "supervisory signaling" channel. But because these circuits were more-or-less symmetrical, that term came to embrace the comparable forward signaling channel as well.

As a result of this history, the two states of a supervisory signaling channel, in either direction, whatever they may mean under a given operating protocol, are generically described as "on hook" and "off hook". In many cases, we can consider the "on hook" state to be the "idle" state.

2 CAVEAT

In the wide world of US/Canadian telephone practice (to which this article is limited), there are many variations of application situations and implementations of the various basic circuit concepts discussed here, and many subtleties of circuit design and operation. In this article I don't at all seek to "cover that waterfront", but rather to illuminate the important operating principles of the several DC signaling systems.

3 SYMBOLOGY

In the various illustrations to follow, I will use the "detached contact" schematic notation system for relays and the like.

For those not familiar with that notation, I will give a brief review here. Figure 1 is a quick guide to the symbols that will appear here (and one that won't).

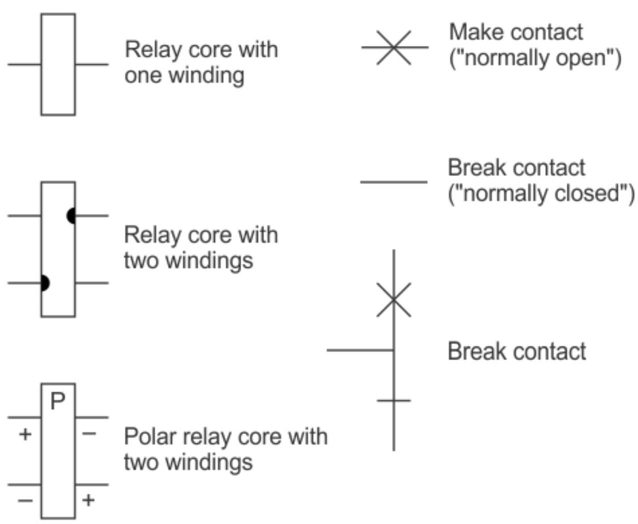

Figure 1. Selected detached contact schematic symbols

The defining characteristic of this system of notation (from which it gets its name) is that the symbols for the various contacts of a relay are not drawn adjacent to the symbol for the core and relay windings of that relay. Rather, each symbol is drawn where it will best participate in showing the various circuits path involved.

A second characteristic of this system is that the symbols for the relay windings and for the different types of contacts are nott "cartoon" versions of the actual physical form of that element, but are arbitrary (and much easier to draw) symbols.

Although it will not appear in any of the illustrations in this article, for continuity of the story I include in the figure the symbol for the core and coil windings of basic two-winding relay. Here the two little half dots show comparable ends of the two windings, that is, the ends that, if both receive the same polarity of voltage, the magnetic effect of the two windings will be additive.

The two windings are often distinguised by the markings “P” (primary) and “S” (secondary). If there is s third winding (not seen in this illustration) it is usually designated “T” (tertiary).

An important player in all the following illustrations is the *polar relay*, a relay whose response is based on the polarity of current through its winding(s. I show one with two windings, since all those to be seen here are such.

Each winding carries plus and minus narks. If the current through a winding is such that the resulting voltage across the winding matches those marks, the relay is put to its “operated” state. If the polarity of the voltage across the winding is opposite to the marks, the relay is put to its “released” state.[1]

If there are two or more windings, the result on the relay state is based on the algebraic net effect of the current through all windings.

4 DUPLEX TELEGRAPHY

4.1 Introduction

Each of the three systems I will discuss for conveying the supervisory signaling states in both direction by way of DC signals depends on a principle originally developed in connection with telegraph networks (especially with respect to international telegraph “circuits”). I will here digress from discussion of telephone network signaling to discuss this principle in its original context.

4.2 Basic telegraph circuit

Figure 2 shows in simplified form the basic circuit used for long (typically international) telegraph circuits.

[1] If there is no current through any winding (or a net effect of zero for all windings), the most common form of polar relay will remain in the state to which it was last put by current through one or more windings.

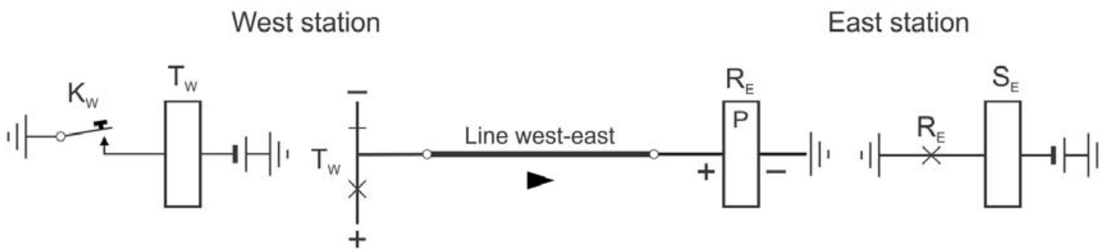

Figure 2. Basic international telegraph circuit

Here, a single conductor (operated "against ground") is used to carry the telegraph signal.

