# Between Telecommunication Efficiency and Instability: Towards an Historical Approach

*Aristotle Tympas*

In the 1933 edition of the *Major Greek Encyclopaedia* the author of the entry "Telephone" noted:

> It is worth observing, that it is possible, through the use of repeater coils on two existing telephonic circuits, to superimpose a third circuit, so that all three can operate simultaneously and independently from each other. The attached illustration is a symbolic presentation of this. Non-real materially, the telephone circuit formed in this manner is called a *phantom* or *artificial.*[1]

Exemplars *par excellence* of efficiency for telecommunication circuitry, these circuits theoretically provided additional lines without having to pay firstly, to erect additional poles, and secondly, to draw additional wire over mountains and under seas. In the accompanying illustration proffered by the Greek Encyclopaedia, the phantom circuit afforded the addition of a gentlemanly communicating male coupler to the two male-female communicating couples serviced by the existing lines – upon the configuration of a phantom circuit (also called "derived," "plus," "superimposed," or "superposed" circuit), the existing lines were called "physical" (or "side") circuits. Absent from this 1933 symbolic representation of technical efficiency is any sketch of the social work required to make such efficiency real. In the technical vocabulary of the history of those working in order to produce "phantomed" telecommunication circuits that I introduce over the course of this paper, the name of what differentiated between abstract and concrete phantom circuit efficiency was lack of balance, in other words, "instability". In the terminology of economics, technical efficiency meant profitability. In the case of phantom circuits, the instability, which resulted from the failure to construct or maintain an adequate "balance" between the physical and the phantom circuit, was manifested usually as "cross-talk". For example, having been theorized as the ultimate in efficient telecommunication circuitry at the time, when tried in practice the first generation of the Bell Labs "carrier multiplexing" circuits was marked by the perpetuation of the instability issue (I define multiplexing in general and carrier multiplexing in particular later in this paper, which is were I move on to relate multiplexing to phantoming). We learn by reading the relevant part in the series of volumes that have recorded the technical change at the Bell system, which were written and published by Bell Labs staff (I refer to these series, edited under the title *A History of Engineering and Science in the Bell System*, as HBS). The story goes on with generations of carrier multiplexing succeeding each another as the ultimate in telecommunication efficiency.[2]

In phantoming a circuit to make profit, writes Paul Wills in his textual and diagrammatic exposition of its workings, "one and one make three"[3]. In Will's and, for that matter, in every other technical definition of profit from the phantom circuit, "balance" between the phantom and the physical circuit is emphatically introduced as the prerequisite of such profit[4]. Without balance there would be instability. Depending on the context, that could be manifested in several alternative ways.[5] Balance means that the phantom circuit must be equal to the physical circuit in respect to the phenomena that come to affect transmission. In other words, with respect to these phenomena, the phantom circuit is an analog of the physical circuit. When then the phantom circuit is unconnected to the physical circuit, it can function as what would now be call an "analog" computer thereof.[6] When connected to the physical circuit, the computer is transformed from off-line to on-line, i.e., into a balancer. Balance, to emphasize, means equivalence, i.e., equality only in respect to the response to phenomena of interest. The physical circuit is placed on the one side of the balance and its equivalent (with respect to telecommunication transmission) on the other. The key, I would suggest, as in all balances, is to observe that equivalence requires that unnecessary action on the one end can be negated by a reaction on the other end. In the familiar weight balance (scales), for example, we avoid the drop in the earth's gravitation of what we place on the one side by negating it through placing something that gravitates equally towards the earth on the other side: the two are equivalents in that they have to be equal only in respect to what we care about in this case, namely gravitation by the earth. This is to say that, in order to have balance, the equivalents are connected negatively to each other. In other words, we have a negative connection between the artificial (phantom circuit) and the real (physical circuit) circuit. If artificial circuits are negatively connected to both ends of a real circuit, an extra signal can be received (and/or sent) along the artificial line, without interfering with the reception of a signal along the real line. This can allow for the simultaneous sending of signals from the two ends of a single-wire line, e.g., in "duplex" telegraphy, or, for the sending and receiving from the two ends of a two two-wire line, e.g., in phantom telephony.

Several tradeoffs are possible. The equivalence can be full or partial. Constructing and maintaining full equivalence means that the artificial line can negate any phenomenon that may destabilize the real. Full equivalence is more costly to produce than partial equivalence. On the other hand, partial analogy can offer stability from a more limited set of destabilizing phenomena. Several distinct sub-functions are possible. Making the artificial circuit equivalent only in respect to the phenomena to be selectively eliminated and connecting this negatively to the real circuit can filter something out from the real circuit. In this case, the artificial circuit is called a "filter". A special-purpose filter at the other end of what was called an "artificial line" – an artificial line that was as close to being a miniature analog of the real line as possible. In a sense, phantoming and duplexing were based on a full analogy, i.e., on employing an artificial line in the two ends. By contrast, "loading" was based on employing a partially analogous artificial circuit on the line. For the same quality of transmission, with phantoming-duplexing the number of lines was increased; alternately, with loading the length for the same length, loading could increase the quality of transmission. The *ad infinitum* reproduction of the phantom principle gave circuits that were called "superphantoms" (or "plus-plus"); the ad infinitum reproduction of the duplex principle gave rise to the multiplex. Duplex was called "diplex" when the purpose was to double one-way traffic capacity rather than to provide with two-way traffic. Two-way communication was called "simultaneous" communication; we now call it "interactive" communication.

