The Transition from the Legacy Public Switched Telephone Network to Modern Technologies

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Executive Summary

Carriers and consumers are increasingly moving away from the legacy public switched telephone network (PSTN) and toward modern network architectures and their more expansive suites of services. The transition is largely a healthy development, as both carriers and consumers are moving toward technologies that offer vastly increased functionality and even mobility; however, as with many other economic processes, there are opportunity costs (tradeoffs) associated with advancements in network design and technology. This paper discusses those opportunity costs and suggests actions that state commissions might take to address them.

With legacy PSTN loops, a phone will work as long as the line between the central office (CO) and a wired handset remains intact, because the line transmits both information and power. Unlike the legacy PSTN, modern networks no longer rely on the robustness of the CO, with its common battery and backup power generators, to maintain service on end-to-end copper loops. Newer network architectures rely greatly on fiber-optic cables and wireless facilities. These networks transmit information through one medium but require power to be supplied through another medium—in this case, the commercial power grid. Now, therefore, both the transmission medium and the power supply must be operating properly for service to be maintained. Changes in network design have also moved electronic equipment and the associated power requirements away from the core and toward the edge of the network. In the case of fiber-to-the-home/node (FTTH/FTTN) networks or cable telephony, power must be supplied to network electronics as far downstream as the customer premises. This is arguably true of wireless networks as well.

Although this paper discusses a wide range of issues resulting from the transition of the PSTN from a circuit-switched model to an IP-based network, we focus on the reduced reliability caused by the loss of the common battery from the CO to the handset. We note what carriers and consumers can do to mitigate the increased risk and what state utility regulators may do to address the associated public-policy concerns.

This paper is organized as follows. Section I begins by defining the transition in conceptual terms and documenting the pace of legacy PSTN access-line losses, using publicly available data and summary statistics provided by CenturyLink. Section II describes the evolution of the current telecommunications network and the technology involved in the transition. We begin with the legacy PSTN and follow with a brief description of modern network architectures and how they differ from the legacy PSTN. Section III discusses how telecommunications networks behave during power failures. This section focuses on electric power, because reliable power is necessary for telecommunications to take place, regardless of whether it is TDM or IP based. Section IV discusses the practical implications of the transition, as well as issues affecting its timing. Finally, we conclude in Section V with a discussion of the public policy implications of the transition and recommendations for state utility regulators to consider.

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I. Describing the Transition

A. Conceptually

The telecommunications transition that is currently underway is both complex and multidimensional. From a physical-facilities perspective, the transition is away from copper cables and toward fiber-optic cables and wireless facilities. From a protocol perspective, the transition is away from TDM (time-division multiplexing)[1] switched circuits and toward IP (Internet Protocol).[2] Viewed from a regulatory perspective, the aforementioned physical and logical transitions are causing customers and their communications to shift away from the firms, networks, and services that traditionally fall under the jurisdiction of state regulators. These new firms, networks, and services are typically subject to less regulation, and often only at the federal level.[3]

We note that consumers are largely indifferent to, if not completely unaware of, the physical and logical aspects of the transition. With few exceptions, consumers care about the price and functionality of the suite of services to which they subscribe, not the medium of transmission or the switching protocol.[4] We believe that the sum of these unknowns has resulted in a mismatch between actual network reliability and the average consumer's perception of network reliability. This mismatch is often highlighted during natural disasters or other disruptions to the supply of commercial power. Customers merely assume that the reliability record established by the legacy PSTN will transition seamlessly to the new networks, because these new networks are faster, offer more functionality, and, in many cases, are provided by the same brands that once provided the legacy PSTN. Customers also assume that subscribing to

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[1] Time-division multiplexing (TDM) is a type of multiplexing in which two or more voice signals are transmitted over a single circuit by taking turns in individual time slots created on that circuit. *See:* http://en.wikipedia.org/wiki/Time-division_multiplexing

[2] Internet Protocol (IP) is a packet-switched technology where information is broken up into packets that are transmitted individually and can take different routes to their common destination. This technology also allows multiple data streams to be transmitted more efficiently over a single route as compared to a switched circuit.

[3] The measure of state regulatory involvement is a complicated mix based on the interpretation of federal law and state legislation. For example, legislation in 21 states expressly forbids or limits the jurisdiction of state regulators with respect to Voice over Internet Protocol service. Sherry Lichtenberg, Ph.D., *The Year in Review: The Status of Telecommunications Deregulation in 2012*; NRRI, June 2012. http://nrri.org/documents/317330/0179150e-ef83-4e94-bf94-80c7af830ab6

[4] From a facilities perspective, the most relevant consumer issue is fixed versus mobile. In many cases, consumers choose both fixed and mobile.

multiple networks (e.g., wired and wireless) will provide increased reliability even though these separate networks share a common point of failure: the commercial power grid.

Even less transparent to consumers are the regulatory aspects of the transition. The average consumer is unaware of how or why a specific telecommunications service receives regulatory treatment and whether that service is under the jurisdiction of a federal or state agency, both, or neither. Thus, this paper addresses the transition largely from the perspective of the consumer so that public-policy goals may be achieved by giving consumers the proper incentives.

Network reliability has traditionally been a subject area monitored and governed by state public utility commission (PUC) quality-of-service rules. In this paper, we focus on how a failure of the commercial power grid may affect the provision of telecommunications services, be they provided on a legacy circuit network or a next-generation IP network. While a power outage can affect quality of service, the impact can also be characterized as an outage that affects "public health and safety." Therefore, in addressing the impact of new technology, we are suggesting that state regulatory commissions consider broadening their mandate to include taking steps to "protect[t] the public health and safety of…residents in an emergency situation."[5]

B. By the numbers

1. Access-line loss

The most obvious evidence of the current transition away from the legacy PSTN can be seen in the access-line-count data. Since their peak in 2000, legacy PSTN line counts have been falling steadily.[6] In June of 2011, the Federal Communications Commission (FCC) Technical Advisory Council (Technical Advisory Council)[7] recommended that the FCC take steps to prepare for the inevitable transition away from the legacy PSTN.[8] The Technical Advisory Council observed that a significant decrease has occurred in the number of residential access

[5] California Public Utilities Commission, *Order Instituting Rulemaking on the Commission's Own Motion into Reliability Standards for Telecommunications Emergency Backup Power Systems and Emergency Notification Systems Pursuant to Assembly Bill 2393*, Rulemaking 07-04-015, January 21, 2010, p. 18 (Hereafter, CA PUC Order, 2010).

[6] Federal Communications Commission, *Statistics of Communications Common Carriers*, 2006/2007 edition. Table 5.1, "Total U.S. Wireline Telephone Lines," p. 235.

[7] The FCC's Technological Advisory Council provides technical advice to the FCC. It is organized under the authority of the Federal Advisory Committee Act. The charter of the Critical Transitions working group is to "identify and evaluate high impact opportunities to accelerate transitions from legacy information and communication systems." http://www.fcc.gov/encyclopedia/technological-advisory-council

[8] http://transition.fcc.gov/oet/tac/TACJune2011mtgfullpresentation.pdf, p. 11/57.

lines in recent years. They forecasted that by the year 2018 only 6% of the residential population in the United States would obtain service from the legacy PSTN.[9]

Private-sector research tells a similar story. Figure 1 illustrates the actual line loss through 2011 and the forecasted values through 2017 contained in a recent report on the wired telecommunications industry written by telecommunications analyst Doug Kelly.[10]

Kelly's values correspond with the values for end-user switched access lines of incumbent local exchange carriers (ILECs) and competitive local exchange carriers (CLECs) reported in the last version of the *Statistics of Common Carriers*[11] published by the FCC.[12]

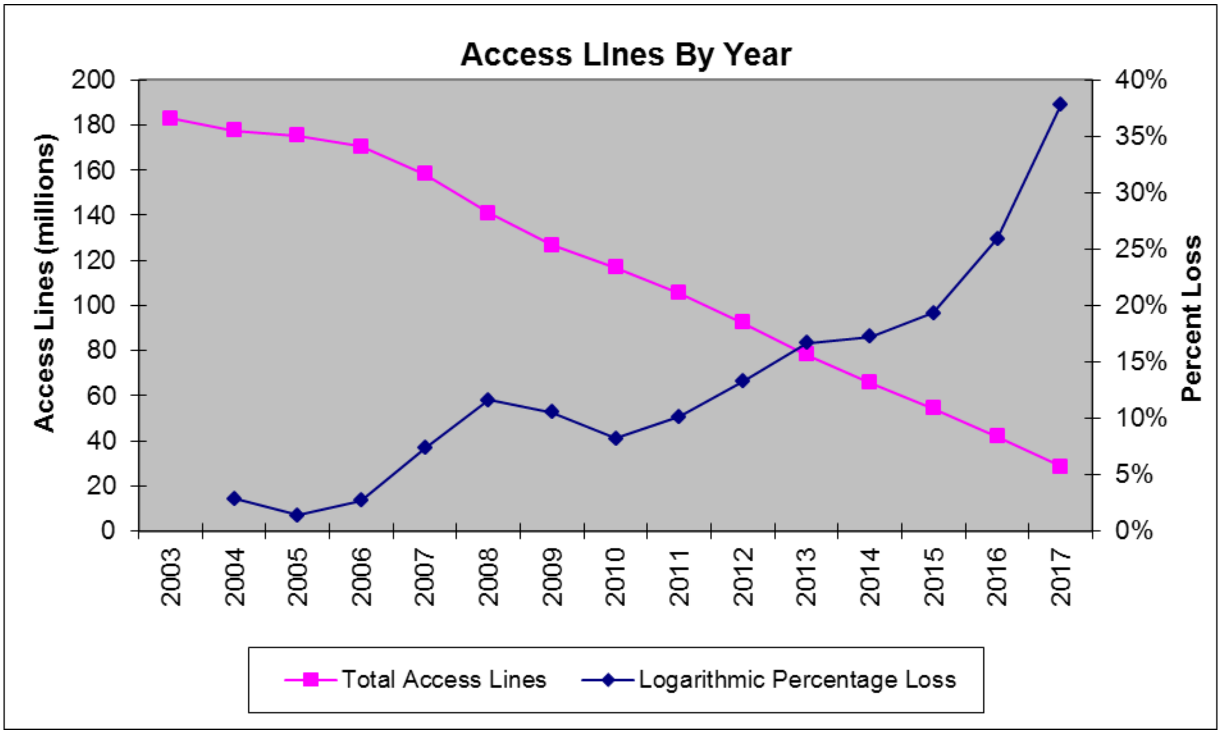

Figure 1 - Access-Line Losses

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[9] The Technical Advisory Council did not present access-line data for the business or government market.

[10] Doug Kelly, "IBISWorld Industry Report: Wired Telecommunications Carriers in the US," March 2012, p. 36.

[11] Federal Communications Commission, *Statistics of Communications Common Carriers*, 2006/2007 edition. Table 5.1, "Total U.S. Wireline Telephone Lines," p. 235.

[12] This is the most recent available data because the FCC significantly reduced ARMIS filing requirements for carriers in 2008. *See:* http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-08-203A1.pdf

Figure 1 also illustrates that Kelly anticipates a somewhat constant level of line loss: approximately 12.75 million lines per year from 2012 onward. However, because the relatively constant level of line loss would be occurring over an ever-smaller installed base of access lines, the expected percentage rate of decline is accelerating over time. We note that the wired access-line loss reported by Kelly is slightly higher than the ILEC loss reported in the FCC's *Local Telephone Competition Report*,[13] shown in Figure 2 below. Between the years 2005 and 2010, Kelly reports a logarithmic line loss of 40.5% for ILECs and CLECs, while for the same time period the FCC's data indicates a logarithmic loss of 38.8%. The ILECs' line-loss data is of greater interest to us than the CLECs' data because ILECs control the overwhelming installed stock of copper lines. On the other hand, Kelly's data is also of interest because he forecasts that the decline will accelerate in the coming years.

While the line-loss data and forecasts shown indicate the aggregate change in the demand for access, a more detailed look at the data shows that the change in demand for access is not homogenous across markets. Thus, in order to better understand which portions of the legacy PSTN have experienced the greatest line loss, we now present ILEC line-loss data by market segment (residential versus business market segments).