Note that I use the subscript letters "W" and "E" to distinguish components at the west and east stations, respectively. This is not really needed for this illustration, but will become more important in the subsequent illustrations, so I use it here for consistency.

Unlike in local telegraph practice, where the two signaling states ("key up" and "key down" [2]) are represented by current *not flowing* and *flowing* in the line (respectively)[3], here *polar signaling* is ordinarily used. In that, voltages of the same magnitude but opposite polarity are used to represent the two signaling states.

I show a relay, T_W (transmit), operated in a local DC circuit by the contact of the key (K_W). The contacts of T_W apply this polar signal to the telegraph line conductor.

At the distant end, this signal (typically quite weakened by the attenuation of the conductor) operates a sensitive polar (that is, polarity-sensitive) relay, R_E ("receive"). Its contact, through a local circuit, operates the receiving telegraph sounder (S_E).

For the transmission of messages in the opposite direction, we have a second identical setup, just like the first, requiring of course a second line conductor. We see this situation in Figure 3.

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[2] Actually in telegraph practice the two states are spoken of as "space" (or "spacing") and "mark" (or "marking"), respectively.

[3] An approach called *neutral signaling*. to be distinguished from *polar signaling*, which is spoken of next.

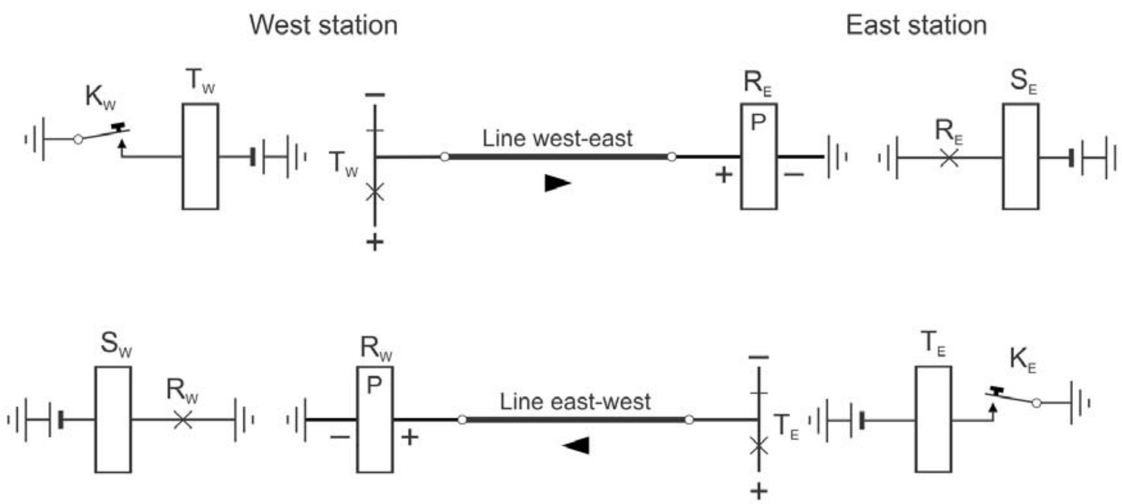

Figure 3. Bidirectional telegraph operation

4.3 The duplex telegraph

An important improvement in this field was the development of a scheme by which telegraph signals could be, independently and simultaneously, sent in both directions over a single conductor, a system called the *duplex telegraph*. Figure 4 shows, in simplified form, the principle of this system.