As negative feedback connections could range from the most partial to the more inclusive analogy between the artificial and the real circuit, there emerged a spectrum of efficient circuit configurations. In their 1929 presentation of a relevant taxonomy, Bell Labs engineers T.E. Shea and C.E. Lane identified the following general types: wave filters, equalizers, transformers, artificial lines and balancing and simulating networks. In commenting on their presentation, S.B. Covey stated that more than a quarter of million of such circuits were in service in the Bell System, ranging from a simple resistance weighing no more than an ounce to complicated assemblies of coils and condensers weighing perhaps as much as 50 lbs[7]. Shea and Lane gave brief histories of each. Depending on one's viewpoint, the same histories could be told from a specific perspective. For example, in the inaugural issue of the *Bell Laboratories Record*, Paul C. Hoernel subsumed the history of filters under that of the artificial line. For him filters were artificial lines taken to the limit – in his own words, they were artificial lines of "lines of impossible physical construction". "The story [of the artificial line]," wrote Hoernel under the title of his paper, is that "of a device, not widely known but of increasing importance throughout the history of electrical communication"[8]. A more appropriate name to describe balance in case of filtering is "control."

Another important trade-off was that between dynamic balance, which is more appropriately called "regulation," and static balance, i.e., balance proper. In negatively connecting to the mechanical circuit of his steam engine the equivalent mechanical circuit of the steam engine governor, Watt was choosing a relatively bad analogy between the artificial and the real circuit (worse regulation) that would be better for negating more destabilizing phenomena, over a better analogy (better regulation) that would be better for negating a more limited set of destabilizing phenomena. Another way to put this, is that he chose lower-quality dynamic over higher-quality static balance. In the electronic form of negative connection found in "negative feedback amplification" this is also the choice made. Negative feedback amplifying is the best known version of a negative connection of a dynamically analogous artificial circuit, the loading and phantoming of a statically analogous artificial circuit. Combining the pursuit of dynamic and static analogy was possible, as in carrier multiplexing, a crucial feature of which was negative feedback amplification. This trade-off suggests that, for example, loading and phantoming were different manifestations, not as we read in the HBS, "interim" and "limited" solutions[9].

To the degree that the previous interpretation of phantoming, loading, multiplexing and negative feedback amplifying holds[10], it must be apparent that the stability required for efficiency was based on the successful design, construction, and maintenance of an artificial analog of a real circuit. Skilled and painstaking work was required throughout; the value of which could be kept at a minimum (to make these circuits profitable) by successfully mystifying the efficiency of these circuits as being due to a technical imperative, regardless of social context. Instead of being stabilized by the successful appropriation of labor power as such (variable capital that produces surplus value); these circuits were presented as being self-stabilized artifacts, automata (as if constant capital was the source of profit). We know from Marx's critique of classical political economy that, unlike the commodities that capital – in the form of money – can assemble together in order to produce new commodities and form the elementary circuit of profit, the commodity of labor power has the unique property to make more value than the value that it receives in the form of a money wage. In other words, when variable capital (labor power) and machinery (constant capital) form a circuit, "one and one make three" – the third is the surplus value, over and above the value paid to purchase them. In this sense, the efficient circuit of telecommunication was an exemplar of the circuit of capital. In introducing the concept of surplus value, Marx showed that the theoretical circuit of classical political economy, which looked for the source of extra value in the wrong place (outside production and in exchange), had obscured the source of extra value to turn it into a "specter." When he described the circuit of capital in technical rather than socio-economic vocabulary, Marx preferred to describe the same circuit as an automaton, as the much-sought circuit of perpetual motion[11].

While the merits of simultaneously using some combinations of the efficient circuit variations on a network line could be an issue, the use on the network as a whole was always assumed beneficial. Advances in one technique quickly affected the rest. Squier explained that "[I]n the experiments described in multiplex telephony and telegraphy it has been necessary and sufficient to combine the present engineering practice of wire telephony and telegraphy with the engineering practice of wireless telephony and telegraphy"[12]. Expanding from wired (open air, land and sea cable) to wireless communication (point-to-point to satellite-mediated, station-based or mobile, land to sea and/or to air and vice versa), and from telegraphy and telephony to radio and television came the configuration of an infinite number of alternative loading, phantoming, multiplexing, and negative feedback amplifying (and combinations of the above) circuit configurations. Depending on the context, the interaction of, for example, phantoming and loading, could shift the balance towards preferring either task, or, as was also the case, towards a certain combination of modified versions of both. One form (or spatial-temporal context), for example, of multiplexing required loading whereas another required its removal[13]. Depending on the intended use and the versions employed, loading and phantoming could be totally incompatible or highly compatible[14]. The combined use of loading and phantoming, for example, required the modification of both[15]. Depending on the context, side benefits or disadvantages could tip the balance in favor of a certain configuration[16].