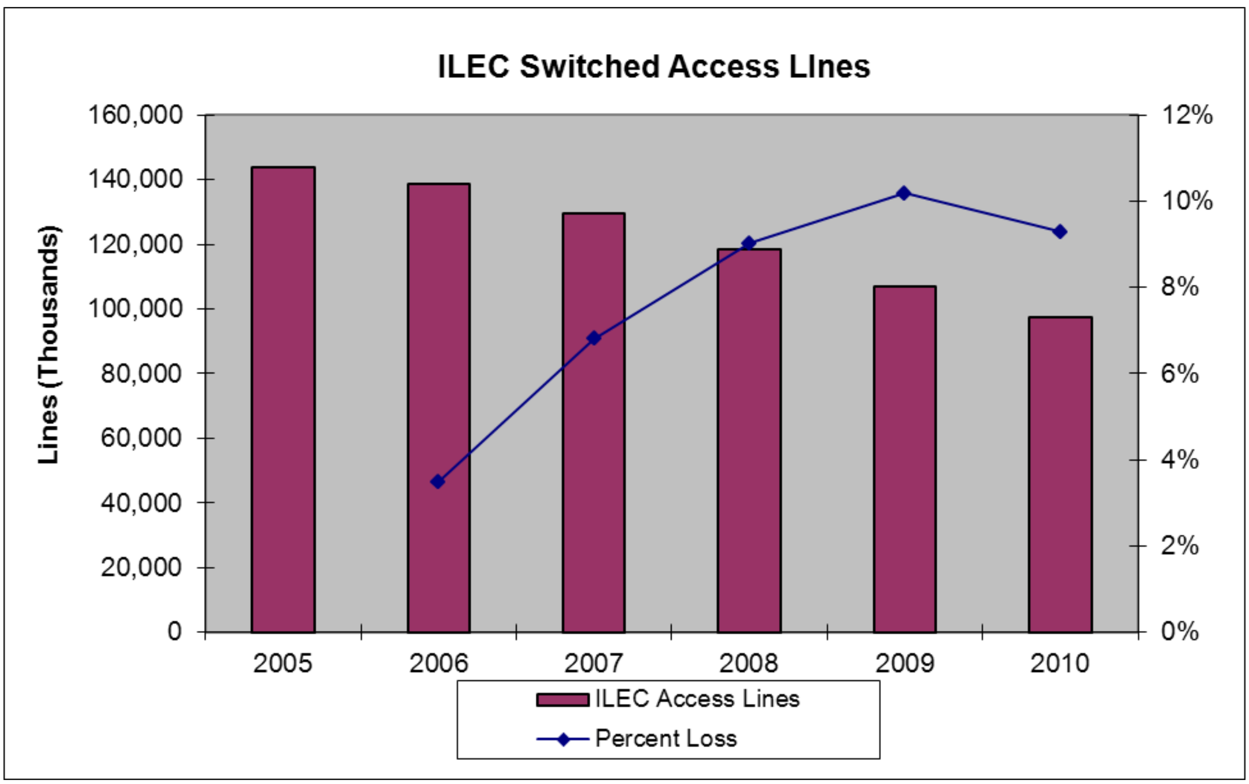

Figure 2 - ILEC Switched Access Lines

[13] FCC, *Local Telephone Competition: Status as of December 31, 2010*, October 2011, Table 1. http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-310264A1.pdf

2. Decomposition of ILEC line loss

Figure 3 shows the percentage loss in CenturyLink's (Qwest[14]) switched access lines across its 14-state service territory from 2002 to 2011.[15] The data used to create the histogram does not include data for special access lines.[16] The data indicates that between December 2001 and December 2011, CenturyLink's overall logarithmic percentage decline was 67%. The rate of decline was significantly higher for the residential market than the business market (83% versus only 35%). The larger decline in the residential market is possibly attributable to mobile and cable telephony substitution, which is less common for business customers. As reported by the Centers for Disease Control, nationally, as of June 2011, 31.6% of households did not have a landline but did have a wireless telephone.[17] The wireless-only household data for the 14 CenturyLink states are, in general, higher than the national average.[18]

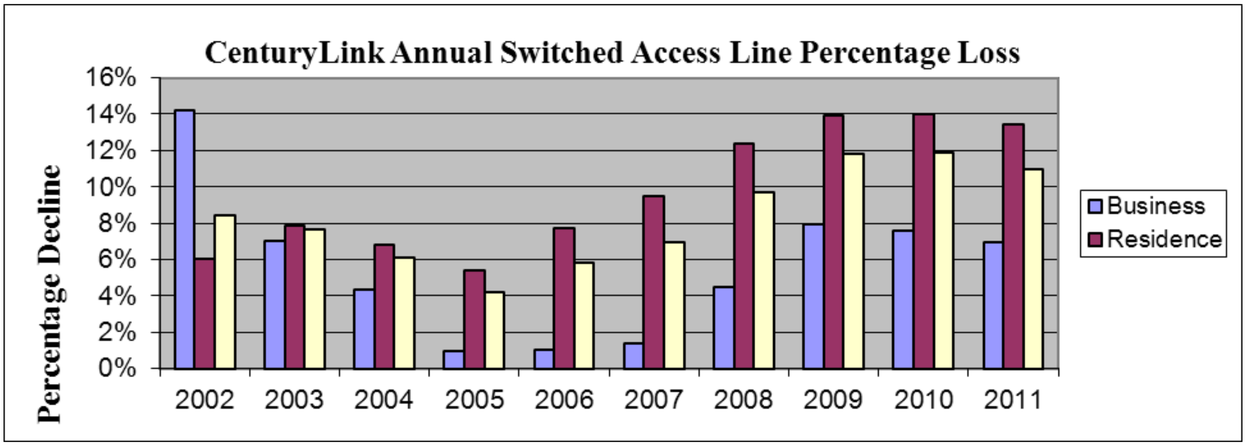

Figure 3 - CenturyLink Line Loss

The more rapid decline in CenturyLink's residential access lines is echoed in the FCC's most recent *Local Telephone Competition Report*. Between June 2005 and December 2010, the

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[14] Qwest, which was acquired by and began operating as CenturyLink in August 2011, provides service in the following 14 western U.S. states: Arizona, Colorado, Idaho, Iowa, Minnesota, Montana, Nebraska, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming.

[15] CenturyLink is used in this example because the company was willing to provide the authors with the necessary data. Absent similar data from other carriers, we cannot show that CenturyLink's access-line losses are representative of the nation as a whole. However, at this time we have no reason to assume that CenturyLink's experience is an anomaly.

[16] *See:* Appendix B – Special Access Lines

[17] CDC, Stephen J. Blumberg, and Julian V. Luke. *Wireless Substitution: Early Release of Estimates from the National Health Interview Survey*, December 21, 2011.

[18] CDC, Stephen J. Blumberg, et al., "Wireless Substitution: State-level Estimates From the National Health Interview Survey, January 2007–June 2010," http://www.cdc.gov/nchs/data/nhsr/nhsr039.pdf.

incumbent local exchange carriers reported that their switched-access-lines count had declined by 39%. The residential-switched-access-line loss, 49%, was more than twice the line loss experienced in the business market, 21%.[19] The data clearly show that the transition is currently occurring faster, and to a greater extent, for residential customers.

The decomposition of ILEC line losses illustrates that where the FCC's Technical Advisory Council has focused on the decline in residential access lines, it is important to keep in mind that the losses in this market segment are not representative of the overall access-line losses.

[19] Wireline Competition Bureau, "Local Telephone Competition: Status as of December 31, 2010," October 2011, Table 2.

II. Evolution of Telecommunications Networks and Technology

As part of its ongoing investigation into the way in which the PSTN is moving from a circuit-switched TDM network to an IP-based network, the FCC conducted workshops on "The Public Switched Telephone Network in Transition" in December of 2011.[20] On the web page rebroadcasting the workshops, the FCC noted: "Circuit-switched wireline voice technology has created a high standard for reliability, accessibility, and ubiquity. Consumers will continue to expect and demand these qualities, even as they shift from PSTN services to services provided over different networks."[21] To better understand why consumers came to expect and demand such qualities and how realistic it is for consumers to maintain these positions as they transition to services provided over modern networks, we must first describe the networks in question. We begin this discussion with a description of the legacy PSTN and follow with a brief description of more modern network architectures.

A. Legacy public switched telephone network architecture

The PSTN has greatly evolved since the invention of the telephone in 1876. Unlike the original networks, modern telecommunications networks offer high-speed data services, entertainment services, and even mobility. These types of service advancements were unimaginable when the first telecommunications engineers created standards that were designed primarily to provide uninterrupted voice service 24 hours a day, 365 days a year.[22] As with so many other economic processes, there are opportunity costs (tradeoffs) associated with advancements in network design and technology. Put simply, gains in one area have been offset, at least partially, by losses elsewhere.

1. Introduction of the common-battery network

When we dig deep into our memories for an image of the first telephone, we are likely to envision a magneto[23] telephone with its distinctive hand crank. Like a modern cordless phone, the magneto telephone relied on power supplied from the customer's premise. However, communicating with a magneto telephone actually required power from two separate local sources. The telephone transmitter was powered by up to three batteries, while power for signaling and ringing was provided by the end user as he or she turned the hand crank attached to the magneto. This power configuration, though charming when seen in period films, was not

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[20] David Gabel was a panelist in the Economic Rationales for PSTN Transition workshop held on December 14, 2011.

[21] http://www.fcc.gov/events/public-switched-telephone-network-transition

[22] Unfortunately, there is currently no data in the public domain that would allow us to determine the likelihood of all networks being simultaneously down or largely inoperable. The likelihood of such an event is a question that needs to be addressed. We return to this issue in Section III.

[23] A magneto is an electric generator that uses magnets to produce a current.

only laborious to use but also expensive to maintain because it required a craftsman to visit customers on a regular basis in order to replace the batteries.[24]

To overcome these problems, the first "common-battery" central office was constructed in 1893 by the American Telephone and Telegraph Company (AT&T).[25] AT&T would eventually own numerous operating companies throughout the United States. Acting as the holding company, AT&T established engineering standards that were implemented by its operating companies. Collectively, AT&T and its operating companies were known as the Bell System.[26]

This new type of central office engineered by AT&T contained a number of batteries through which power was provided to all of the telephones served from that office. The term *"common-battery" central office* was coined to reflect the fact that the batteries in the central office were "common," or shared by all subscribers, as opposed to the dedicated batteries that had previously been used at each customer premise. The new common-battery network configuration eliminated the need for a hand crank, and the costly and cumbersome process of periodically sending craftsmen to each subscriber's premise in order to change out the batteries on the telephone.[27]

Even prior to 1900, telecommunications engineers realized that the benefits provided by the introduction of the common-battery network had an associated opportunity cost. With the

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[24] M.D. Fagen, Editor, *A History of Engineering and Science in the Bell System: The Early Years (1875-1925)*, 1975, pp. 79-81, 109, 694.

[25] AT&T was effectively founded in 1876, when Alexander Graham Bell was credited with inventing the telephone. 1893, coincidently, was the year in which Bell's patent expired and the market for telephone service became competitive.

[26] The Bell System, or "Ma Bell," refers to the four principle divisions of AT&T: (1) AT&T Long Lines, which provide long-distance service and interconnection between local exchanges; (2) Western Electric Company, which manufactured telecommunications equipment; (3) Bell Labs, which conducted research and development for AT&T; and (4) the individual Bell operating companies (BOCs), which provided local telephone service to end users. An antitrust lawsuit brought by the U.S. Department of Justice in 1974 led to a negotiated settlement on January 8, 1982 in which AT&T agreed to divest its operating companies. On January 1, 1984, AT&T's combined local operations were split into seven independent companies known as Regional Bell Operating Companies (RBOCs), or "Baby Bells." For additional information, *see:* http://en.wikipedia.org/wiki/Bell_System_divestiture

[27] Fagen, *A History of Engineering and Science*, p. 81.

magneto system, power was supplied locally, so a power failure was limited to a single subscriber's telephone, and "failure seldom occurred since it was usually forewarned by a gradual deterioration of transmission as the battery voltage dropped with age."[28] However, with the common battery, because power was provided exclusively through the central office, a failure of the common battery would cause everyone in that central office to lose telephone service. Thus, when the network evolved from local power to common battery, central offices were also equipped with backup power systems. In order to minimize further the likelihood of a mass outage, central offices were sometimes served by two independent commercial power systems plus a backup engine.[29]

> Battery capacity was designed to carry the system power load [for] anywhere from a few hours to several days, depending on the size of the office, the reliability of the commercial system, and the charging procedure. Frequently, two commercial lines supplied from separate power stations were connected to an office for additional reliability, but even this was often inadequate. More commonly, in very large cities, where uneconomically large batteries would be required for extensive periods, a generator powered by an internal-combustion engine was furnished to provide a local substitute for commercial power during an outage. The engines were often designed for normal use on illuminating gas with gasoline as an alternative.[30]

Given that the copper connection from the central office to the handset provided both a communications path and the power necessary to communicate, an end user would likely maintain voice service so long as the copper loop was not damaged.[31] The reliability provided through AT&T's engineering efforts was impressive. After reviewing the record of power outages at Bell exchanges during the period 1905 to 1925, a Bell historian wrote that "[a]s a result of all these precautions, telephone system failure due to loss of power was almost unheard of, short of a natural disaster such as a fire, flood, or earthquake.[footnote omitted]"[32]

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[28] Id., p. 697.

[29] The legacy PSTN is powered indirectly by the commercial power grid. Transformers convert the high-voltage alternating current (AC) from the commercial power grid to the lower-voltage direct current (DC) used by the PSTN. Power flows downstream from a large bank of batteries which provide backup power and a limited amount of surge control and electrical line conditioning. *See:* http://www.inetdaemon.com/tutorials/telecom/pstn/central_office/index.shtml

[30] Fagen, *A History of Engineering and Science*, p. 699.

[31] An individual loop did present a single point of failure for the typical household or small business because there was little if any redundancy in loops. However, between 1900 and 1910 competing telephone systems served most urban areas. Because the competing phone companies did not interconnect, some customers would order service from multiple providers so that they could contact all subscribers. If one telephone network failed, a subscriber who had service from multiple suppliers might still be able to use another common-battery telephone system to place and receive calls.

[32] Fagen, *A History of Engineering and Science*, p. 699.

2. Demise of the common-battery network

The high standard for reliability provided by the common-battery system persisted well into the post–World War II era, until two significant design changes, one in handsets and the other in outside plant construction, greatly reduced the degree to which power for the telecommunications network was provided solely through the common battery in the central office.

a. Cordless telephones

In the landmark Carterfone decision of 1968, the FCC determined that individuals could connect terminal equipment that was not manufactured by AT&T (such as a handset) to the PSTN, so long as the equipment did not harm the network.[33] As a result of this decision, a number of manufacturers introduced many innovative products, one of which was the cordless telephone. Though first invented in 1956, cordless telephones were not widely produced or marketed to consumers until the 1980s.[34]

Cordless telephones typically have a fixed base station that is wired to a standard telephone line. To communicate with its portable handset, a base station relies on the commercial power grid rather than on power provided by the common battery. To communicate with the base station, the handset contains a battery that is typically recharged when the handset is “hung up” on the base station. While the introduction of the cordless telephone provided tremendous benefits to consumers who did not want to juggle cords or be physically connected to the wall when making and receiving calls, it also raised the likelihood that a household would lose telephone service during a failure in the commercial power grid. Service could also be lost if the customer neglected to keep the handset battery charged or if the battery failed for any reason.