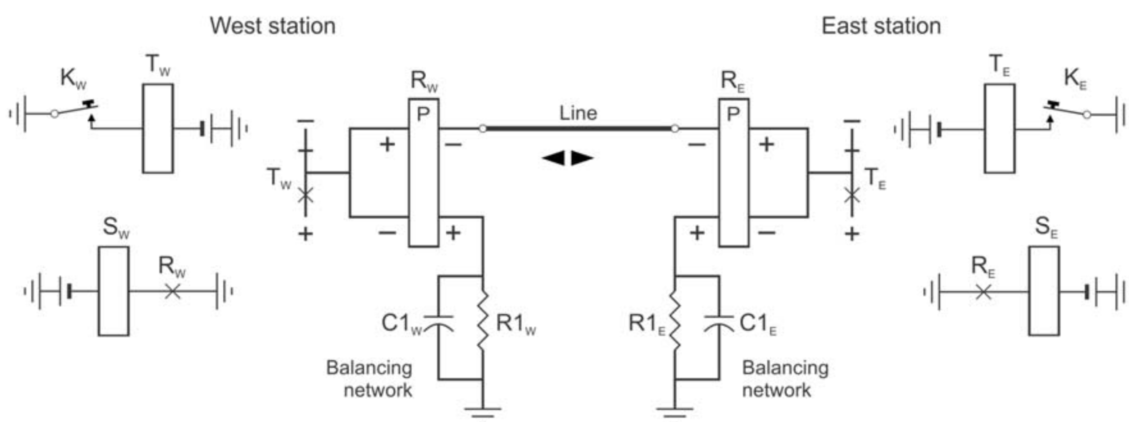

Figure 4. Duplex telegraph

Consider first sending from the west station. Again the contacts of the key (K), via a local circuit, operate the T_W (transmit) relay. As before, that creates a polar signal. Now, rather than this going directly to the line conductor, it goes to the line conductor through the primary (P) winding of the receive relay at this end (R_W). It also goes through the identical secondary winding (S) of relay R_W to an R-C network called the *balancing network*.

The balancing network is designed such that its resistance (actually its impedance at various frequencies contained in the telegraph signal) closely approximates the impedance "looking into" the telegraph line itself.[4]

The intended result is that, for either voltage applied by the contacts of T_W, equal current flows through the two (identical) windings of the relay. These are "oppositely poled" (as shown by the polarity markings on the winding terminals. Thus there is no net magnetic effect on relay R_W from the telegraph signal generated by relay T_W. So relay R_W is not affected by the signal being **sent** into the telegraph line.

Now we go to the distant (east) station, where we have the identical circuit. The current arriving there (from the voltage applied at the west end) passes through winding P of relay R_E, adding ("algebraically") to the current through that winding at that time from the voltage applied by relay T_E.

But it does not pass through winding S of relay R_E. Thus this current, representing the telegraph signal from the west end, has a net effect on relay R_E, causing it to change state, which in turn results in the operation of sounder S_E.

And of course the complementary thing happens for signaling by the key at the east station, which will affect relay R_W at the west station.

Thus the manipulation of the telegraph key at the west station operates the sounder at the east station, and vice versa, independently and perhaps simultaneously, this all happening over a single line conductor.

4.4 Duplex vs. simplex

Since this provided two "telegraph channels" over the line conductor, this system came to be called the "duplex telegraph". So what is the opposite, where a single line conductor only supports one telegraph channel. Is that then "simplex telegraph"? Yes, that term was sometimes used. But we must be mindful that this is a wholly different usage of the term "simplex" than we will shortly encounter.

5 KEEPING IT SIMPLE

5.1 Introduction

In telephone transmission using metallic conductor pairs, the basic *modus operandi* is that one pair supports one circuit. But there were two important departures from this in actual practice. I digress from my discussion of DC signaling to speak briefly of this.

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[4] In reality this network is more complicated than shown, with several resistors and capacitors. I use this simplified version to save "clutter" in the illustration.

5.2 4-wire operation

In the “basic mode”, the speech signals are sent in both directions over the same pair of conductors (just as in a local telephone line). But when we need to insert amplification into the line, in order to overcome its attenuation, the two directions of transmission need to be separated, each given the benefit of an amplifier (for its direction of propagation), and then the two combined again. These amplifiers are actually called “repeaters” in the business.

This separation process can only be imperfectly accomplished, and the result is that “echo” is created at each repeater station. In a long line, with many repeater stations, the accumulated echo becomes intolerable.

At one point, AT&T decided that the “best bang for the buck” would be attained by dedicating two conductor pairs to each circuit, one used exclusively for each direction of transmission of the speech signals.

Not surprisingly, this came to be called “4-wire operation”. Then, by contrast, the earlier *modus operandi* came to be called “2-wire operation”).

The existence of 4 conductors for a circuit gives the potential of more DC paths for carrying signaling signals. But since the point of this article is to explain the principles of three DC signaling systems, not to explore the details of their implementation in various settings, I will from here on assume that the circuits involved use 2-wire operation.

5.3 Phantom circuits

In many cases, toll circuits were implemented in a way that uses two conductor pairs to carry three circuits. We might at first visualize the use of these four conducctors with three of them each carrying the “hot” side of a circuit and the fourth being the “common” for all of them.