Each of these techniques could change over time in a manner that has been all but linear. Take the example of multiplexing, which could usually be "time division multiplexing" or "frequency division multiplexing – alternatively, if the emphasis was placed on the software rather than on the hardware, "code multiplexing". Many sub-classes and many combinations of classes and/or sub-classes have been tried with various degrees of success. A version of multiplexing could disappear for longer or shorter periods before reappearing along the emergence of a new overall configuration (or before reappearing in another place). For example, frequency division multiplexing, which became an option with the 1918 emergence of carrier multiplexing, was actually an updated version of "harmonic telegraphs" such as the ones that both Alexander Graham Bell and Elisha Gray had introduced as early as in 1876[17]. Noticeably, a re-conceptualization of multiplexing was responsible for the transition from telegraphy to telephony.[18]

Starting in 1918, multiplexing – in this case carrier multiplexing – should have rendered phantoming unnecessary. However, since phantoms were especially suitable for adding traffic without nearly as much rebuilding as that required in carrier multiplexing, the development of carrier multiplex sparked the emergence of new sub-classes of phantoms[19]. Should we decide to keep the concepts "telegraphy" and "telephony" constant, we will find an interesting inversion of fortunes in that, in many cases, telegraphy remained an option only by being given one of the circuits of carrier telephony. Some went as far to argue that telegraphy was accordingly reduced to a limited version of telephony to be profitably chosen for specific uses[20]. Still, one could find contexts within which the initial pursuit of using existing telegraph lines in order to carry telephone ones was still the dominant one[21]. From open metallic wire to coaxial cable and, later, fiber optics transmission, multiplexing could take new forms or return to variations of older ones.[22] Eventually, in whatever spaces left within telephone multiplexing (or other) one could try to find space for the transmission of any kind of "data" possible[23]. Perusing, by chance, a sizable body of engineering literature on the disturbing interference between communication and power networks, I was surprised to find there exists an equally sizable body of engineering literature devoted to carrier communication multiplexing based on a power line[24].

In regards to international differences, when discussing Patrick Delany's contributions to early multiplex telegraphy (late 19th century), Paul Israel notes that the British Post Office telegraphy adopted his multiplex telegraph, but its use in the United States was limited to the short-lived Standard Multiplex Company[25]. Tucker has detected a difference in the early success in phantomed telephony circuits in Britain compared to the United States (c.1900). Evidently, the British Post Office was moving ahead despite a demonstrated difficulty to offer the desired quality of transmission. In addition, Tucker finds that there has been a difference between the United States and Germany in respect to the choice between composite and simplex circuits. In Germany the "simplex" circuit was widely adopted whereas in the United States the "composite" circuit was preferred – in a simplex configuration the whole pair of telephony was giving one telegraphy phantom; in the composite one each wire of the telephony pair was used so as to give two telegraphy phantoms (by what, as Tucker explains, was essentially a lowpass-highpass filter arrangement). Interestingly, in Britain both simplex and composite circuits were used[26]. As far as loading goes, Kragh has retrieved several variations within Europe and between Europe and the United States[27]. The Bell system record is suggestive of variations in the deployment of carrier multiplexing within the United States. For example, the development of different carrier systems within the first generation Bell carrier system was a response to regional variations[28].

I believe that the pioneering observations mentioned above are too few to allow us to go too far in advancing hypotheses on variations between and within contexts and to hypotheses about the source and the meaning of such variations. The complexity was such that at times it is difficult for an historian to even identify what the circuit under consideration is, especially when a common third concept was used. Depending, for example, on the time and the space, a superimposed (or superposed) circuit described in the technical literature could be a phantom or a multiplex circuit. Similarly, the physical circuit could be the carrier current of multiplexed communication or the one of the two side circuits of a phantomed circuit. There are also cases where conceptual continuity threatens to conceal important technical change, as, for example, in the aforementioned example of the generations of the carrier multiplex telephony developed at the Bell Labs. The *a posteriori* characterization of multiplexing and phantoming as "interim" and "limited" solutions, and of amplification and carrier transmission as the ultimate solution, may have turned out to be as problematic as all whiggish history[29]. For one thing, phantoming and multiplexing have been used consistently whenever suggested by overall network profit[30]. Moreover, carrier itself was a form of multiplexing, which rediscovered principles that went back to the early days of harmonic telegraphs and related artifacts[31]. Finally, the history of carrier telephony is not linear because there were special economies with each carrier generation and between generations that required combining old-new hybrids and variants[32]. As far as phantoming goes, I find it indicative of its rich history that we have reports of post-World War II engineering students and other knowledgeable amateurs who could devise variants of the phantom principle in order to make free phone calls[33]. Incidentally, multiplexing transmission could affect all aspects of the process, including, for example, from the mode of inputting a message to a transmitter to the mode of printing the receiver's output[34].

Everything said so far suggests that there has been no simple evolutionist march towards the apex of the evolution of the form of the efficient circuit. Technical efficiency was a socially situated pursuit, which varied in time and place according to the outcome of efforts to weight efficiency against instability. Before I introduce instability as what haunted efficiency throughout the history of telecommunication transmission, I invite us to wonder if there has actually been a commensurate conception of efficiency over time and space (so that historical comparisons can be possible in the first place). In my opinion, neither a technical nor a social (e.g., economic) essentialist conception of efficiency is possible. To argue thusly, I take the example of wired transmission in the context of the Bell telecommunication network during its first half century of existence. My evidence is based on the information offered in the section on "Ancillary Transmission Problems" of the chapter on wired telephone transmission in HBS.