Even though the central office could continue to operate during a commercial power failure, thanks to its batteries and generators, a household or entire neighborhoods might lose telephone service during a power outage because the base-station transmitter would not function unless the customer had provisioned backup power for their cordless phones.[35] In the early days of cordless telephones, the chances of customers losing telephone service during a power failure were relatively low because cordless phones were most often used to supplement the existing stock of wired telephones in a home or small business. However, as quality has increased and prices have fallen, customers’ use of cordless telephones has increased to the point that they are often the only type of telephone in use in a home or small business. Now a power failure at a

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[33] http://en.wikipedia.org/wiki/Carterfone

[34] http://en.wikipedia.org/wiki/Cordless_telephone

[35] While backup batteries and uninterruptable power supplies (UPS) are more common today, these devices did not become popular in residential settings until recently. Even so, these devices are rarely provisioned by residential end users.

customer's premise will likely cause loss of telephone service unless backup power is supplied to the base station or a traditional corded phone is kept handy for when commercial power fails.[36]

b. Subscriber-line-carrier systems

Beginning in the late 1970s, telephone companies made a concerted effort to reduce distance-sensitive facilities costs by introducing subscriber-line-carrier (aka "pair gain") systems that used electronics to weave a larger number of voice channels onto fewer pairs of copper wire.[37] The case for installing subscriber-line-carrier systems also grew over time because of the physical limitations of transmitting an analog signal over copper wire. These limitations require signal amplification on copper loops that are longer than 18,000 feet. Amplification of analog voice signals was achieved through the use of load coils.[38] However, because load coils interfere with the provision of high-speed data services, as the demand for such services increased, so did the demand for telephone companies to remove load coils and install subscriber-line-carrier systems instead.

A subscriber-line-carrier system eliminates the need for load coils by reducing the length of analog copper loops. This is accomplished by delivering a digital signal from the central office to an intermediate point in the field, where it is converted to an analog signal and carried the remaining distance to the customer over a copper loop.[39] Just as with earlier advancements, as the engineers solved one set of problems, they introduced a new concern. In this case, the introduction of subscriber-line-carrier systems created the need for reliable power to be supplied to telecommunications equipment outside of the central office (CO).[40] If the commercial grid

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[36] We note that this type of backup plan assumes that telephone service is received over the common-battery network. As the next section explains, this assumption is often no longer reliable.

[37] For example, a two-wire (DS0) loop can carry one voice channel, but a four-wire (or DS1) loop can carry 24 voice channels through multiplexing.

[38] For a description of load coils and their uses, *see:* http://en.wikipedia.org/wiki/Loading_coil

[39] Subscriber loops are generally comprised of three types of facilities: feeder, distribution, and drop. The portion of the loop from the CO to the intermediate point is the feeder. These are generally large-capacity cables that serve a large number of customers in a serving area. The distribution portion of the loop is a smaller-capacity cable that serves only a fraction of the customers in that serving area. The remaining portion of the loop is the drop. This last portion is the shortest and has least capacity, as it usually serves only a single customer.

[40] "The question of uninterrupted telephone service due to extended power outages is a growing problem due to the proliferation of Digital Line carrier in the outside plant. The problem will be compounded as local telephone companies extend digital line carrier and fiber-optic cable systems into the distribution plant on its journey to the home." Dave Petruziello, "Operational and Strategic Implications of Powering the Fiber Loop," *Broadband '89*, pp. 289-97, at 289. http://books.google.com/books?id=7tkNCRZNAWoC&pg=PA289&lpg=PA289&dq=operational+and+strategic+implications+of+powering+fiber+loop&source=bl&ots=j2nes5b3WZ&sig=GvgLFhdmjSCCQ5zEOLFJAK8Leh0&hl=en&sa=X&ei=Zpa6T6XAM-PM6QHG5O3yCg&sqi=2&ved=0CFoQ6AEwAw#v=onepage&q=operational%20and%20strategic%20implications%20of%20powering%20fiber%20loop&f=false

fails to supply power to the remote terminal, the signal conversion described above cannot be made, and every customer served through that remote terminal may lose service.[41]

To overcome this concern, backup batteries are typically installed at the remote terminal.[42] However, the number of hours for which these batteries can keep the remote terminal in service is limited in comparison to the backup facilities at a CO. For example, the remote terminal backup battery systems have an expected life of approximately four to eight hours, while CO backup power facilities are generally capable of maintaining service for 24 hours.[43] Engineers deemed four to eight hours to be reasonable, but not the ultimate solution. Engineering work undertaken by BellCore[44] in 1988 suggested that the batteries would provide sufficient power for 95% of expected outages if the battery life could be increased to 10 hours.[45]

The likelihood of an outage could be further reduced if the central office could provide power to the remote terminal. However, this engineering scheme was rejected in 1989 on the grounds that "[c]onstructing and maintaining a power distribution system which parallels the telecommunications cables introduces problems in areas [in which telephone companies] have little expertise or experience."[46] It was also observed that the provision of power from the central office would "negate any saving that fiber in the loop promises…"[47] For these reasons, the power for remote terminals is provided locally.

B. Modern telecommunications network architecture

The technological changes described in the prior section—putting electronics in the loop between the customer and the CO—introduced greater functionality, efficiency, and convenience

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[41] In this case, service downstream from the remote terminal may only be maintained so long as battery or generator power is available.

[42] Some large-footprint remote terminal locations serving many lines have fixed generators installed, but most remote terminal locations rely on portable generators towed in by carrier or contract personnel. Fixed generator installation may be uneconomic, physically impossible due to the size of the location, or aesthetically undesirable.

[43] California Public Utilities Commission staff, *Reliability Standards for Telecommunications Emergency Backup Power Systems and Emergency Notification Systems: Final Analysis Report* (hereafter CPUC), p. 59.

[44] AT&T retained ownership and control over Bell Labs during the divestiture, so when the RBOCs were spun off, they created their own research and development company called BellCore. BellCore was sold to Science Applications International Corporation (SAIC) in 1996 and renamed Telcordia Technologies in 1999. As of January 2012, Telcordia is wholly owned by Ericsson.

[45] Dave Petruziello, "Operational and Strategic Implications of Powering the Fiber Loop," *Broadband '89*, pp. 289-90.

[46] Id., p. 291.

[47] Id., p. 291.

in the legacy PSTN. However, a portion of these gains were achieved in exchange for resiliency, because the aforementioned technologies also introduced breaks in the end-to-end link to the common battery. The major telecommunications technology advancements that followed would continue this evolution by introducing mobility and tremendous increases in the number and types of services available to consumers. The opportunity cost of these advancements was to further sever the end users' link to the common battery by driving a wedge between the facilities providing a communications path and the facilities providing the power to make communication possible. Thus, these more modern network configurations generally require both the communications network and the commercial power grid to be operational for communications to take place. A high-level description of modern telecommunications networks follows.

1. Fiber-optic network architecture

In the simplest terms, fiber-to-the-home (FTTH) and fiber-to-the-node (FTTN) networks are an extension of the subscriber-line-carrier systems discussed above. Instead of using an intermediate point in the field, in an FTT[x] network the outermost "remote terminal" or network node and its electronics are placed at or near the customer's door and are connected to the CO by a fiber-optic cable. With respect to an FTTH network, such as Verizon FiOS:

> Inside the home, the [fiber-optic] cable terminates at an ONT (optical network termination) box that typically contains an Ethernet 10/100Base-TX network interface. This services an Ethernet network within the home. The ONT performs an optical-to-electrical conversion on the signal arriving from the central office. Multiple services may be extracted from the signal, including voice telephone signals, high-speed data, and television signals.[48]

For an FTTN network, such as AT&T U-Verse,[49] the optical-to-electrical conversions occur in the field at a remote terminal. Copper cables, generally no longer than 3,000 feet, are then used for the connection between the remote terminal and customer.

Because the length of copper cabling is reduced or eliminated in the outside plant, there are tremendous increases in speed and capacity relative to the legacy PSTN. But these gains come with a potential cost: specifically, the further decentralization of power needs. Fiber-optic cables carry information but not the power that telecommunications equipment requires to function. With FTT[x], the backup power facilities of the remote terminal, which had the potential to keep hundreds or thousands of lines working for approximately eight hours during a commercial power failure, can no longer maintain service all the way to a wired handset if the customer loses power. Backup power must now also be placed at each customer premise.[50]

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[48] *See:* http://www.linktionary.com/f/fiber_home.html

[49] We note that AT&T does have a small percentage of existing FTTH installations in the former Bell South territory. FTTH is also used by AT&T in some greenfield applications, but new service for existing dwellings is provided using FTTN.

[50] Generally, FTTH installations require battery backup power for the ONT at the customer premise in case commercial power fails. FTTN customers who receive POTS over copper may not need additional battery backup if they use a wired telephone.

Relative to the CO or the remote terminal, customer premise locations are larger in number, smaller in size, and not as well suited to overcome power failures because they are not purpose-built to house communications equipment.

2. CATV network architecture

What we now commonly refer to as a *cable television network* began in the United States in the late 1940s as a means to overcome reception-quality problems associated with over-the-air broadcasts to mountainous and rural locations. These networks were known originally as *community-antenna television* or *CATV networks*, because their primary feature was the "community antenna," which was usually placed on a mountaintop or other high point to collect broadcast signals that were then retransmitted downstream from the headend[51] over a cable to TV sets in homes located in a valley or other area with poor reception.

At a high level of abstraction, the network configuration of CATV systems and its evolution is similar to that of the telecommunications networks described above. Original CATV networks were tree-and-branch, end-to-end copper coaxial cable.[52] As with the telephone network, CATV network engineers also introduced fiber-optic feeder cables and intermediate electronics in the field to overcome the physical limitations of transmitting an analog signal over copper wire and to increase the available transmission capacity so as to provide multiple services.

Because early CATV networks were designed to provide only television service, few if any accommodations were made for backup power in the event that the commercial power grid failed.[53] CATV engineers saw no need to have extensive backup power facilities to broadcast a CATV signal to homes lacking the power to operate either the set-top box or the television. However, as CATV companies expanded their service offerings to include voice and data, they also began to install powering schemes similar to those provided by the traditional telecommunications service providers, including backup batteries and generators at both the headend and some remote optical node sites. However, without significant battery backup or a generator, the loss of commercial power to the optical node will quickly interrupt service to a wide service area (approximately 300 to 600 homes).[54]

As with the FTT[x] networks described above, modern CATV networks offer tremendous increases in speed and capacity relative to the legacy PSTN in exchange for the further decentralization of power needs. In order to maintain voice service during a failure of the

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[51] "A cable television headend is a master facility for receiving television signals for processing and distribution over a cable television system." *See:* http://en.wikipedia.org/wiki/Cable_television_headend

[52] In this case, from the headend to the customer instead of the CO to the customer.

[53] This is because television was purely an entertainment service, so it was not as vital as phone service in emergency.

[54] CPUC, pp. 101-3.

commercial power grid, backup power facilities must now also be placed at each customer premise to keep the cable modem operating.

3. Wireless network architecture

Contrary to what the name implies, a significant number of wireless networks are composed of wired facilities.[55] At a high level of abstraction, a wireless network is similar to the wired networks described above.[56] The primary difference between a wireless network and a wired network is that a wireless network offers its end users greater mobility within the coverage area. For example, while a cordless telephone attached to a wired network allows a person to move around within the coverage area of a single base station, wireless networks are designed to allow customers to roam over greater distances by facilitating the handoff of traffic from one base station to the next. A cordless phone base station and its mobile counterpart, the base transceiver station (aka "cell tower"), both require local power. Upstream, both rely greatly on wired facilities to transport traffic.[57]

Because wireless network architecture requires network electronics to be placed at or near the edge of the network, there is also a need for power in these locations. As with the other types of networks discussed above, local power is provided by the commercial power grid, with batteries and sometimes generators installed at each location to address backup power needs. However, many base transceiver stations are placed on top of buildings or other non-purpose-built structures, so it is often difficult or impossible to provide backup power facilities.

[55] *See:* http://www.forbes.com/sites/techonomy/2012/04/01/the-future-of-wireless-is-wired/

[56] The connection between a cordless handset and its base station is similar to the connection between a cell phone and cell tower.

[57] We note that some interoffice or backhaul links on both types of networks may use point-to-point microwave instead of physical cables.

III. Telecommunications Networks During Power Failures

Telecommunications network failures can be placed in one of three general categories: physical destruction of network components, disruption in supporting network infrastructure, and network congestion.[58] This paper focuses on how the current transition places increased importance on supporting network infrastructure—specifically, the commercial power grid, which is "by far the most important supporting infrastructure for telecommunications networks."[59]

When telecommunications networks are functioning properly, most consumers neither care about nor understand how these networks function and where the vulnerabilities lie. Often, it is only after finding themselves unable to communicate that customers even consider the opportunity cost of their choice of telecommunications provider(s) or equipment. For example, during the 2011 Halloween nor'easter in Connecticut, heavy snowfall resulted in many downed electric and telecommunications wires. Even after learning of the damage, many residents assumed that their cell phones would still work because such phones do not send or receive phone signals directly by wire. This assumption was flawed, because the storm had also downed the electric utility wires that the mobile networks require to operate.[60]

One customer noted that she also "…couldn't use the landline service because the cordless phones connected to it require electricity to operate and stopped working when the lights went out."[61] Surely many Connecticut residents found themselves in the same predicament when the storm drove a wedge between their network-resiliency expectations and reality, as neither their wired nor wireless calls could be completed due to a lack of power to both network and customer-premise equipment.

We believe this disconnect is due to the fact that most people are so well connected, and by so many devices and networks, that they simply assume that at least one means of telecommunications will always be available, regardless of the circumstances. This assumption is incorrect; there is no such thing as perfect reliability in a network or group of networks, especially when these networks often share common failure points, such as the commercial power grid. The remainder of this section discusses how both the legacy PSTN and more modern network technologies react to failures of the commercial power grid.