But this would have severe problems as to noise and “crosstalk”, and so a somewhat more sophisticated arrangement is used.

Conductors 1a and 1b (pair 1) carry circuit 1; conductors 2a and 2b (pair2) carry circuit 2.

Circuit 3 is carried by a “pair” one of whose conductors is conductors 1a and 1b, effectively in parallel, and the other of whose conductors is conductors 2a and 2b, effectively in parallel.

This third circuit is spoken of as the “phantom,” circuit (and the other two as “side” circuits), and this whole scheme is called “phantom operation”.

The existence of 4 conductors for three circuits calls for some special arrangements regarding the transport of DC signaling signals. But since the point of this article is to explain the principles of three DC signaling systems, not to explore the details of their implementation in various settings, I will from here on assume that the circuits involved do not use phantom operation.

6 AC VS. DC

We look to a circuit to carry (separately):

- Speech signals (AC)
- Signaling signals, which we speak of as DC (but in fact, since the voltages change, this is not strictly DC, but rather an AC signal of low fundamental frequency). But I will speak of them as DC signals.

Accordingly,. an important part of the DC signaling systems that will discussed here is how to introduce those two classes of signals onto the circuit pair at one end and extract them separately at the other end. Two different approaches to this are used over the three signaling systems to be discussed.

7 THE SX ("SIMPLEX") SIGNALING SYSTEM

Figure 5 shows the principle of the "SX" ("simplex" signaling system.

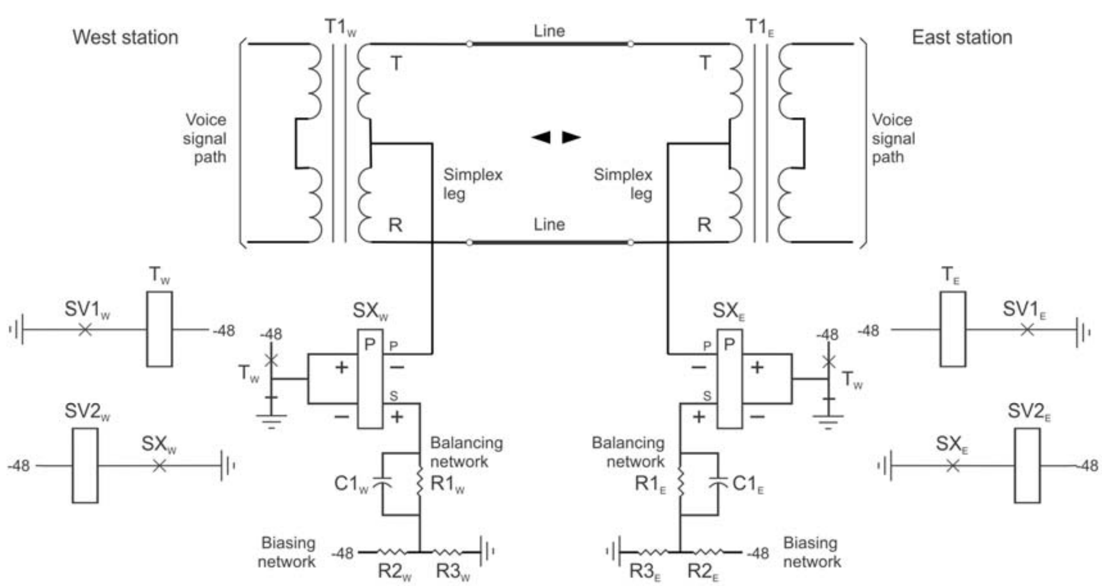

Figure 5. SX ("simplex") signaling system

If we connect our voice signals to the two conductors of the line though a transformer (called a "repeat coil" in the business), such as $T1_W$ and $T1_E$ in the illustration, a connection to the center of the line side winding of that transformer (the "simplex leg") will effectively allow a current to be sent through the two line conductors in parallel. This is spoken of as “simplex operation” (SX).

Meanwhile, the AC voice signal is coupled “across the line” by the transformer.

This signaling system indeed uses a simplex connection to derive what is in effect a single conductor over which the DC signaling signals are conveyed. This one “conductor” carries the signaling signals in both directions using the “duplex telegraph’ technique described in Section 4.3.

But there is an important difference from the simplex telegraph circuit. In that, voltages of the same magnitude but opposite polarity were applied for the two signaling states.

But the context in which the SX signaling system is used (a telephone central office) might not have such opposite polarity DC sources available. Accordingly, in the SX signaling system, ground is applied for one signaling state and “battery” (usually nominally -48 V DC) is applied for the other.