I start from a technical perspective. The sub-section on "Transmission Objectives and Standards" offers an exposition of the problems that make it "difficult to describe the grade of transmission provided during the first 50 years of telephony in terms that have significance today". The first problem starts by the fact that transmission performance and standards were specified on a volume basis in terms of the standard cable references system. This reference system and the commercial Bell Labs transmission were designed "for maximum efficiency at about 1,000 hertz, the response falling off rapidly above and below that frequency". As the pursuit of lengthening the transmission distances as much as possible prevailed over that of operating at standard frequency, a highly non-linear change in efficiency makes any comparison impossible, because sending a loud signal as far as possible makes any comparison of efficiency according to the standard impossible. Efficiency, then, was a matter of subjective experience[35].

Another problem in describing early transmission performance arises from the fact that, as we read immediately below in the same sub-section, standards were usually specified in terms of "limiting loss", i.e., the loss when all the components of the plant (the subscribers' loops" and the "trunks") were at the limit.

Since many loops and trunks were much better than those operating at the limit were, the average performance was better. It is difficult, however, to say how much better and so it is hard to estimate the probability of obtaining a limited connection. Worse, the performance could even fall below limited losses "during bad weather, or under trouble conditions, or on particularly long switched connections". A final problem was the lack of specific and detailed information standards as peripheral personnel realistically chose a bad connection to no connection, regardless of what the ideal of a central manager might have been. The result, again, is a subjective notion of efficiency[36].

This sub-section concludes by stating that loading and repeaters (necessary for phantoms) made it easier to establish technical standards[37]. Revisiting the issue from an economic angle, however, implies that things were not all that easy. Evidently, conceptions of general economic principles ought to be "endlessly" supplemented by considerations of specific economic contexts. I quote from the following sub-section on "Cost Studies":

> The advent of loading, phantoms, and repeaters stimulated the development of other types of cost studies aimed at determining the most economic way to use these facilities for reducing wire size. Some of these studies were rather straightforward since it was relatively easy to balance the cost of loading coils or repeaters against the cost of copper. However, developing technology presented the designer with many choices affecting economy. For example, the resistance and core losses of loading coils reduced their effectiveness and hence required some offsetting increase in the wire size. For a price, these losses could be reduced, and it became important to determine how much should be spent on loading coils in order to save line wire. Similar questions arose endlessly in connection with the design of phantom coils, composite sets, repeater balancing networks, and so forth. Many of these problems justified specific, detailed cost studies, but others required a more general approach and for these an interesting concept was developed known as the W.A.C. (Warranted Annual Change) of transmission. This was the annual cost of providing a transmission improvement of 1 mile of standard cable (or db) in the most economic manner.[38]

Ironically, even the W.A.C. was vulnerable to spatial and temporal variance. "Originally," we read below in the same sub-section, "this concept seems to have begun at a time when the use of additional copper was the only way to improve transmission, and it provided a useful means for repeating coils, central-office equipment, and so forth. Later the W.A.C. of transmission was derived in the course of loop and trunk studies for a plant with troops and trunks in economic balance"[39]. Incidentally, one function of the loop and trunk differentiation was the efficient direction of traffic to those lines – instead of direct interconnection according to the physically shorter route, efficiency was pursued in interconnecting according to what was rendered more profitable by the artificial construction of the transmission network. Loops were short and large in number and low-quality and minimum-cost facilities; whereas trunks were the opposite. In other words, what was efficient was not the shortest in terms of physical mileage but in terms of network efficiency mileage. I may add that I leave out of consideration the difficulty to compare quality because of local variations in the measurement techniques, which was a prerequisite of any discussion about standards. This is why the first sub-section of this HBS section is devoted to the difficulties of measurement and entitled "Measuring Instruments".

The remaining sub-section on "Control of Interference" introduces us directly to the issue of the differences between the theory and practice of efficient Bell circuits. I choose to discuss in detail the 1929 opinions of two of the protagonists, the Bell Labs engineers Shea and Lane mentioned above. The concluding section of their taxonomic paper, which was on "Engineering Limitations on Network Design and Construction," started by stating that:

> [T]o work out theoretically a network of inductances, capacitances, and resistances which will offer certain desirable transmission characteristics over a frequency range, is a matter of following certain theoretical design methods. To build actual networks which will possess and retain these characteristics involves a large number of factors which come into play and which must be balanced against one another[40].

Indicated and actual performance could differ along four major directions, namely, difference between the indicated theoretical performance and the exact theoretical network chosen (1), difference between the actual form or configuration of what the network is and what it is theoretical supposed to be (2), inaccuracy in the construction of the network (3), and instability of the network characteristics during operation (4)[41]. Each of these depended on several other factors. For example, accuracy of network construction for a given design depends, primarily, on the accuracy of the electrical circuits used in conjunction therewith (a), the fidelity of test conditions (b), and the care and skill exercised in making adjustments (c). "How much care and skill enter into making adjustments," they emphasized, "is chiefly an economic question"[42].

The first factor had to do with computing approximations. Approximations, were necessary when mechanical aids were used in computations. They were responsible for the two sources of error which affected the theoretical exactness of the computed performance of a network. One source of error was due to the computation of the network constants from chosen significant frequencies, impedances, or other design bases, and the other in determinations of the characteristics themselves either from the network constants, or from the bases referred to.

In his detailed discussion of engineering computations in his celebrated engineering mathematics textbooks, Charles Proteus Steinmetz had explained how better electric network engineering computations in general and better approximations in particular required more care and skill[43].