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[58] *See:* http://www.nyu.edu/ccpr/pubs/NYU-DisasterCommunications1-Final.pdf, p. 6.

[59] Id., p. 10.

[60] http://farmington.patch.com/articles/snowstorm-brings-to-light-major-weaknesses-in-the-wireless-phone-system-in-connecticut

[61] Id.

A. Legacy PSTN

The FCC requires wireline network operators to provide service-disruption data where 30,000 or more people are affected and the duration of the problem is 30 minutes or more.[62] Data for the years 1996 through 2003 indicated that approximately 1,500 such outages were reported in the United States and that 10% of these outages were caused by power problems.[63] But, as noted by the study's author, Kavitha Chayanam, a commercial power outage should not result in a major network outage because of the central-office backup batteries, which are designed to last for eight hours;[64] and the generator, which has the potential to run indefinitely.[65] Chayanam's research also indicated that up to 75% of the power-related outages could have been avoided if existing best system practices had been followed.[66]

B. Modern wired networks

The change in robustness as customers move from the common-battery network on to FTT[x] and CATV networks mirrors the change caused by the introduction of subscriber-line-carrier systems and cordless phones, with one exception where robustness is further reduced. Managed Facilities-Based Voice Network (MFVN) VoIP providers (e.g., voice over CATV, FTTH, or IP voice over FTTN)[67] also place additional electronics at the customer premise to make analog/IP conversions.[68] Conversion is necessary because, although these network architectures are based on IP switching, the customer-premise equipment is almost always analog.

The challenges faced by current MFVN VoIP providers to maintain thousands of batteries in a given geographic area are quite similar to the challenges faced by the Bell System more than a century ago, prior to the advent of the common-battery central office, when hand-cranked magneto telephones were in vogue. For these reasons, it is typically the responsibility of

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[62] Kavitha Chayanam, "Analysis of Telecommunications Outages Due to Power Loss," master's thesis, Ohio University, 2005, pp. 12, 14, and 15. http://etd.ohiolink.edu/view.cgi/Chayanam%20Kavitha.pdf?ohiou1125024491

[63] Id., p. 16.

[64] Id., p. 17.

[65] In theory, the CO generators can power the network and recharge the batteries as long as they are supplied with fuel. A typical supply of diesel fuel in a CO will feed the generators for 24 hours.

[66] Id., p. 74. Best system practices have been established by the Network Reliability Steering Committee and are available at https://www.fcc.gov/nors/outage/bestpractice/BestPractice.cfm

[67] This paper does not separately address nomadic or non-MFVN VoIP providers, such as Skype, Magic Jack, and Vonage, as these services rely on the facilities of another network provider.

[68] These conversions are made by a cable modem (CATV), ONT (FTTH), or residential gateway (FTTN), depending on the network.

customers to maintain[69] the batteries in the equipment at their premises and to replace them as necessary.[70]

While most major MFVN VoIP providers include backup batteries for the modem, ONT, or gateway at no additional charge, a few, such as CableVision[71] and Charter Communications,[72] only offer it to residential customers as a paid option. When the backup battery is offered as a paid option, it appears that either very few customers are concerned about the possibility of losing service during a power failure or they simply do not understand the dilemma (or the risk) involved. For example, Charter claims that less than 1% of its residential customers purchase the backup battery.[73] Because major MFVN VoIP providers typically make the customer responsible for the cost of replacing the batteries when they fail, Charter's experience also suggests that very few customers will actually pay for replacement batteries when the time comes.

In most instances, the batteries are estimated to last anywhere from two to ten years, depending upon standard physical constraints such as battery type, usage, environmental temperature, and so on. The batteries are expected to last for between four and eight hours during a commercial power failure, depending upon the system, battery age, usage patterns, and environmental conditions. Recharge times for batteries are estimated to be between 18 and 24 hours. Therefore, even with battery backup, a customer is likely to lose service during long-duration commercial power failures, as these backup systems are clearly designed to address

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[69] According to Verizon, "the BBU contains a series of indicator lights that tell you whether your service is being powered by your location's electricity or the battery. The BBU also indicates when the backup battery needs to be replaced." http://www22.verizon.com/Support/Residential/tv/fiostv/general+support/new+to+fios+tv/questionsone/121498.htm

[70] For example: "AT&T will not provide support for, or be responsible for, ongoing maintenance or management of equipment, including the initial RG battery backup unit or the initial ONT backup battery provided to AT&T U-verse Voice customers." http://www.att.com/u-verse/explore/battery-backup.jsp

"Verizon considers the battery in your BBU as a power source that you own. Much like you would need to replace the batteries in a portable radio from time to time, Verizon does not provide free replacement batteries for your BBU unless: The battery is still under warranty (warranties last for one year). You are currently enrolled in a Verizon Protection Plan." http://www22.verizon.com/Support/Residential/Internet/fiosinternet/troubleshooting/connection+issues/questionsone/128014.htm

[71] See http://www.optimum.com/home-phone-service/customize/battery-backup.jsp

[72] See http://www.myaccount.charter.com/customers/support.aspx?supportarticleid=1351#PurchasingBatteryBackup

[73] http://www.consumerreports.org/cro/2012/01/surprise-your-high-tech-home-phone-system-could-go-dead-in-an-emergency/index.htm

only short-duration disruptions. Moreover, even with fully functional batteries in the modem or ONT, the customer must still have a wired phone or separate backup power supply for cordless phones in order to place or receive calls.

In a 2008 study, the staff of the California Public Utility Commission used data from published electric-utility reliability reports for the State of California to identify the time distribution of large commercial power outages. The staff quantified the number of electrical-company customers that lost service due to a major event, such as a flood, lightning storm, earthquake, or human error. The staff equated the number of electrical customers affected with the number of telecommunications customers affected. This assumption was made in order to envision the impact of a power outage in a world in which fiber to the premises was ubiquitous. No data was available regarding the number of telephone subscribers affected by the outages.[74]

The data was collected over a ten-year period. During this time period, in the Pacific Gas and Electric service territory, one power outage affecting more than 500,000 customers occurred in six out of the ten years reviewed by the staff. In 1998 and 2002, there were two major outages affecting over 500,000 customers.[75]

Carriers had informed the CPUC staff that customer-premise backup-power systems generally had an expected service life of four to eight hours.[76] The outage data was organized to estimate the percentage of the population that would be without wireline service if subscribers were only served by FTTH and had a backup power system of four or eight hours, and if there was a major power outage. The staff concluded:

> The number of customers affected by power outages lasting over four hours in duration ranges from 1.4% to 14.2% of the power utility's customer base, with an average of 6.8%. The corresponding percentage of customers impacted by power outages lasting more than eight hours ranges from 1.0% to 9.1%, with an average of 3.9%. Therefore, the implementation of an eight-hour backup solution at the customer premises could reduce the potential exposure of users losing telephony (voice) service from 6.8% to 3.9% of customers, compared to a four-hour backup power solution.[77]

The staff also provided a useful narrative to aid readers' understanding of its findings. The following passage not only illustrates how longer battery lives will reduce the percentage of customers without service during an emergency, but it also highlights that an average outage value can be deceptive, because in the area impacted by the natural disaster, the percentage of affected customers will, by definition, be greater than the average for the total service territory of the power company:

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[74] CPUC, pp. 260-1.

[75] CPUC, p. 271.

[76] CPUC, p. 261.

[77] CPUC, p. 271-2.

> [I]f a major earthquake occurred and caused utility power to be lost for many days, 14.2% of the customers in the affected area will lose their telecommunications services if their FTTH system has four hours of battery backup. If their system has eight hours of battery backup, the number of customers at risk of losing telecommunications service drops to 9.2%. An earthquake event may be localized to an area within a few miles of the epicenter or have levels of decreasing damage radiating out from the epicenter. At the epicenter, the percentage of affected customers would be higher than the average value calculated across all the customers of a particular utility company.[78]

The percentage of customers completely cut off from communications will be lower than the values identified by the staff study to the extent that their wireless network remains in operation. Nevertheless, the data is instructive regarding how the movement away from the common-battery network configuration may decrease connectivity during a major power outage.

The CPUC staff estimated that the carrier's equipment cost for extending battery operating time from 6.5 to 13 hours was approximately $20 per unit.[79]

C. Modern wireless networks

Because the architecture of a wireless network is similar but not identical to the wired network architectures discussed above, particularly at the edge, it is difficult to make direct robustness comparisons. This is because the "last mile" connection to the customer relies on radio waves instead of physical infrastructure, and because this connection is mobile, not fixed. The elimination of vulnerable distribution and drop cable may result in the wireless network being more robust than a wired network, at least as far as the last mile is concerned.[80] That said, while poor wireless connections resulting in failed or dropped calls are common even when the network is fully functional, these disturbances are usually temporary in nature and are resolved without intervention from the customer or provider. In the case of a localized network failure, such as when a single base transceiver station loses power or backhaul connectivity, it is possible for an adjacent BTS to establish a radio link for communication with the end user. In this case, wireless networks may be more resilient than their wired counterparts.[81]

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[78] CPUC, p. 272.

[79] CPUC, p. 274.

[80] We note that distribution and drop cable are more likely to be exposed aerial, which has a shorter service life and higher failure rate than the underground or buried cables used closer to the core of the network.

[81] "[T]he need for backup power for wireless systems is reduced because their architecture may allow for possible re-configuration of the coverage zone for a specific antenna to reduce outage impact through:

a. Remotely or automatically modifying the emitting power of the transmitter, or

Once the radio connection is established, the communications upstream from the base transceiver (BTS) station (cell tower) to the core of the wireless network becomes more similar to wired network architecture. The BTS and upstream components all require power from the commercial grid. Similarly to wired networks, the components at the edge of the wireless network, such as the BTS, are more numerous, and more difficult to provision backup power for, than core network elements.

In its Katrina Panel Order[82] of 2007, the FCC attempted to require a minimum of eight hours of backup power for cell sites. However, these rules never came into effect and were vacated; the issues are the subject of a current FCC investigation.[83] Comments filed by wireless carriers in that proceeding generally suggest that carriers only make best efforts to supply backup power through batteries and generators because one-size-fits-all requirements would be hard to comply with, given, among other things, local zoning requirements and environmental concerns. According to a *Seattle Times* article published after the District of Columbia Court of Appeals decision to stay the Katrina Panel Order:

> Miles Schreiner, director of national operations planning for T-Mobile, said it can take 1,500 pounds or more of batteries to provide eight hours of backup energy in areas with a lot of cell phone traffic.
>
> "In urban areas, most of the sites are on rooftops, and those sites weren't built to hold that much weight," Schreiner said.[84]

The same article noted that "[i]n regulatory filings, the FCC has said the wireless carriers chose to put their equipment in areas that can't be readily expanded" and that "[t]here are almost 210,000 cell towers and roof-mounted cell sites across the country, and carriers have said many would require some modification [to accommodate backup power facilities]. At least one industry estimate puts the per-site price tag at up to $15,000."[85]

Comments filed with the FCC by a manufacturer of power generators estimated that generators can be found at only about 20% of cell sites nationwide.[86] This firm claimed that the

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b. Expanding effective coverage through joint roaming agreements with other wireless companies in times of emergency or high traffic congestion, or

c. Using power-saving technologies such as beacon based wireless control and monitoring networks, to minimize power use at cell site."

CPUC, p. 56.

[82] *See:* FCC 07-107. http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-07-107A1.doc

[83] *See:* FCC 11-55. http://fjallfoss.fcc.gov/edocs_public/attachmatch/FCC-11-55A1.pdf

[84] http://seattletimes.nwsource.com/html/businesstechnology/2004267375_apcelltowersfcc.html

[85] Id.

[86] *See:* http://apps.fcc.gov/ecfs/comment/view?id=6016875456

actual percentages varied widely by carrier and network strategy. This last statement finds support in articles and reports written about the Northeast blackout of 2003, Hurricane Irene in 2011, and the 2011 Halloween nor'easter in Connecticut. For example, as noted in the *Seattle Times* article:

> Not all carriers have joined the fight. Verizon Wireless is not a party to the appeal and has a history of installing backup generators and batteries to its cell sites. Most famously, during a 2003 blackout that kept much of the Northeast in the dark for hours, Verizon customers could still communicate.[87]

Similarly, during the aftermath of the power outages caused by Hurricane Irene in 2011, Verizon Wireless stated that:

> More than 90% of Verizon Wireless' cell sites throughout New England have both backup batteries and permanent generators designed to maintain our wireless network during the loss of commercial power. We were also able to stage additional mobile generators to address cell sites that lack a permanent generator due to landlord or permitting restrictions…[88]

According to the Verizon Wireless website:

> The Verizon Wireless network is built for reliability in emergencies, with battery backup power at all facilities and for additional reliability, generators installed at all switching facilities, and many cell site locations. The company also owns a fleet of portable generators that can be deployed to provide emergency power during extended power outages to those cell sites without permanent generators.

Many of AT&T's customers were not as fortunate. For example, Connecticut governor Dannell P. Malloy was credited with saying that, during Hurricane Irene, close to 300 AT&T towers were nonfunctional. This article went on to state: "What appears to be happening is that while some of AT&T's Connecticut cell towers are largely intact, they are simply not getting electricity. Inexplicably, other networks are functioning with equipment on many of the same towers."[89]

Despite these power-outage limitations, wireless telephones are now widely used as the primary source of communications for many people in the United States. Data provided by the CDC indicates that 31.6% of homes in the United States have only wireless phones.[90] It appears

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87 http://seattletimes.nwsource.com/html/businesstechnology/2004267375_apcelltowersfcc.html

88 http://www.ctnewsjunkie.com/ctnj.php/tech/entry/analysis_att_not_offering_much_on_why_cell_service_still_down_throughout_pa/

89 Id.

90 http://www.cdc.gov/nchs/data/nhis/earlyrelease/wireless201112.pdf

that some customers are unaware of (or simply do not care about) the power issues associated with wireless phones. As we noted above, during the 2011 Halloween nor'easter, one Connecticut resident assumed that downed power and telecommunications lines would not affect mobile phone service "…because they don't send and receive phone signals directly by wire. He and many others hadn't realized that with no power the signals [for] the calls just don't go through."[91] Furthermore, when there is an extended power outage, wireless customers will also need to find a way to recharge their mobile telephones. During the aforementioned Connecticut storms, many people without electricity were forced into libraries and coffee shops to find power to keep their mobile devices working until power was restored to their homes.[92]

91 http://farmington.patch.com/articles/snowstorm-brings-to-light-major-weaknesses-in-the-wireless-phone-system-in-connecticut.