Here, the receiving relay, which I arbitrarily called “R” in the discussion of the duplex telegraph, is designated “SX”, as is the usual practice for this type of signaling circuit.

But this means that the “slice point” of the receiving relay (the value that divides its “operated” and “operated” states) is no longer “zero”, but rather is (ideally) half the battery voltage.

To provide for that, the “bottom” end of the balancing network is connected not to ground but rather to a tap on a voltage divider (resisters R2 and R3), the “bias potentiometer”, fed by battery. This in effect puts the “reference voltage” of the receiving relay circuit at half the battery voltage.[5]

An advantage of this system is that the effective resistance of the path for the DC signaling signals is half the resistance of an individual conductor (since two conductors are essentially in parallel for these signals). This is beneficial as to the length of line over which this system will operate reliably.

A disadvantage comes from the fact that the signaling voltages are applied, and observed, with respect to local ground at each end. Should there be a difference in ground potential between the two end

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[5] For subtle reasons I will not discuss here, in actual practice the tap on the bias potentiometer is not at exactly half the battery voltage.

stations (which can arise from many causes), that adds to the intended voltages and can cause the receiving relay to respond improperly.

Note that this system gets it name from the way that the DC path for signaling signals is derived from the line conductor pair.

8 THE CX ("COMPOSITE") SIGNALING SYSTEM

Figure 6 shows in simplified form the basic concept of this system,

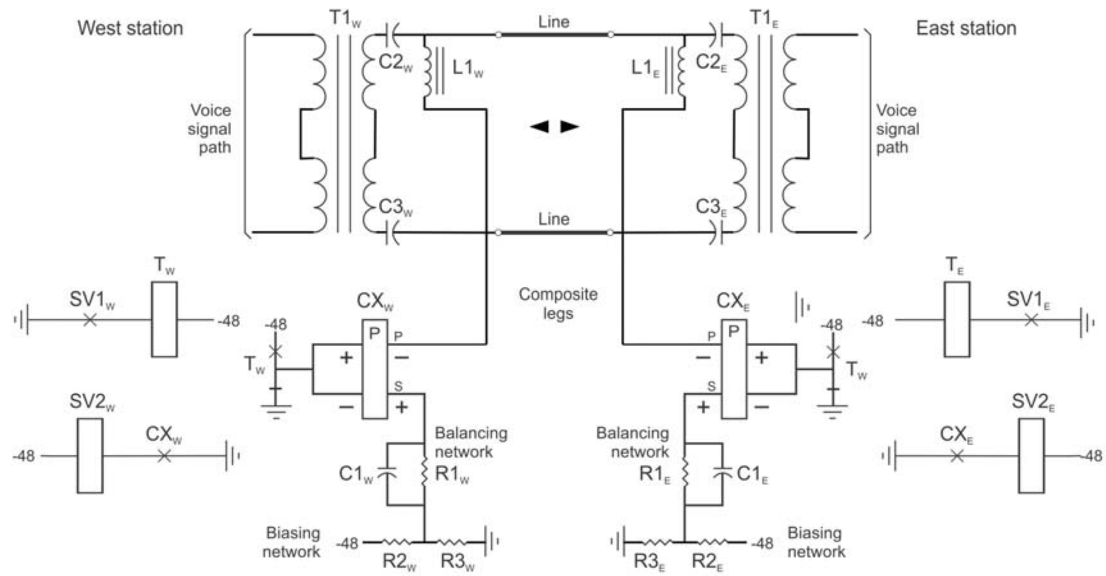

Figure 6. CX ("composite") signaling system–basic concept

In this system, the path for the DC signaling signals is derived from one of the line conductors by what is essentially frequency division. Capacitors C2 and C3 (in the path for voice signals) in effect become a high-pass filter for voice frequency signals. Inductor L1, (in the path for the DC signaling signal, the "composite leg" connection) in effect becomes a low-pass filter for such signals.

This arrangement of separating the paths for voice and DC signals by frequency is called "compositing" (based on the notion that the voltage on the conductor is the *composite* of the AC voice signal and the DC signaling signal). And it is from this that the system gets its name (and designation).

As before, that single DC path carries signaling signals in both directions, using the principle of the duplex telegraph.

Here, the receiving relays, which I arbitrarily called "R" in the discussion of the duplex telegraph, are designated "CX", as is the usual practice for this type of signaling circuit.