The discrepancies introduced by the from or configuration of a network could be placed under four sub-factors: interactions between network elements arising from the difficulty of confining electrical effects within exact boundaries (i), distributed impedance effects in network elements (ii), admittances from elements to ground (iii), and effects of the wiring system (iv). All four require identically external or internal symmetries (natural or constructed). I take the example of the second sub-factor. "It is simplifying from a mathematical standpoint," they wrote in respect to it, "to deal with definite lumped inductances, capacitances, and resistances". "But," they immediately explained, "it is only proper to realize that lumped constants do not occur strictly in nature". The problem of substituting the artificially lumped for the naturally distributed is the same as the familiar problem of representing the continuous by the discrete, or, as we would say now, the problem of choosing between the efficiency of the digital and the flexibility of the analog[44]. Producing a better analogy for a given efficiency is also an issue of care and skill[45].

Finally, we must consider the issue of stability under operating conditions. The obvious approach would be to refer to unpredictable change due to the natural. Shea and Lane mentioned temperature and humidity fluctuations[46]. Another way to approach this – that chosen mostly by Shea and Lane – would be to refer to resistance to unpredictable change by the artificial. Instead of passively blaming natural instability, the two engineers pointed to the active pursuit of how to negate it, by equivalent artificial stability. Thus, they placed the emphasis on "suitable materials". Such materials could resist, for example, the "group of changes called "aging", which has to do with releases of strains and fatigue of materials". "Suitable materials," explained Shea and Lane, "are usually limited in number either by economic considerations or by the limitations of engineering knowledge". In other words, an economic trade-off was involved once again[47]. In conclusion, the analysis of all four factors by Shea and Lane showed that the issue of efficiency was a social (economic) question to be answered in practice, not, as a technical answer to be provided by what is efficient theoretically.

This is also the conclusion when we visit the issue of what it took to produce – design, construct[48] and maintain[49] – stability from other angles[50]. It is indicative of how laborious and ingenious the balance ought to be, that the alternative ways to space the physical circuits in order to phantom them were an art and science in themselves[51]. Also indicative of the complexity of designing balance is, I believe, the proliferation of alternative ways to twist together twisted pairs in order to manufacture cable structures in as symmetrical a manner as possible. The choice of which double twisting, called "quad", was better for a given context was by itself a trade-off. For example, in the United States the less expensive but more asymmetrical "twin" quad was chosen over Europe's "star" because, as we read HBS, "[A]n important consideration was the belief that if phantoming proved to have limited use, the twisted side circuits would prove superior to the side circuits of a star-quad."[52]. From HBS we also learn that the reason that this was the choice in the United States is story "too complex"[53].

By way of concluding, I may add that a suggestive angle to look at the efficiency-instability technical trade-off (and the economic tradeoff that this corresponds to) would be to take a holistic view at the telecommunication network so that the desirable change by phantom and related circuits in the transmission line was contrasted to a disturbing change in the terminals of the line. I offer the example of carrier transmission. "Economically," clarified William Everitt, Professor of Electrical Engineering at Ohio State University, author of the chapter on "Wire Telephony and Telegraphy" in the 1941 (7th) edition of the McGraw-Hill standard electrical engineering handbook, "carrier-current systems must balance a reduction in line cost against an increase in terminal equipment cost". "This," he explained, "limits their application to relatively long lines when permanent installations are to be made"[54]. In arguing the same in respect to lengthening power transmission lines, Harold Buck, had argued that it was "grotesque" that the regulating facilities at the terminals of long lines were approximating in size "the power house itself"[55].

## Notes

1 *Μεγάλη Ελληνική Εγκυκλοπαίδεια* (1933), 23. Εκδόσεις Πυρσός: 10-16, quoting from page 14. Unless mentioned otherwise, the author of this paper translates all quoted Greek passages into English.

2 See Fagen, M.D. (ed.) (1978), *A History and Engineering and Science in the Bell System: National Service in War and Peace, 1925-1975*. Bell Telephone Laboratories; Fagen, M.D. (ed.) (1975), *A History of Engineering and Science in the Bell System: The Early Years, 1925-1975*. Bell Telephone Laboratories; O'Neill, E.F. (ed.) (1985), *A History of Engineering and Science in the Bell System: Transmission Technology, 1925-1975*. AT&T and Bell Laboratories. I refer to these as *HBS I, II*, and *III* respectively.

3 I borrow the expression "one and one make three" from Paul Wills' exposition of the principle of the phantom circuit. See Wills, Paul (1998), "The Phantom Circuit, Singing Wires". *Telephone Collectors International Newsletter*, March 1998.

4 See, for example, Chapter 17.4, in *Principles of Electricity applied to Telephone and Telegraph Work: A Training Course Text Prepared for Employees of the Long Lines Department*. American Telephone and Telegraph Company. January 1953: "In the theory of phantom it should not be forgotten that the conductors are assumed to be electrically identical, or in other words, the conductors are perfectly "balanced". The phantom is very sensitive to the slightest upset of this balance, and circuits that are sufficiently balanced to prevent objectionable cross-talk or noise in physical circuit operation, may not be sufficiently balanced for successful phantom operation."

5 Instability would usually take the form of signal distortion (noise, cross-talk, etc.). In introducing, for example, phantom circuits of wired telephony in the *Standard Handbook for Electrical Engineers* [Knowlton, A.E. (editor-in-chief) (1941), New York: McGraw-Hill. 7th edition], William L. Everitt wrote: "[S]uch circuits have a lower transmission equiva-

lent than the physical circuits. However, they are generally more noisy and more difficult to maintain than the physical circuits."