92 http://www.westportnow.com/index.php?/v2_5/comments/35716/

IV. Transitions

Not all transition scenarios are created equal. For example, transitioning from drinking Coke to drinking Pepsi is easy and can be accomplished in a quick cutover, even if you happen to have a large existing stock of Coke. This is because you can instantaneously switch to your new choice of beverage with little or no financial loss by consuming the old stock, giving it away, pouring it down the drain, or just ignoring it in your pantry. However, in capital-intensive industries such as telecommunications, which are characterized by high sunk costs and long build times for capital projects, an instantaneous cutover is impractical, if not impossible. Even assuming that a telecommunications firm is willing and able to abandon its older technology network all at once, it is simply not possible to build the new technology network fast enough so that both the old and new networks are not operating simultaneously for a significant period of time. Ignoring the new network until it is time to shut down the old is also impractical. A firm will seek to generate revenue using the new infrastructure as soon as possible to recover the associated capital costs.

When the industry in question is also regulated, as telecommunications is, additional time must be built into the transition to accommodate transitioning the regulatory construct as well as the physical infrastructure. In some cases, new enabling legislation that accommodates the new regulatory construct will have to be created, debated, and passed.[93] Such coordination takes time, in part, because sometimes it is the change in network architecture that necessitates new regulations or legislation, while sometimes it is the change in regulations or legislation that encourages new network architecture. Coordination is also difficult, as it is not always clear whether the actions of the market or the regulator/legislator will move the transition past the tipping point. This is because the goals of each party are not always transparent to each other, and often nobody can be certain as to the actual location of the tipping point, even after the transition is complete.

Even when one type of network is superior to another, transitions can be difficult and drawn out. For example:

> Despite the clear advantage of alternating current—it can be transmitted over long distances far more economically than direct current—direct current has taken decades to phase out of Manhattan because the early backbone of New York's electricity grid was built by Mr. Edison's company, which had a running head start in the first decade before Mr. Tesla and Mr. Westinghouse demonstrated the potential of alternating current with the Niagara Falls power project.[94]

The DC transition began in 1928, and an engineer predicted at the time that it would take 45 years to complete. However, as with many such predictions, Con Edison still provided

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[93] Alternatively, the existing legislation could have to be modified or rescinded.

[94] *See:* http://cityroom.blogs.nytimes.com/2007/11/14/off-goes-the-power-current-started-by-thomas-edison/

customers with DC power up until 2007, almost 35 years longer than expected. The same will presumably hold true for the legacy PSTN.

In June 2011, the FCC Technical Advisory Council recommended that the Commission "should take steps to prepare for the inevitable transition from the PSTN." The Technical Advisory Council recommended that 2018 be the sunset year for the PSTN. A number of reasons were identified for sunsetting the PSTN, such as the high cost of maintaining it and the migration of residential customers off of the PSTN.[95]

The members of the Technical Advisory Council pointed out that sunsetting the legacy PSTN does not mean that the copper network would have to be retired. Rather, it would no longer be the official network of the country.[96] By "official network," the Technical Advisory Council meant that the legacy PSTN is at times the network of "record, whose use is mandated by standards, regulations, building codes, business practices, etc."[97] The Technical Advisory Council members noted that in the future, legacy PSTN voice services would be just one of the many applications running on IP networks.[98] The sunsetting of the legacy PSTN would imply that these functions no longer have to be provided on the PSTN, but would still be available on the IP networks.[99]

In the remainder of this section, we provide an example of the ways in which the legacy PSTN is, or has, at times been the network that "is mandated by standards, regulations, building codes, business practices, etc."[100] The discussion illustrates how government agencies and private firms have already taken steps to ease the transition from TDM-switched circuits and toward IP and packet switching. In the following section, we present cost data that suggests to us that the retirement of TDM switching and copper loops, although often predicted, is not imminent.

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[95] http://transition.fcc.gov/oet/tac/TACJune2011mtgfullpresentation.pdf pp. 10-12.

[96] "[W]hen we talk about sunsetting the PSTN we are talking about: (a) the orderly transition from the PSTN's role as a system of record for achieving key national goals; and (b) the identification of and migration to alternative mechanisms of achieving the subset of those goals that remain important to our society and economy." Critical Legacy Transition Working Group, 18 September 2011, PowerPoint Presentation. http://transition.fcc.gov/oet/tac/tacdocs/meeting92711/Sept2011_mtg_full.ppt

[97] Id.

[98] The general consensus of the panel was that standards, regulations, building codes, business practices, etc. would need to transition as well.

[99] http://www.fcc.gov/events/technical-advisory-council-meeting

[100] Critical Legacy Transition Working Group, 18 September 2011, PowerPoint Presentation. http://transition.fcc.gov/oet/tac/tacdocs/meeting92711/Sept2011_mtg_full.ppt

A. The network of record

The National Fire Protection Association (NFPA) publishes the National Fire Alarm and Signaling Code. The purpose of the code, as with a multitude of other codes published by NPPA, is to put in place standards that reduce the threat from fire and other hazards.[101]

A digital alarm communicator transmitter (DACT) is a widely used means of transmitting alarm and other signals.[102] The NFPA code states that "[a] DACT shall be connected to the public switched telephone network upstream of…the protected premises."[103] Stated differently, the code has traditionally required that a premise fire alarm be transmitted to control equipment via the legacy PSTN.

The 2010 edition of the Fire Alarm Code recognizes that:

> [t]he evolution of the deployment of telephone service has moved beyond the sole use of metallic conductors connecting a telephone subscriber's premises with the nearest telephone service provider's control and routing point (wire center). In the last 25 years, telephone service providers have introduced a variety of technologies to transport multiple, simultaneous telephone calls over shared communication's pathways. In order to facilitate the further development of the modernization of the telephone network, the authorized common carriers (public utility telephone companies) have transitioned their equipment into a managed facilities-based voice network (MFVN) capable of providing a variety of communications services in addition to the provision of traditional telephone service.[104]

Starting with the 2010 code, NFPA accepts that a DACT can either connect to the alarm center using "traditional copper-wire telephone service (POTS…) or by means of equipment that emulates the loop-start telephone circuit and associated signaling and then transmit[s] the signals over a pathway using packet-switched (IP) networks or other communications methods that are part of an MFVN."[105]

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[101] http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=72

[102] According to Honeywell, between 20 and 22 million U.S. homes have monitored security systems. The majority of these home security systems, somewhere on the order of 12 to 15 million, use the PSTN network to connect the protected premise to the alarm company. "Definitive Answers Elude FCC Workshop on PSTN Phase-Out" 12/7/11 by Joan Engebretson, http://www.telecompetitor.com/definitive-answers-elude-fcc-workshop-on-pstn-phase-out/

[103] National Fire Alarm and Signaling Code, 2010 Edition, 26.6.3.2.1. The code permits the use of a cellular telephone service as the secondary means of transmission. Id.

[104] Id., A3.3.141.

[105] Id.

The code requires that the MFVN provide a connection that "is functionally equivalent to traditional PSTN-based services." This can be done through, among other provisions, the provision of a loop-start telephone, "8 hours of standby power supply capacity for MFVN communications equipment…located at the protected premises," and "24 hours of standby power supply capacity for MFVN communications equipment located at the communication service provider's central office."[106]

The 2010 Fire Alarm and Signaling Code illustrates how historically standards, regulations, building codes, and business practices were written on the presumption that the legacy PSTN would be used to transmit information.

B. Copper and time-division multiplexing

In the previous section, we provided an example in which public policy has evolved to accept and ease the transition to new technologies. In this section, we explain why the legacy technologies may remain relevant for some time and what could increase the pace of the transition.

In Appendix A – Economics of Transition, we provide an estimate of the avoidable costs associated with shutting down the PSTN network, which we summarize here. Shutting down the PSTN network involves a two-step process. First, we use data from a 1997 UNE proceeding to estimate the cost of maintaining TDM-based digital switches and legacy PSTN loops. The second step is to convert the historical cost to a current or future cost. The historical cost is transformed to a current or future cost by taking into account inflation and the significant decline in access loops.

Our results indicate that the level of avoidable switching and loop costs provided by shutting down the legacy PSTN is not large—they vary from $5.20 to $6.80 per line today, depending on which costs are classified as "avoidable." The lower avoidable-cost estimate reflects the assumption that certain investments used on the legacy PSTN can still be used on a modern IP-based network (e.g., the copper drop wire).[107] The level of avoidable costs will be smaller if the existing copper-distribution plant is used to deliver IP packets.

Moving customers off the legacy PSTN also has its own costs. For example, the connection cost for the drop cable and inside-premise wiring to an all-fiber network may be on the order of $800. If a customer is being moved to an FTTH connection, the provider will need to spend four to eight hours at the customer's premise installing the ONT and inside wiring. This cost estimate does not include the expenditures associated with running the fiber-optic cable

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[106] Id. We note that non-facilities-based or "over-the-top" VoIP services like Skype, Vonage, and Magic Jack do not meet the requirements.

[107] If the exit from the copper network remains high, the avoidable costs could be in the range of $11.39 to $14.89 by 2017.

from the CO to the premise. Furthermore, notifying each legacy PSTN subscriber about a pending shutdown will be challenging and costly.[108]

Arguably less money has to be spent notifying customers of this change if the carrier does not have an obligation to serve. The cessation of carrier-of-last-resort obligations may reduce a carrier's obligation to serve an existing subscriber; this in turn would suggest that a carrier could make less of an effort to notify existing customers that it was shutting down its legacy PSTN facilities.[109]

Currently, though, a carrier does not appear to have an economic incentive to shut down the PSTN. The revenue per voice line is on the order of $35 to $55 per line, well below the avoidable loop and switching costs. Discontinuing service will result in additional avoidable costs, such as billing, customer service, and interoffice transport. These additional costs still likely leave the avoidable costs below the level of foregone revenues.

Additional reasons exist for carriers to maintain portions of the legacy PSTN. Wired connections will remain important for data transmission, despite the growth of mobile data traffic. As noted by the President's National Security Telecommunications Advisory Committee, "[A]lthough mobile data traffic will grow rapidly by 2015, it will remain a small percentage of overall data traffic given the spectrum limitations inherent in wireless infrastructure." This point is illustrated on the following chart, which was published in a 2011 report by the Committee.[110]

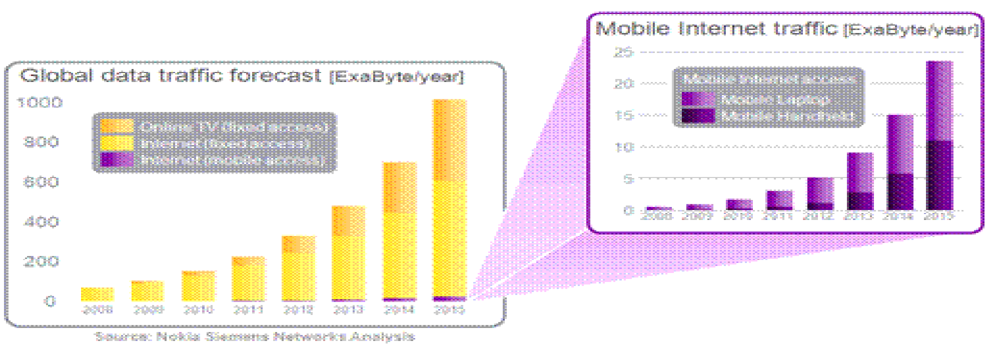

Figure 4 – Global Data Traffic Forecast

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[108] Informal conversations with carriers revealed that confirming receipt of its shutdown message by all parties was very difficult for a small percentage of customers.

[109] As of 2012, Wisconsin, Michigan, Indiana, North Carolina, Mississippi, Alabama, and Florida have eliminated carrier-of-last-resort requirements. Texas has done so only in competitive areas, and Missouri has eliminated the requirement in St. Louis County, St. Louis, and Kansas City.

[110] The President's National Security Telecommunications Advisory Committee, *NSTAC Report to the President on Communications Resiliency*, April 19, 2011, pp. 4-5. http://www.ncs.gov/nstac/reports/NSTAC%20Report%20to%20the%20President%20on%20Communications%20Resiliency%20%282011-04-19%29%28Final%29%28pdf%29.pdf

The explosion in the demand for data over fixed access lines suggests that a fair likelihood exists that portions of the existing copper network will remain in use for the foreseeable future.

V. What Can State Regulators Do?

In this section of the paper, we identify three actions that state PUCs should consider in light of the transition away from the legacy PSTN toward modern technologies.

A number of states have passed legislation (or PUCs have issued rulings) declaring that VoIP services will not be regulated by the state PUC. We do not see this as an impediment to addressing this public-safety issue. Although well aware that the FCC had exercised its authority over VoIP, the California PUC concluded that the establishment of rules to protect the public during an emergency does not constitute regulation of a VoIP provider. The Commission added that the requirements of the relevant state statute, AB2393, were aimed at:

> protecting the public health and safety of California residents in an emergency situation and, therefore, meeting those requirements necessitates the exercise of the state's historic police power. A state's police powers are not considered to be superseded by a federal statute unless that is the "clear and manifest purpose of Congress." (*Rice v. Santa Fe Elevator Corp.* (1947) 221 U.S. 218, 230.) In this case, the Commission is implementing a state statute that deals with emergency backup power for "telephony services." No party has pointed to any case indicating that the Commission is preempted from imposing the education requirements adopted here on facilities-based providers of telephony services, regardless of the technology used by such providers. [footnote omitted] Further, we find it unlikely that the FCC would issue a declaratory order concluding that the exercise of such traditional police power is preempted. [footnote omitted][111]

A. Backup power

The telecommunications industry has undergone a remarkable transformation in the past 30 years. New technology has enabled providers to deliver a plethora of information, entertainment, and data services at speeds and prices that were inconceivable when electronics were first widely deployed in the loop.