For purposes of the story here, I have arbitrarily designated the relay in the trunk circuit that controls the sending signaling state "SV1", and the relay in the trunk circuit that responds to the received signaling state "SV2". ("SV" is for "supervisory".)

Relay SV1 in the trunk circuit controls relay T in the signaling circuit, which actually applies the signing voltage to the signaling DC path. Relay CX in the signaling circuit, which responds to the arriving signaling state, operates relay SV2 in the trunk circuit.

I spoke in Section 7 of the prospect that differences in the ground potential between the two stations could disrupt proper operation of the SX signaling system.

There would be the same risk here, but it is overcome by an addition to the system shown in simplified form in Figure 7.

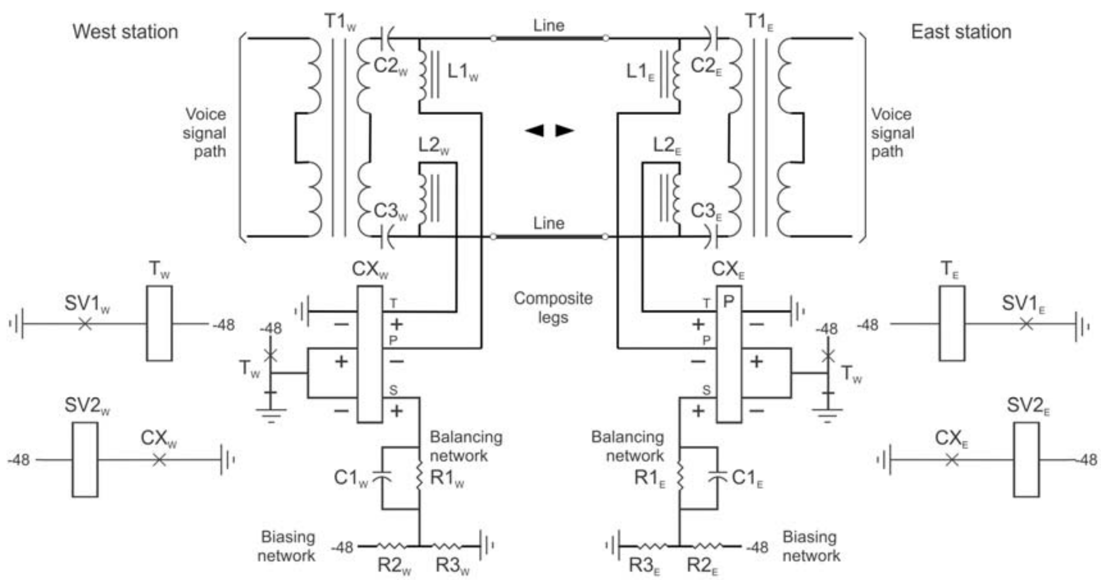

Figure 7. SX ("simplex") signaling system– with ground potential compensation.

Here a second DC path is derived from the second line conductor by the "composite" technique (through inductor L2). That path is connected to local ground at each end through a third ("tertiary", "T") winding on the CX relays. A current flows in that path proportional to the difference in ground potential between the two stations.

The various resistances and number of turns in the relay windings are chosen so that the magnetic effect on the CX relays from this "ground potential compensation" circuit exactly cancels out the undesired effect of ground potential difference on the basic operation of the CX relays.

Note that again this system gets is name from the way that the DC signaling path is derived from the line.

9 THE DX ("DUPLEX") SIGNALING SYSTEM

Figure 8 shows in simplified form the DX signaling system.