6 For an example of the use of the artificial line as a computer, see the employment of an artificial line for preparing for the Bell "carrier A" system in mid-1910s. See HBS I: 282. I discuss aspects of the history of the artificial line as used in order to compute communication and details of the history of the artificial lines as used in order to compute power networks in Tympas, Aristotle (2001), *The Computor and the Analyst: Computing and Power*, 1870s-1960s, Doctoral Dissertation; Chapter V.

7 Shea, T.E. and Lane, C.E. (1929), "Telephone Transmission Networks: Types and Problems of Design". *AIEE Transactions* July 1929: 1031-1044. For Covey's comments see page 1044.

8 Hoernel, Paul C. (1925), "The Artificial Line". *Bell Laboratories Record* 1.1: 51:60. The quotes on the importance of the history of the artificial line and on filters are from the first and the last pages respectively. For an indication of the importance of filters, see *HBS I*: 280.

9 For "interim" and "limited" see *HBS I*: 236 and 253 respectively.

10 It is indicative perhaps of the technical complexity of phantoming and duplexing that the only two article-length historical relevant studies that I was able to locate are written by electrical engineers. Aspects of the early history of duplexing are discussed in Strange, P. (1985), "Duplex telegraphy and the artificial line: the beginning of system modeling". *IEE Proceedings* 132.A.8: 543-552. An introduction to phantoming is offered in Tucker, D.G. (1979) "A technical history of phantom circuits". *IEE Proceedings* 126.9: 893-900. It would take an electrical engineer who was professionally trained as an historian to suggest the historiographical significance of studying the history of loading. See Brittain, James E. (1970), "The Introduction of the Loading Coil: George A. Campbell and Michael Pupin". *Technology and Culture* 11.1: 36-57, which was followed by Espenschied, Lloyd (1970), "Communications: the Campbell-Pupin Loading-Coil Controversy". *Technology and Culture* 11.4: 596-597. Brittain's retrieval of competing conceptions-practices to loading within the United States was nicely supplemented by what Helge Kragh wrote in respect to competing conceptions-practices within Europe and between Europe and the United States. See Kragh, Helge (1994), "The Krarup Cable: Invention and Early Development". *Technology and Culture* 35.1: 129-157. In updating the history of the pursuit of self-regulating circuitry to the electronic era, David Mindell, also an electrical engineer, who was professionally trained as an historian, has recently updated us on the historiographical significance of studying the issue of instability in the history of electronic negative feedback amplification. See Mindell, David (2000), "Opening Black's Box: Rethinking Feedback's Myth of Origin". *Technology and Culture* 41.3: 405-434.

11 For a historiographical call to pay attention to the hidden place labor in the history of the formation information networks, see Downey, Greg (2001), "Virtual Webs, Physical Technologies, and Hidden Workers: The Spaces of Labor in Information Internetworks". *Technology and Culture* 42.2: 209-235.

12 See Squier, George (1911), "Multiplex Telephony and Telegraphy by Means of Electric Waves Guided by Wires". *Proceedings of the American Institute of American Engineers*, May 1911: 857-862, (Introduction. Wireless duplex attracted attention from very early). See, for example, Anonymous (1901), "The Slaby system of wireless duplex telegraphy". *Scientific American* March 9, 1901: 146-147.

13 Quote from *A Training Course Text for Employees of the Long Lines Department of the American Telephone and Telegraph Company*. June 1961 edition: 158-159: "Many open

wire lines, with an arrangement of wires on poles as shown in Figure 18-1, are still in use in the long distance plant. Loading, however, is no longer used on open wire facilities (this figure is reproduced here as Illustration IV). This is a result of the fact that the characteristics of open wire circuits-particularly the leakage change markedly with varying weather conditions. In dry weather, open wire loading is effective in reducing the attenuation of the circuits considerably. But due principally to the increased leakage, loading may actually increase the attenuation of open wire circuits in wet weather". Due to this, once the telephone repeater became an option, loading was removed. However, additional repeaters had to be used to compensate for the increase in attenuation.

14 For differences between the United States and Britain in the loading and phantoming combination, see Tucker (1979), *op. cit.* In the United States, the experience gained in developing the loading coil made the repeating coil (thus phantoming) possible. See *HBS I*: 238 and 247-248.

15 Loading was taking place within a wire; phantoming between wires. For the Bell system mode of loading phantoms, see *HBS I*: 250.

16 For example, while the principal benefit from phantoming was cost reduction through an increase in the number of circuits per pair, there was an "additional small bonus" for very long hauls. Since phantoms used two conductors in parallel, the resistance was cut in half, and since the capacitance was increased by only 50 percent, the net result was an about 20 percent reduction in attenuation. This is why phantom circuits were for some time preferred over side circuits for very long hauls. See *HBS I*: 239-240.

17 In his insightful overview of the history of telegraphy, Steven Lubar writes that, as demand for telegraph transmission grew during the last quarter of the nineteenth century, "[T]he most important multiplex telegraph, which allowed several messages to be sent over the same line, and machines that encoded messages and sent them more quickly than human operations could". See Lubar, Steven (1993). *Infoculture: The Smithsonian Book of Information Age Inventions.* Boston: Houghton-Mifflin: 91. For details on the introduction of multiplex in the form of duplex, see Strange, "Duplex telegraphy and the artificial line: the beginning of system modeling". For details of Edison's involvement in the story, see Israel, Paul (1992). *From Machine Shop to Industrial Laboratory: telegraphy and the Changing Context of American Invention, 1830-1920.* Baltimore: John Hopkins University Press: 116-118 and 167.