The most notable engineering shortcoming of the new technologies is the movement away from reliance on the common battery and the adoption of terminal equipment, such as the cordless telephone and computer, which are more likely to fail during a power outage than equipment powered through the central office.

Carriers are aware of the risks associated with a power failure and have established best system practices designed to reduce the likelihood of a communications failure during a power outage. The practices, which were established by an industry-led committee,[112] appear to be widely followed by the industry. The CPUC staff reported in 2008 that:

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[111] CPUC, pp. 18-19.

[112] *See:* https://www.fcc.gov/nors/outage/bestpractice/BestPractice.cfm and http://www.nric.org/.

- Most RT (remote terminal) sites of wireline providers use the eight hours of backup power as the design criteria for:
    - 95% of RT nodes of larger service providers
    - >80% of RT sites of medium and small providers
- Some critical RT sites had 12 hours of reserve designed into them and/or had external hookups points for additional power or portable generators (gasoline-, natural-gas-, or propane-powered).
- Although wireless companies sites have a broader range of capacities because of the intrinsic nature and history of the wireless networks, the average levels are as follows:
    - 88% of cell sites have emergency power backup.
    - 80% of these sites have four or more hours of backup reserve.[113]

The CPUC staff also noted that these companies are prepared to recharge the batteries if the power outage lasts beyond the time of the initial charge.[114] If the outage lasts longer than is provided for by the design criteria at the remote, the customer-premise battery will likely stop working because of the conventional belief that the life of the battery at the customer's premise should be the same as the life of the battery at the remote.[115] It does not make sense to install a battery that lasts ten hours at the home if the nearby remote will shut down four hours after a power outage.[116]

State public utility commissions individually, or jointly across wireline-provider territory, might consider investigating whether these best system practices are still in place and whether they are congruent with the interests of the public. While on their face the practices of the industry strike us as reasonable,[117] letting the industry determine what is in the best interest of

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[113] CPUC, p.56.

[114] CPUC, p. 59.

[115] CPUC, p. 26.

[116] Throughout our readings on this topic, it has always been the case that on a wireline network, the battery life at the customer premise has been equal to or less than the battery life at the remote terminal, head end, or central office.

[117] The CPUC staff reports that "the current backup reserve capacity and design criteria used for RT and CO facilities have proven successful in providing emergency telecom services in more than 95% of power outages" (p. 59). This conclusion seems inconsistent with staff's statement that "no statistics [are] available on the number of customers affected by" power outages. CPUC, p. 261.

Little data is available from other states on how power outages affect telecommunications systems. The data that is in the public domain is for *major* outages, where 30,000 or more people are affected and the duration of the problem is 30 minutes or more. Kavitha Chayanam, "Analysis of society when it comes to public safety may not be the best practice. The amount of reserve power available during an emergency is analogous to the dollar reserve that banks need in case of an emergency. The Federal Reserve Bank, not the financial industry, establishes the reserve requirements for the banks. The government establishes the reserve requirements because it recognizes that the bank's private interests may not be congruent with society's best interests. The same is true in the case of protecting public safety. The degree to which the telecommunications industry's interests do or do not coincide with society's interests cannot be determined until a study is done to measure the costs and benefits associated with the current practices, as well as alternative standards. State PUCs could consider undertaking such a study and publishing the results so that consumers will understand the risks, as well as the rewards, of moving to an IP telecommunications solution. We address this issue in the following section.

1. Best system practices

Seeking to increase the reliability of our nation's communications networks, the telecommunications industry and the FCC have embraced best system practices for maintaining electronic communications during a failure of the commercial power grid. These practices have largely been established by a panel comprising persons from the industry and members of industry associations, using the opinion of subject-matter experts (SMEs) rather than any rigorous analysis of the costs and benefits associated with different engineering practices.[118] We believe that this methodology is flawed. In this section of the paper, therefore, we provide our opinion of how a proper analysis of best system practices should be undertaken.

SMEs may be in a good position to estimate the cost of installing backup power, but they are not necessarily the appropriate source for determining the best system practice in terms of what is in society's best interest. In order to determine which practices are optimal for society, a cost/benefit analysis is required.[119] While the cost of providing backup power facilities is relatively straightforward, estimating the benefit to society is more complicated. To illustrate these points, we use the example of providing a backup battery in a single-family home that receives electronic communications from both a wired and a wireless network.

Telecommunications Outages Due to Power Loss," master's thesis, Ohio University, 2005, pp. 12, 14, and 15. http://etd.ohiolink.edu/view.cgi/Chayanam%20Kavitha.pdf?ohiou1125024491

[118] A consensus of what constitutes a best system practice emerges through a dialogue between industry experts. The industry experts use their knowledge, and firm's experience, to identify best system practices. Communications Security, Reliability and Interoperability Council, Working Group 6: Best Practice Implementation, *Final Report*, January 2011, pp. 9, 20. http://transition.fcc.gov/pshs/docs/csric/WG6-Best-Practice-Implementation-Final-Report.pdf.

Also see, for example, ATIS, *NRSC Best Practices Tutorial,* November 2011, pp. 1 and 2, http://www.atis.org/bestpractices/Tutorial.aspx

[119] We are unaware of any significant effort having recently gone into estimating the benefit to society of maintaining electronic communications during a commercial power failure.

Consider the backup battery that may be located at a home. A network operator can easily estimate the cost of installing a backup battery. The cost of the hardware is easily ascertained from equipment suppliers, or even from a neighborhood hardware store. Furthermore, a network operator can observe the practices of its technicians in order to determine how much time it takes to install the backup battery. The estimated labor cost of installing a backup battery is the product of the time estimate multiplied by the technician's loaded labor rate.[120] The readily attainable information on the cost of materials plus labor is essentially all the information needed to determine the cost of installing a battery backup, or adding additional batteries.[121]

The challenging part of conducting this cost/benefit analysis is estimating the benefit to society (i.e., value) of maintaining electronic communications during a commercial power failure. The benefit analysis has essentially two components. First, there is a need to calculate how incremental expenditures would affect the ability to maintain communications. This first calculation can be broken down conceptually into two steps.

In Step A, the analyst must determine the probability distribution of a communications outage due to a commercial power failure. In our example, this is a joint probability—that is, a probability that involves two or more events. One event is the likelihood that power is lost at the home.[122] Absent battery backup and assuming that the home's communication system runs through an electronic gateway, wired telecommunications service will stop functioning due to the power failure. Nevertheless, communications will not be impaired at the home unless the wireless network concurrently stops functioning due to a commercial power failure.[123] Therefore there is a need to determine, or estimate, the probability of a joint outage on both the wired and wireless networks.[124] These joint probability values need to be estimated for different lengths of commercial power failures. It may be the case, for example, that the local wireless transmission equipment has adequate battery backup power for six hours and will go off line at that point, but within 16 hours it may be possible for the network operator to restore service through a mobile power generator. In this scenario, the joint probability of a complete communications-network outage—that is, an outage of both the wired and wireless networks—is zero for the first six

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[120] Telephone companies regularly produce these types of labor-cost estimates in the course of estimating the cost of installing and removing equipment.

[121] The same methodology would also be used for other types of backup power facilities, such as generators and fuel cells.

[122] A similar calculation should also be done for businesses.

[123] The cellular network may continue to operate because the power failure may not extend to the location of the cell tower, the cell tower may have adequate backup batteries or a generator, or another cell tower may provide coverage during the power failure.

[124] Ultimately, the analysis will need to take into account that other households may have only one mode of communication: wireless or wireline. In such a situation, the relevant statistic is a marginal probability (i.e., a single event) rather than a joint probability.

hours,[125] as it is beyond 16 hours, but starts at 100% at hour six and declines to zero at hour 16.[126]

In Step B, the analyst needs to determine how the probability of a complete communications outage is impacted by the installation of backup power facilities, or extending the life of an existing system. Suppose a backup battery is installed in the home to provide eight hours of power.[127] In the prior paragraph, we described a scenario wherein the cellular network goes down at hour six. The eight-hour wireline-battery backup would result in the continuation of communications during hours six through eight. The analyst would determine the probability that homeowners would find themselves in a position to benefit from the eight-hour battery backup.

Parenthetically, we note that when these probabilities are calculated, they will likely vary both across and within states. For example, the likelihood of a commercial power failure is lower in areas served by buried or underground power cables. Earthquake-prone areas are more likely to experience a commercial power failure than an area without a major fault line. The same holds for an area that is more likely to be hit by a severe storm, such as a hurricane, tornado, or blizzard. These factors that influence the likelihood of a commercial power failure suggest that no single answer may exist to the question of what constitutes best system practices. Best system practices may vary across states depending on the type of geological and environmental factors just identified, as well as the condition of the electric distribution plant. In short, this is an issue ripe for study by public utility commissions.

The second part of the analysis would involve estimating the benefits to society of the increased ability to use electronic communications during a commercial power failure. Three obvious benefits present themselves. First, there is the value associated with being able to reach emergency services. For example, an individual might need to reach E911 services for medical reasons, or because of the need to notify the fire department of an emergency condition. The second and third factors are likely less valuable but are still tangible: Increased connectivity will allow people to minimize disruptions to their social and commercial activities; as well, increased connectivity will allow people to obtain, and provide, assurance to others that they are safe. The cost-benefit analysis would estimate these three values and weight them according to the probability of increased connectivity resulting from the availability of backup power.

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[125] Connectivity on the standing wireless network will be constrained due to the added usage. The analysis should also take into account the probability that a customer will not be able to complete a call on the wireless network because of the shifting of calls from the wireline network, as well as the spike in usage due to the power failure.

[126] Most, if not all, state PUCs already have some information on the time distribution of commercial power failures.

[127] As discussed earlier in the paper, it does not make sense to extend the life of the household battery backup system unless concurrently the backup life of the batteries housed in the cabinet is extended to equal or exceed the household battery.

At the end of the undertaking, the incremental cost of installing the batteries would be compared to the incremental benefit of increased communications connectivity. The best system practice would be the installation of batteries up to the point where the incremental cost is equal to the incremental benefit of increased connectivity.

We are unaware of these tasks being undertaken as part of the process of establishing best system practices. Whereas these probabilities and values may vary by locality, we believe it would be sensible for the state PUCs to undertake such an analysis in order to determine the optimal level of backup power in light of their local conditions.

Questions also arise, however, as to whether state commissions or the federal government should mandate battery backup for customer systems. It is not obvious that society's interests dictate an increase in battery life at the customer's premise. When offered the option of purchasing backup power, 99% of Charter's customers declined to make the $30 to $40 expenditure. If society's welfare is equivalent to the choice made by individuals, the decision made by Charter's customers suggests that backup power at the premise is unnecessary.[128] We are a bit reluctant to make this leap in logic. Battery backup service is needed, among other reasons, because people may need to reach E911 during a commercial power failure. The national fire code requires that a fire alarm located at a protected premise have eight hours of standby power.[129] If it is in society's interest to have eight hours of backup power supply supporting an automated fire alarm, it is arguably also in society's interest to maintain connectivity via a conventional dial-up telephone.

The dial-up telephone could be either a wireline telephone supported by battery backup or a mobile telephone. If the owner of the premise has a wireless phone, and if that telephone works during a power outage, there is no need to extend the life of the batteries used to support the wireline network. Regulators should evaluate the degree to which mobile telephones operate during a commercial power outage.[130]

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[128] Ignorance of the issues contributes to, but is not the sole reason for, the decision not to purchase a backup battery. For example, we note that the authors currently receive telephone service from different MFVN VoIP providers, one of which is CableVision, which does not supply backup batteries for its voice-capable modems. Multiple times since the service was installed by CableVision, including during the writing of this report, the decision to purchase a backup battery has been considered but not acted upon.

[129] *National Fire Alarm and Signaling Code*, 2010 Edition, A3.3.141.

[130] We have seen little data on how well a wireless network operates during a public emergency. The scant data that is available pertains to the operation of the wireless networks in Washington D.C. and New York City on September 11, 2001. The wireless networks were highly congested, with 75% and 56% of the calls being blocked that day in New York City and Washington D.C., respectively. National Research Council, Computer Science and Telecommunications Board, *The Internet Under Crisis Conditions: Learning from September 11* (2003), http://www.nap.edu/openbook.php?record_id=10569&page=R1, pp. 37-38.

State PUCs, under their current legislative mandate, may have the authority to undertake an analysis of the optimal backup power configuration. The legislation that charged PUCs with establishing quality-of-service standards may also provide the authority to investigate, propose, and establish power-backup requirements, at least for some eligible telecommunications carriers (ETCs).[131] Alternatively, state PUCs might ask their legislatures for explicit authority to investigate the power-backup question, and then report back to the legislature their findings and recommendations.

B. Wired telephones

Extending the life of the customer-premise battery-backup system may or may not have incremental benefits that exceed the associated costs. The answer to this question will, in part, depend on the estimated environmental cost of deploying more batteries. Batteries can be an environmental hazard. According to the staff of the California PUC, "[b]atteries have been identified by the Environmental Protection Agency (EPA) as the largest source of mercury, cadmium and lead to the solid-waste stream during the last decade."[132]

Increased connectivity may also be realized, without requiring additional batteries, by taking steps to ensure that end users will be able to use the telephone during a power failure. As noted above, a commercial power outage will disable cordless telephones, routers, and computers, unless this equipment is supported by its own backup power supply. Nevertheless, customers will be able to make and receive calls if they have corded telephones that can be plugged into the RJ11 telephone jack on the ONT. We recommend that the state PUCs consider educating consumers regarding the need for battery backup and wired, rather than cordless, CPE for use during an emergency. In states where commissions have some oversight of VoIP providers, the commission might consider mandating that network operators provide a corded telephone when an ONT, or equivalent equipment, is installed at the customer premise.