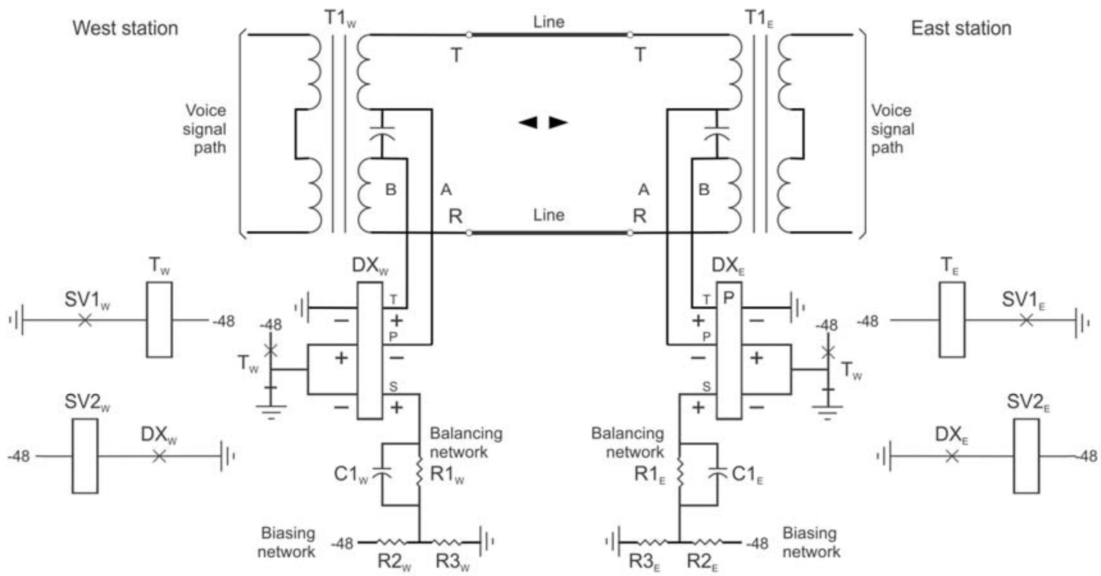

Figure 8. DX ("duplex") signaling system

The basic concept of this system is identical to that of the CX system. But an important difference is the way in which the voice (AC) and signaling (DC) signals are separated and combined on the line conductors.

Again the voice signals are coupled to the line through a transformer, T1. But here the line side winding is split. The split is bridged by a capacitor, C1, so to the AC voice signals the secondary appears to be uninterrupted.

Leads "A" and "B" provide "DC access" to the two line conductors, used for the signaling operation.

The path accessed by the "A" leads is used under the principle of the duplex telegraph to carry the signaling signals, just as in the CX system. And the path provided through the "B" leads is used to compensate for the difference in ground potential between the two stations, just as in the CX system.

Here, the receiving relay, which I arbitrarily called "R" in the discussion of the duplex telegraph, is designated "DX", as is the usual practice for this type of signaling circuit.

Note that this system gets is name from the fact that the two directions of signaling signals can coexist on a single conductor is by way of the principle of the duplex telegraph, Of course, that is equally true of the SX and CX systems!

10 THE UNIVERSAL SIGNALING INTERFACE

In the descriptions of each of the three DC signaling system of interest here, I showed examples in which the DC signaling was “practiced” by the *trunk circuit* ay each end. That is the equipment unit that in effect mediates between the “circuit” provided by the transmission system and the switching equipment at the end.

There are many kinds of trunk circuits required by the many types of switching equipment and various protocols that may be used with and between them. For each of those types of trunk circuit, there had to be at least three different variants, to utilize the SX, CX, or DX signaling schemes.

AT&T decided that this situation could be improved by having the actual signaling signal transmission and reception done by *signaling units*, distinct from the trunk circuits. These would all interface with the various kinds of trunk circuits at a standard signaling interface, comprising two leads, which would carry the two signaling states with a consistent set of voltages.

Then, for each kind of trunk circuit, there would only need to be one version, which again would meet the appropriate kind of signaling unit at this universal signaling interface.

Figure 9 shows this “division of labor” in the case of DX signaling.

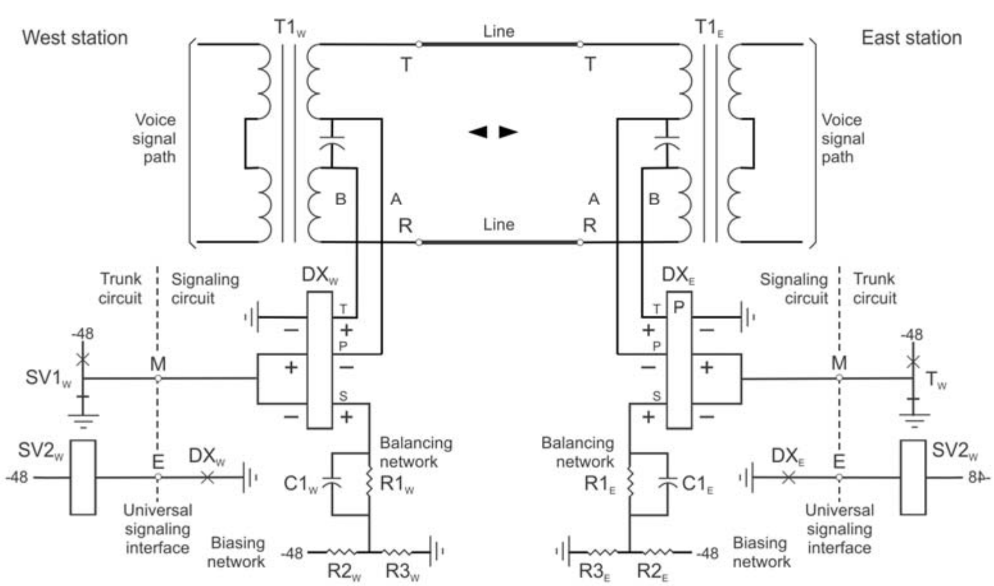

Figure 9. DX signaling system with E&M lead interface

The dashed lines show the boundary between the trunk circuits and the signaling circuits, the location of the “universal signaling interface”. It comprises two leads, designated “E” and “M”.