18 This interpretation is lucidly synopsized by Lubar: "The origins of the telephone lay in attempts to invent a multiplex telegraph – a telegraph that could send more than one message over a single wire simultaneously. The need for this was obvious: it would cut the telegraph company's spending on copper wire, a major expense. It would also help to clear up the astonishing clutter of wiring that was beginning to blight American cities". The concept of the telephone as a "talking telegraph" and the fact that Bell's March 7, 1876 patent for "Improvements in Telegraphy," included both a tuned-reed harmonic telegraph and a magneto-electric telephone is a case in point. See Lubar (1993): 121-122, here quoting from page 121. For a detailed argumentation of the same point, see Israel (1992): 113.

19 In the 1941 edition of the McGraw-Hill electrical engineering handbook, the section-long treatment of carrier-current telephone and telegraph systems is matched by a section entirely devoted to phantom circuits. Different phantom configurations were to be used for different purposes. For example, "repeating" and "impedance" coil phantoms were more suitable for line and in station use respectively. "Grounded" or "half" phantoms were obtained by employing an earth return for one side of the phantom. By then, the older versions of multiplex were treated in a separate section on "low-frequency systems" in contradistinc-

tion to the high-frequencies of carrier multiplexing. Bridge polar and the differential polar duplex were mentioned as classes of low frequency multiplexing and the half-duplex operation polar duplex as a further sub-option. See the chapter on "Wire Telephony and Telegraphy" in *Standard Handbook for Electrical Engineers*, op. cit. On the same point, see also *HBS I*: 252: "Perhaps the best indicator of the importance of these measures is their effective life. Phantom remained an important technique for over a third of a century, and loaded circuits are still being added to the telephone plant in large numbers after some 65 years".

20 The telegraph was subsequently thought as "non-voice communication". A summary of its history from multiplex telegraphy of nineteenth century to high-frequency carrier telegraph systems of 1920s is given in *HBS I*: Chapter 7. See the diagram on page 744 for a comparison between multiplex and manual telegraph for contracted (private) lines.

21 For an indication of the many combinations possible, I refer to the contrast between "simple" and "composite" sets of simultaneous telegraphy that we find in the *Standard Handbook for Electrical Engineers*, in the relevant section of the chapter on wired telephony and telegraphy. The simplex and the composite set described a pair of wires of a telephone circuit could be used so as to derive one or two phantom telegraph circuits respectively – the second option was, naturally, more difficult to construct and maintain. This type of telegraphy derived in either case was called "low-speed (Morse) telegraph operation". As such, it was to be distinguished from "high-speed d-c telegraph operation", which was also possible through a different composite configuration. The differentiation between terminal and intermediate composite sets was analogous to that between and impedance and repeating-coil phantoms, which, as mentioned above, were preferable for line and in-station use respectively. See *HBS I*: 240-41 and 735-37.

22 The principle of multiplexing resurfaced every time there was a new transmission medium. For an example of multiplexing in the context of early microwave telephony in general (and an interesting 1944 alliance between IBM and GE, who had teamed up in order to develop multiplex microwave services, which they expected would supplement and eventually replace the existing coaxial cable network in particular) see Cantelon, Philip (1995), "The Origins of Microwave Telephony: Waves of Change". *Technology and Culture* 36:3: 560-582, here referring to page 571. For earlier wire multiplexing, carrier and other, see *HBS I*: Chapter 4. On radar and duplexing, see *HBS II*: Chapter 2, Section II. For later carrier multiplexing, see *HBS III*: Chapter 15.

23 For a Greek example, see Karoumbalis, G., Molibakis, M. and Valakas, J. (1990), "New TDM (Time Division Multiplexing) Method of Embedding Binary Data into Stereo FM Transmission of Analog Signal (Radio Data System)". *Technica Chronika* 10.B.1: 57-61.

24 In the 1933 (6th) edition of the McGraw Hill *Standard Handbook for Electrical Engineers* [Frank F. Fowle (editor-in-chief), New York, 1933] the topic was treated in the chapter on "Radio and Carrier Communication" as a sub-section of one of the chapter's sections. In the following (1941, 7th) edition, this sub-section was enlarged into an independent section. See Knowlton (ed.) (1941): section on "Electronic Applications to Power Systems" in Chapter 24 ("Radio and Carrier Communication"). Noticeably, both editions treated carrier multiplexing both under the chapter on wired and the chapter on wireless communication. In the case of wireless communication it was actually so important a consideration that it figured in the chapter's title. For the early difficulties in connection to this issue, see *HBS I*: 289.

25 Israel (1992): 156.

26 Tucker (1979): 898.

27 Kragh (1994).

28 Tucker (1979): 898.

29 See *HBS I*, Chapter 4.

30 They even persisted in the U.S., *HBS I*: 252.

31 See *HBS I*: 277: "The basic concept of increasing line capacity by carrier multiplexing is older than telephony. It will be recalled from Section II of Chapter 1 that Bell was experimenting with telegraph multiplex (which he called the "harmonic" telegraph) when he recognized the possibility of transmitting the voice".