As with the prior recommendation, the state PUCs may need first to seek authority from their legislatures for the authority to undertake a cost-benefit analysis. After the study is completed, PUCs could make recommendations to their state legislatures.

A concern about the reliability of wireless networks during a major disaster may explain why the National Fire Alarm and Signaling Code requires that a digital alarm communicator transmitter have two transmission channels and that the primary channel be a wireline connection. The backup channel can be a wireless telephone. http://www.nfpa.org/Assets/files/AboutTheCodes/72/72-2010_FAQs.pdf question six, and Code, 26.6.3.2.1.1 and 26.6.3.2.1.4.

[131] For example, Maine's 2012 telecommunications law requires that ETCs provide line-powered service to their customers to ensure that emergency services are available when a commercial power failure occurs.

[132] CPUC, p. 124.

C. Education

In the course of our research, we were struck by how little consumers know about the reliability of their telecommunications equipment and networks during a power outage. For example, only a small minority know how long the home battery on their ONT, or equivalent equipment, will last during a power outage, or how to determine when it is time to replace the battery. We recommend that the state PUCs consider a public-education campaign that could be organized along the lines suggested by the staff of the California Public Utilities Commission. The CPUC report suggested that the following type of information be provided through brochures, marketing materials, bill inserts, and so on:

- Why the backup power was installed
- What that backup power does and does not do
- How long the phones can operate under backup power
- Capability to call E-911 in power outages (e.g., lack of backup power may hinder the customer's ability to reach E-911)
- Maintenance requirements for such backup power systems
- Potential risks from such backup power systems
- Where to find information to Frequently Asked Questions (FAQs) regarding these backup batteries—part of an emergency checklist for telecommunications in case of power outage
- Battery-replacement information (800 number, supplier chain stores, etc.).[133]

These educational subjects were adopted by the CPUC in 2010. The CPUC requires providers regularly to inform customers of the risks associated with different technologies,[134] as well as the steps that can be taken in order to improve customers' ability to make phone calls during a power outage.[135]

D. Conclusion

The evolution of telecommunication networks in the past 40 years has been remarkable. Technological progress has provided consumers with reduced prices, increased mobility, and the opportunity to subscribe to many new services. But as with all economic processes, there are opportunity costs. Modern telecommunications network technology has reduced or completely severed the end users' link to the common battery by driving a wedge between the facilities that provided a communications path and the facilities that provided the power to make

[133] CPUC, pp. 43-4.

[134] "Customers should be told they are served by technologies that require backup power on the customer's premises and informed of the limitations of service during a power outage." CA PUC Order, 2010, p. 29.

[135] "Customers should be educated as to how to maximize their ability to make or receive necessary phone calls by proper use of their phones during an outage." CA PUC Order, 2010, p. 29.

communication possible. As described above, this separation may reduce network reliability during an emergency.

We believe that state PUCs should investigate to determine whether current industry practices provide adequate safeguards during an emergency, and take steps to educate the public about the risks associated with new technology. We believe these steps should be taken in advance of the day in which a legislature may ask the state PUC, “Why didn’t you warn us of these dangers? Why didn’t you take actions that would have reduced the likelihood that people were cut off from the communications grid during an emergency?”

Appendix A – Economics of Transition

The FCC's Technical Advisory Council recommended that the FCC sunset the PSTN in part because "[a]s the number of subscribers on the PSTN falls, the cost per remaining customer increases and the overall burden of maintaining the PSTN becomes untenable."[136] This view of the economics of the PSTN was echoed in comments filed by AT&T, in which the company supported the transition from the circuit-switched legacy network to broadband and IP-based communications and asked the FCC to establish a firm date for the completion of the regulatory transition. AT&T argued that the decline in customers was making the PSTN "unsustainable" in the long run:

> Revenues from POTS are plummeting as customers cut their landlines in favor of the convenience and advanced features of wireless and VoIP services. At the same time, due to the high fixed costs of providing POTS, every customer who abandons this service raises the average cost-per-line to serve the remaining customers. With an outdated product, falling revenues, and rising costs, the POTS business is unsustainable for the long run.[137]

In this appendix, we look at the economics of shutting down the legacy copper network. To date, this has occurred infrequently. Verizon has shut down its copper network in one locality, Bartonsville, Texas, and is considering doing the same in a second place, Wesley Chapel, Fla.[138]

A. Basic theory

The field of economics provides some useful guidance regarding when it is sensible for a carrier to shut down its older network. The carrier will, not surprisingly, shut down a facility if it can reduce its loss by doing so. In the short run, losses can be reduced, or profits increased, if the foregone revenue from the shutdown is less than the avoided costs. For example, if shutting down a facility causes a supplier to experience an $8M dollar loss in revenues, but costs decrease by a larger amount (say $10M), then it is profitable to shut down the facility. The shutdown will

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[136] http://transition.fcc.gov/oet/tac/TACJune2011mtgfullpresentation.pdf p. 10.

[137] AT&T, "Comments Of AT&T Inc. On The Transition From The Legacy Circuit-Switched Network To Broadband," December 21, 2009, *In the Matter of International Comparison and Consumer Survey Requirements in the Broadband Data Improvement Act*, FCC Docket GN Docket No. 09-47. p.2.

AT&T added that "[d]ue to technological advances, changes in consumer preference, and market forces, the question is when, not if, POTS service and the PSTN over which it is provided will become obsolete." Id.

[138] http://www22.verizon.com/regulatory/pdf/Bartonville-TX.pdf ; and http://www.newtelecomblogs.com/2011/08/12/verizon-cfo-shammo-expanding-wirelines-profit-remains-a-challenge/

increase the firm's profits because the avoided costs of $10M, relative to $8M in foregone revenues, equal a $2M increase in profits.

The short-run avoided costs do not include the sunk, fixed costs of installed copper cables. For example, the cost of installing existing buried copper cables has already been incurred and therefore cannot be avoided by ceasing to use the facility. The depreciation and return costs on the existing buried copper cable are therefore excluded from the calculation that determines whether it is profitable to shut down the existing network.[139]

On the other hand, the cost of maintaining the buried cable is avoidable. If the copper network is used, it needs to be maintained. For example, when a customer complains that there is noise on the line, the source of interference must be identified and eliminated. But if service is moved off the copper facility, there is no longer a need to maintain the copper cable. Hence, the cost of maintaining the copper cable will be avoided if the copper network is no longer used to carry traffic.

The profitability of shutting down the existing network is therefore driven by the relationship between the revenues and costs that would be foregone and avoided, respectively, if the network were shut down. This operational rule is found in many economics textbooks.[140] In the next section of this appendix, we identify a carrier's avoidable costs associated with shutting down the copper network.

B. Avoidable cost estimates

As we stated at the start of the prior section, industry observers have pointed out that the decline in legacy PSTN subscription is driving up the unit cost of serving a customer. The increase in the unit cost will eventually lead to the legacy PSTN being shut down.[141] Economic theory tells us that the network will be shut down when the avoided costs of shutting down the network are greater than the foregone revenue. In this section of the paper, we estimate the avoided costs associated with shutting down the legacy PSTN.

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[139] In the long run, all costs are avoidable. Hence, the long-run avoidable costs are greater than the short-run avoidable costs. Thus a company may be willing to continue to operate an existing network in the short run because the foregone revenues would be greater than the avoided costs, but in the long run, where avoidable costs are higher, it would choose to shut down. According to Craig Moffett, a telecommunications analyst at Sanford C. Bernstein & Company, Verizon's wireline cost of money is 7.5%, 5.9% higher than its 1.6% return on investment. http://www.nytimes.com/2011/08/11/technology/sagging-verizon-landline-division-is-at-the-heart-of-strike.html

While prospective earnings can differ from the historical rate of return, the data suggests that the traditional wireline network will be shutdown in the long run.

[140] See, for example, Jeffrey M. Perloff, *Microeconomics* (Chicago: Pearson, 2012), pp. 235-6.

[141] In this example, to "shut down" means transitioning fully over to IP switching and possibly removing copper from the outside plant.

We focus on the variable costs associated with maintaining the copper loops and digital switching machines. We have focused on the maintenance costs of the loop and switch because these are the avoidable costs associated with shutting down the copper network and circuit switches used to provide PSTN services. We are not expecting the ILECs to go out of business; therefore, the other costs, such as customer billing, will persist even if the legacy PSTN is shut down.

An estimate of the avoided maintenance costs can be obtained from ILEC cost studies. With the passage of the 1996 Telecommunications Act, ILECs spent considerable time estimating the cost of providing a loop, among other network elements. The attractive aspect of these cost studies, unlike published accounting data, is the separation of expenses associated with maintaining the network from the cost associated with moving customers on and off the network. We have only used the former type of expense in the calculation because movement-related expenses are often recovered one-off connection charges.

The following table, developed from a Verizon 1997 cost study, suggests that the maintenance loop cost in its Maine service territory was on the order of $2.28 per month, in 2012 dollars, based on 1997 service volumes.[142] We have relied on data from Maine because, unlike most cost studies, the information in this study is in the public domain.[143] This cost estimate includes the costs of maintaining fiber and metallic feeder facilities, digital line carrier equipment, copper distribution cables, conduit, poles, and ancillary facilities, such as the network interface device and ILEC-owned buildings.

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[142] Maine has a lot of rocky soil and therefore has a disproportionately large share of aerial cable relative to other areas of the United States. Aerial cable is typically less expensive to install than buried or underground cable. On the other hand, because the aerial cable is exposed to the elements, it has higher maintenance costs. Therefore, the maintenance expense data presented herein may be biased upward due to the state's disproportionately freq uent use of aerial cable compared to other states.

The maintenance expenses are divided into two sub-accounts. The first sub-account, rearrangements, is associated with installing, removing, and moving customer lines. The second sub-account, repairs, is associated with repairing facilities. The maintenance expenses reported on the table are associated with the second type of activity, repairs. Rearrangement expenses, the first type of maintenance expense, are typically recovered through non-recurring charges and are therefore excluded from the development of the recurring expenses associated with a line.

[143] In 2007, Verizon sold its legacy PSTN facilities in Maine (plus Vermont and New Hampshire) to FairPoint Communications. These facilities remain in operation.

Location	Line Density (Network Access Lines / sq. mi.)	Network Access Lines	Percentage of Network Access Lines	1997 expense Restated In 2012 Dollars
Urban	> 1,500	57,075	8.66%	$1.52
Suburban	151 - 1,500	241,317	36.60%	$1.67
Rural	< 151	360,973	54.75%	$2.81
Statewide Average		659,365	100.00%	$2.28

Figure 5 – Verizon Maine

The avoidable cost would be higher if we added the cost of maintaining the digital switching machine. The average investment per line was approximately $150 in 1997.[144] The monthly maintenance on the switch, assuming a $213 per line investment in 2012 dollars, would be $0.44 per month.[145]

Therefore, the network avoidable cost in 2012 dollars, but assuming no change in demand, is $2.28 per loop + $0.44 per switch termination = $2.72.

The maintenance expenses reported in the last column of the table are effectively the quotient of total repair expenses divided by the number of lines. We will assume that the fixed expense is independent of the number of lines. This assumption is a good starting point for evaluating how the decrease in network usage affects the profitability of the network. First, it is a worst-case scenario that provides an indication of when it may be unprofitable to continue to operate the copper network.[146] Secondly, absent data in the public domain, another possible approach, assuming that all maintenance costs decrease proportionately with the number of lines,

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[144] See, for example, Washington Utilities and Transportation Commission, *In the Matter of the Pricing Proceeding for Interconnection, Unbundled Elements, Transport and Termination, and Resale,* Docket No. UT-960369, Eighth Supplemental Order, par. 311, May 11, 1998.

[145] Maine Public Utilities Commission, Docket No. 97-505, NYNEX workpapers.

[146] While it may be reasonable to assume for the purpose of this analysis that the cost of maintaining the loops is largely invariant to the level of demand, this is a poor assumption to make for the digital switches. A digital switch is more modular than loops, and line cards can be discarded when a customer terminates service. It is not possible to discard a portion of the copper cable. Therefore, our calculation overstates the cost of maintaining digital switching, once we have adjusted the level of demand.

The layoffs of line workers also suggest that the cost of maintaining the loops is not fixed, and therefore the avoidable cost estimates contained herein are likely biased upward.

would lead to the conclusion that the line loss does not affect the profitability of operating the network. Such an assumption would be seriously flawed.

Assuming that the maintenance costs for the loop and switching facilities are essentially fixed, the cost per line will increase as the number of loops decreases. Analysts have reported a significant decline in the number of in-service loops in the past few years and anticipate that the rate of decline will accelerate in the coming five years.[147] In 1997, the number of ILEC end-user access lines was 157,132,000.[148] Kelly has forecasted that the value will decline to 28,700,000 by 2017. The value in 2017 is 18.26% of the 1997 number.[149] 1997 is used as a reference point because it was the focus year for the Maine UNE study.

Assuming that access lines in 2017 will be 18.26% of the value used to derive the cost estimates in the prior table, the monthly avoidable cost of shutting down the loop would be $2.72 x (1/0.1826) = $14.89.

The avoidable loop cost would be lower if one assumed that the pole and conduit maintenance would not disappear if the copper network was shut down, and neither would the maintenance cost of the digital line equipment. This is because poles and conduit will still be needed to support the fiber-optic network, and electronics will need to be installed at the customer's premise. Zeroing out these expenses decreases the avoidable loop maintenance cost to $1.64 per month in 2012 dollars. Adding the $1.64 to the $0.44 switching maintenance expense, we have an avoidable cost of $2.08. Increasing this 5.47 (1 / 0.1826) fold to reflect the expected decrease in demand, we end up with an estimated avoidable monthly cost of $11.39.