But there is a sort of a surprise here. We might expect that, in the “sending” direction, the trunk circuit might ground a signaling interface lead that would operate the T relay in the signaling unit. The T relay would then apply the proper voltages to the DC path over the line, in accordance with the type of signaling in use.

But it turned out that in all three systems (SX, CX, and DX), those two voltages were the same.

So the decision was made to have the “sending” lead of the signaling interface (from the trunk circuit) itself carry that uniform set of voltages, “ready to send to the line” (usually through a relay winding, of course). Thus there would be no need for a T relay in any of the signaling units.

In the figure, we see that being done by what I have arbitrarily called the SV1 relay in the trunk circuit (the sending supervision relay).

This choice not only reduced the cost of the signaling units, but as well eliminated another component of time delay in the change of signaling conditions.

In the receiving direction, the receiving relay (DX in this example) would ground an interface lead to the trunk circuit, where it would operate what I have called here the SV2 relay (the receiving supervision relay).

The two leads in the universal signaling interface were designated “E” (for the receiving direction) and “M” (for the sending direction). The exact basis for this is unknown to me, But I have suspected that it came from the designation of internal leads in trunk circuits before the “division of labor” was enacted. In any case, this universal signaling interface is most often called the “E&M lead” (or just “E&M”) interface.

This table shows the electrical conditions for the two signaling states on the two leads in the universal signaling interface.

Lead	Electrical condition for	
	on hook	off hook
E	Open	Ground
M	Ground	Battery*

*Through a resistance lamp to limit the current in case of an accidental ground on the “M” lead

Workers who first encounter this interface may be surprised at the difference in the sets of electrical conditions used on the “E” and “M” leads. But this come from the fact that, so as to save a relay in the signaling circuits, the voltages on the “M” lead were those “ready to send to the line”, as had already been established.

We recognize that, given that the voltage conditions on the “E” lead were different from those on the “M” lead, if we wanted to connect two circuits “end to end we could not just connect the E lead from one to the M lead of the other (symmetrically).

One solution was the use of “pulse link repeaters”, simple relay circuits that took in the signaling from the E lead of one circuit and emitted the same signaling state to the M lead of the other circuit (in terms of the proper voltage definitions for each).

Later, optional variations of the voltage definitions of one or the other of these leads were made available through “strapping changes” in the trunk circuits or signaling units, to eliminate the need for pulse link repeaters, and to cater to other special application situations. Sometimes there were additional leads in the interface to allow management of this under different circumstances. That is a topic beyond the scope of this article.

11 ADDRESS SIGNALING

11.1 Introduction

“Address signaling” refers to, in “dial” operation, the sending over a trunk of the number which the connection is intended to reach (its “address” in the network).

11.2 Dial pulse (DP) address signaling

For many years, this was done by sending each digit of the “address” as a series of 1-10 pulses, directly analogous to the way that a number is sent from the dial of the caller’s telephone set.

In this case, the dial pulses are sent as periods of the "on-hook" signaling state against a background of the "off-hook" state, which generally exists in the forward signaling direction when a trunk has been "seized" to participate in a connection. This way of sending address digits was spoken of as the "dial pulse" (DP) method,

There are a number of special considerations involved in this use of the signaling channel, which are beyond the scope of this article.

11.3 Multifrequency (MF) address signaling

The DP way of sending address digits was mostly eventually superseded by a system in which the various address digits were conveyed by bursts of two tone frequencies from a repertoire of five [6], sent over the voice capability of the circuit. This was called the multifrequency (MF) signaling system. [7]

12 ACKNOWLEDGEMENT

Great thanks to my precious wife Carla, who, despite being in the throes of recuperation from major surgery, took time to skillfully apply the fabled Cherokee Red Pencil to the draft of this tedious manuscript.

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[6] There was actually a sixth frequency in the repertoire, used only for combinations representing various "protocol indicators".

[7] Note that this is not at all the same as the system later introduced for tone "dialing" from the subscriber's telephone, which came to be called the DTMF system.