32 See the summarizing table in *HBS*: Chapter 4 (summary table on page 291).

33 For one such experience, see Niquette, Paul (1977), "Phantom Circuit". *Sophisticated: The Magazine.*

34 Israel mentions the example for the synchronous multiple printing telegraph, developed between 1910 and 1912 by the cooperation of Western Union and Western Electric engineers, for the purpose of better handling Western Union's main lines traffic. It used a punched tape transmitter with a five-unit code that was based on the French printing telegraph of Emile Baudot. See Israel (1992): 177-178. It printed on a page form, could be quadruplexed, and allowed correction of the taped message. These features suggest that Marvin is right in stating that the computer is a telegraph with a prodigious memory. See Marvin, Carolyn (1988), *When Old technologies Were New: Thinking About Electric Communication in the Late Nineteenth Century*. New York: Oxford University Press. Introduction. In fact many features of the computer prefigure in the telegraph, including that of time-sharing. Israel writes that the synchronous multiple printing telegraph used a time-sharing distributor similar to Patrick Delany's multiplex. In the United States, attempts at printing telegraphs go back to the 1890s, with Western Union and Postal Telegraph initially adopting the Buckingham-Barclay and the Henry Rowland printing telegraphs respectively. Being more efficient but also more complex, the multiplex printing telegraph of Rowland was eventually aborted by the Postal Telegraph. The multiplex principle upon which it was based was later picked up by those who designed the aforementioned Western Electric-Western Union synchronous multiplex printing telegraph. Both the Buckingham-Barclay and the Rowland telegraphs employed keyboard perforators to prepare a punched tape and printed messages on a page form. See Israel (1992): 164.

35 *HBS I*: 322: "With a little practice, speech from these instruments proved intelligible enough to be usable but was highly distorted and obviously very much poorer than today's reader would infer from the attenuation of the reference system. In some cases, the first transcontinental line, for example) the performance was quite poor by present standards but was considered commercially usable under the conditions and current".

36 *HBS I*: 323: "Much was left to the judgment of individual managers, and the major criterion was often pragmatic. A circuit that could be used, even if many repetitions were required, was obviously better than no circuit at all, regardless of what headquarters said about standards", 323.

37 *HBS I*: 323.

38 *HBS I*: 344.

39 *HBS I*: 344.

40 Shea and Lane (1929): 1043.

41 *Ibid*: 1043.

42 *Ibid*: 1044.

43 On Steinmetz and the care and skill required in computation, see Tympas (2001): Chapter IV.

44 On lumpy and distributed artificial lines, see *Ibid*: Chapter V.

45 See Shea and Lane (1929): 1044.

46 For example, as mentioned earlier, a change from dryness to wetness could turn loading from useful to problematic.

47 See Shea and Lane (1929): 1044.

48 For precision in manufacturing, and for science (material and mental skills) in early period, see Israel (1992). For the same in respect to one critical component, e.g., the transformer (repeating coil), see, Tucker (1979), 895.

49 On maintenance, see, for example, *HBS I*: Chapter 4 (5.3).

50 Tucker finds the practical difficulties in working with phantoms to have been "immense". See Tucker (1979): 895. For early difficulties on constructing and maintaining analogy in duplexing, see Strange, "Duplex telegraphy and the artificial line: the beginning of system modeling". For the difficulties of manufacturing symmetry at the Bell system, see *HBS I*: 238-252 (early phantoming, multiplexing, and loading) and 284 (early carrier multiplexing). I quote, for an example, from *HBS I*: 238: "In theory, the phantom circuit was very simple, but the basic requirement of precise division of the current into equal part was not easy to achieve at all frequencies within the voice range. Difficulties were encountered in attempts to make repeating coils with satisfactory balance, and the state of the electrical art at that time was not such as to enable even a skillful professional to comprehend all the steps involved. Thus for many years the phantom circuit remained scarcely more than an interesting scientific curiosity". Things were getting worse for superphantoms. I quote from *HBS I*: 239: "The phantom technique could in theory be pushed beyond the gain of one circuit for each two pairs. It was, in principle, possible to superimpose a "ghost" circuit on two phantoms and an additional "wraith" on two "ghosts." These were of more theoretical than practical interest, since the gain was small and the difficulty of maintaining balance was formidable. "Ghosts' were, however, occasionally used where the value of an extra circuit was very great, as on some submarine cables. Even phantom circuits were limited largely to long circuits, since on short circuits the cost of achieving good balance could be greater than the copper saving".

51 Even the scheme of spacing on the polls mattered. See *A Training Course Text ...*, op. cit., Chapter 18.2. Tucker provides with a theory of spacing alternatives. See Tucker (1979): 899.

52 *HBS I*: 239, footnote 23.

53 *HBS I*: 239. Tucker shows eight permissible ways of jointing the wires of a quad for balancing. See Tucker (1979): 897.

54 Carrier-current systems, added Everitt, could also be used where a temporary increase in facilities was needed, "since the installation of terminal equipment is often cheaper than the stringing of temporary wire lines". Any gain in efficiency came at some cost. "On longer circuits," he moved on to elaborate, "carrier systems have an additional advantage in that repeaters may be used which amplify each group of channels. This advantage is partly offset by the fact that the higher attenuation of the high-frequency currents used requires repeaters spaced at shorter intervals." See Knowlton (ed.) (1941): Section 22-152.

55 See Dellenbaugh, Frederick S.Jr. (1923), "Artificial Line with Distributed Constants". *AIEE Transactions* 42: 802-823, here quoting from the discussion on page 822.