Note that the primary driver in this analysis was the assumption that per-access-line costs increased ninefold due to decreased usage of the copper network. If the decline of access lines is less severe, then the estimated avoidable costs decrease significantly. For example, the December 2010 ILEC end-user line count value was 97,518,000,[150] or approximately 62% of the

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[147] For example, IBISWorld reports that the number of access lines has fallen from 182.9m in 2003 to 92.5 in 2012. Doug Kelly, "IBISWorld Industry Report: Wired Telecommunications Carriers in the US," March 2012, p. 36. Kelly predicts that by 2017 the number will decline to 28.7m. Id.

Similarly, JSI Capital Advisors Blog reports that between 2007 and 2012 the number of access lines declined from 142 million to 79 million. JSI Capital forecasts that the number of access lines will decline to 33 million by 2017. http://www.jsicapitaladvisors.com/the-ilec-advisor/2011/10/20/communications-industry-forecast-2011-2020-ilec-and-clec-acc.html

[148] Industry Analysis and Technology Division, Wireline Competition Bureau, FCC, "Local Telephone Competition: Status as of December 31, 2003," June 2004.

[149] 1997 is not the year of peak demand for ILEC end-user access lines. Demand peaked in 2000. Industry Analysis and Technology Division, Wireline Competition Bureau, FCC, "Local Telephone Competition: Status as of December 31, 2003," June 2004, Table 4.

[150] Wireline Competition Bureau, "Local Telephone Competition: Status as of December 31, 2010," October 2011, Table 1. Note that the 97,518,000 value excludes 3,177,000 switched access lines and UNEs provided by ILECs to CLECs. Id., Table 4. Hence the decline is slightly less than that suggested by this passage of the report.

1997 value. Kelly assumes that in 2017 the access line volume will be 18% of the 1997 value. If we assume that the decline from the 2017 value falls somewhere between the decline suggested by Kelly and the actual decline observed in 2010, this would suggest that in 2017 the access line count in 2017 will be 40% of the 1997 value.

If the decline is on the order of a 60% decline (i.e., 1–40%), the avoidable cost level for shutting down the PSTN loop and switch will be in the range of $5.20 to 6.80.[151] This example illustrates how the level of demand will play a large role in determining if the avoidable costs are more or less than the revenue that would be lost if the legacy PSTN were shut down.

The data also illustrates that the costs in rural areas are significantly higher than those in urban areas. Rural markets are less likely to have a CATV provider than suburban or urban areas. Therefore, the degree to which rural areas will first experience a shutdown of the legacy PSTN will be based in part on their traditionally higher maintenance costs per line, versus a slower rate of line loss.

C. Revenue estimates

Data on the revenue per voice line can be estimated from some of the annual reports of the ILECs. Data from the Frontier and AT&T annual reports suggests that voice revenue per line is on the order of $50. Frontier's annual report indicates that the average revenue for local and long-distance service is $36.93 per line, with an additional income of $9.57 per line from access and subsidies. These values are exclusive of income derived from data and Internet services.[152] AT&T's financial statement suggests that its customer market generates $51.86 per month, per access line through the sale of voice services.[153]

The revenue per line exceeds the avoidable costs. This suggests that in the coming years it will not be profitable to shut down the legacy PSTN.

Having done these calculations, it is fair to say that shutting down the legacy PSTN is a strawman. We do not expect the incumbents to shut down service in the foreseeable future; rather, we expect the operators of the legacy PSTN to migrate customers from circuit-switched to IP services. Hence, they do not expect to stop serving existing customers and thereby lose the stream of revenues associated with existing legacy PSTN subscribers.

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[151] $2.72/.4 = $6.8; $2.08/.4 = $5.20.

[152] Frontier Communications Corp., *Form 10-Q*, Filed 05/09/12 for the Period Ending 03/31/12, pages 28 – 29. Available at http://investor.frontier.com/secfiling.cfm?filingID=20520-12-36&CIK=20520

[153] AT&T, Inc.., *Form 10-Q*, Filed 05/04/12 for the Period Ending 03/31/12, pages 28 – 29. Available at http://phx.corporate-ir.net/phoenix.zhtml?c=113088&p=IROL-secToc&TOC=aHR0cDovL2lyLmludC53ZXN0bGF3YnVzaW5lc3MuY29tL2RvY3VtZW50L3YxLzAwMDA3MzI3MTctMTItMDAwMDM3L3RvYy9wYWdl&ListAll=1&sXBRL=1

The experience with FiOS suggests that neither will incumbents be switching customers to FTTH. The customer-premise wiring cost of approximately $800, along with the large investment per line, makes this network architecture unprofitable for the residential and small-business market.[154] Hence, the likely evolutionary process will be one of slowly shutting down the circuit-switched facilities and using a combination of copper and fiber-optic cables to reach customers regardless of whether they are served by IP or circuit switching. As noted above, the avoidable costs from moving customers off the digital switching machines are not sizeable—they are on the order of $0.44 per line per month in 2012 dollars. Hence, no strong incentive exists to shut down these switches quickly.

Parenthetically, we note that a more comprehensive analysis of the economics of shutting down the legacy PSTN would need to take into account the cost of notifying all existing customers of the pending shutdown. The cost of reaching all customers will likely be high because it will be challenging to receive confirmation from each customer that he or she is aware of the pending shutdown. Furthermore, the analysis would also take into account that existing customers might continue to be served by the legacy PSTN holding company, but with a different technology, such as wireless. If the subscriber stayed with the legacy PSTN holding company, the level of foregone revenues associated with a shutdown would be lower than the $50 value suggested above.

[154] http://wilsonville.katu.com/news/business/frontier-communications-shocks-customers-500-fee/438931; and

http://www.businessweek.com/magazine/content/11_13/b4221046109606.htm

Appendix B – Special Access Lines

In our discussion of access-line loss, we did not take into account special access lines. Special access lines are typically excluded from line counts because special access is often provided via a high-speed data link, and no widely accepted method exists for converting high-speed data links to access-line equivalencies.[155] Rather than adding a contentious value for high-speed-data equivalent access lines to the line count for this other area of demand for access, calculators generally omit this value from the tabulation, despite its importance. That said, it is important to note that the demand for special access lines from ILECs and CLECs has likely been increasing due to higher demand for transport services from mobile carriers, the Internet, and other data-intensive services. This assumption finds support in the data represented in the following graphs, which show that special-access revenue for large and mid-sized ILECs has increased significantly since 2000.[156]

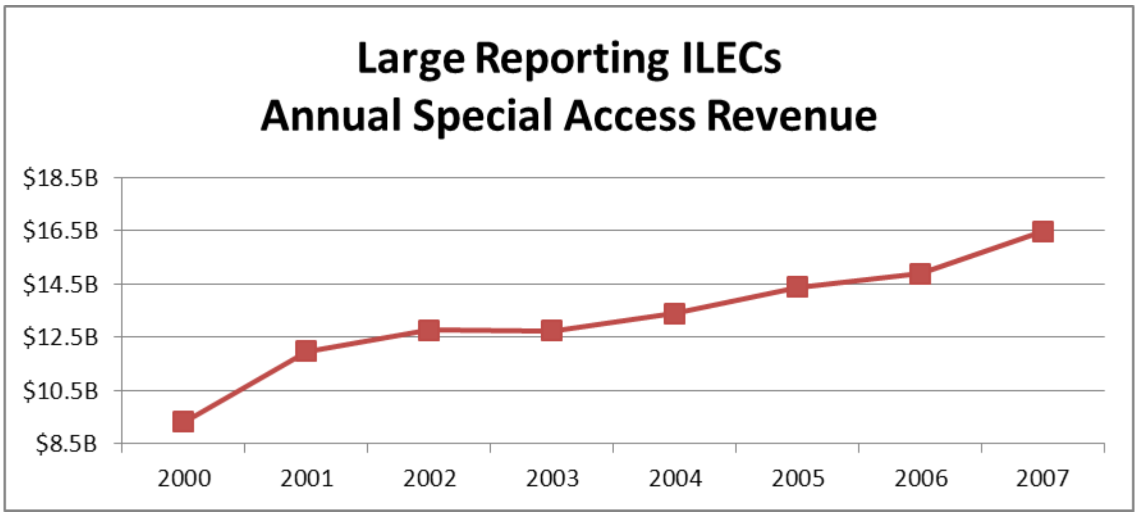

Figure 6 - Large ILEC Special Access Revenue

[155] This is largely due to the fact that the two most intuitive methods for conversion—namely, physical material and voice channel comparisons—yield increasingly different results. For example, a basic copper access line (DS0) generally consists of a single twisted pair of copper cables that is capable of transmitting one voice channel. The next larger increment of copper access line (DS1) consists of two pairs of copper cable. While a DS1 has two times the physical material of the DS0, it can, due to digital concentration, transmit 24 voice channels. Similarly, although usually provisioned over fiber, a DS3 can be provided over four pairs of copper cable and transmit 672 voice channels.

[156] We note that the FCC has an ongoing investigation into the prices charged for special access because of claims that the market is uncompetitive and the rates are too high. However, given the magnitude of the revenue increase and the increasing demand for wireless and data services, we do not believe the increase in revenue for special access could be attributed solely to price increases, if in fact they occurred.

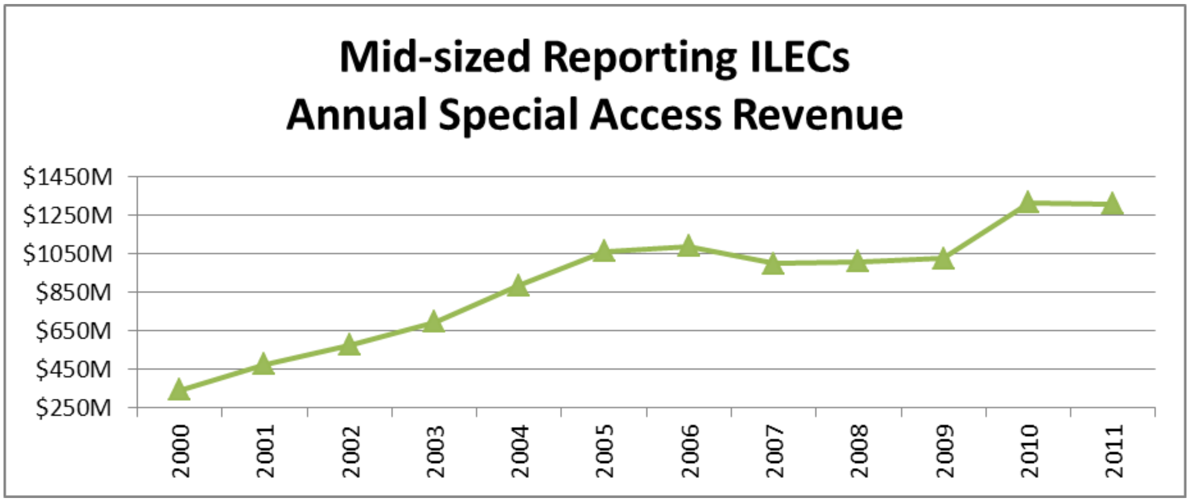

Figure 7 - Mid-sized ILEC Special Access Revenue

If we are correct that special-access line demand has been increasing, we must also assume that Figure 1 - Access-Line Losses overstates both the level and rate of decline in the demand for access.

Appendix C - Redundancy

We note that the goals of public-safety officials today bear a striking resemblance to AT&T's engineering practices in the early 1900s. In 2012, the United States Congress set aside 20 megahertz of spectrum and $7B of funding for the creation of FirstNet, a network to be used by first responders.[157] The network is being created to address the problems that hindered first-responder communications when the World Trade Center was attacked by terrorists on September 11, 2001.[158]

Some public-safety officials have suggested to the wireless carriers that the cell towers used for FirstNet should be constructed with both redundant backhaul and backup power.[159] The recommendation for redundant backhaul facilities is similar in spirit to the decision of the AT&T engineers to obtain commercial power from "two…lines supplied from separate power stations."[160] And, like the Bell engineers circa 1900, some public-safety officials support having backup power.

As reported in *TR Daily*, the wireless carriers did not embrace the engineering standards proposed by the public-safety officials. For examples, spokesmen representing AT&T, Verizon, and Sprint, three of the four national wireless carriers, pointed out that meeting the proposed standards would be prohibitively expensive.[161]

The wireless carriers do not currently provide the type of redundancy sought by the aforementioned first responders. This logically follows from the proposition that the request would not need to be made if the redundancy were already installed. Furthermore, at least one wireless carrier suggested on its website that one form of redundancy, backup generators, is not universally deployed:

> **Redundancy**
>
> The Verizon Wireless network is built for reliability in emergencies, with battery backup power at all facilities and for additional reliability, generators installed at all switching facilities, and many cell site locations. The company also owns a fleet of portable generators that can be deployed to provide emergency power

[157] http://www.ntia.doc.gov/files/ntia/publications/fr_firstnet_bod_notice_120510.pdf

[158] http://www.newsday.com/news/nation/first-responders-network-nears-approval-1.3536974

[159] "Industry Advises Public Safety To Have Realistic Expectations For Network," *TR Daily*, May 14, 2012. http://www.tr.com/tronline/trd/2012/td051412/td051412-01.htm

[160] Fagen, *A History of Engineering and Science*, p. 699.

[161] "Industry Advises Public Safety To Have Realistic Expectations For Network," *TR Daily*, May 14, 2012.

during extended power outages to those cell sites without permanent generators.[162]

In light of the contrast between the current engineering practices of the wireless carriers and those originally adopted by the Bell System, a natural question that emerges is how one might explain the differences in engineering practices. First, we reject two possible conjectures. One strand of the regulatory literature argues that where the authorized rate of return exceeds a regulated firm's cost of money, the regulated firm will overinvest. This is called the Averch-Johnson effect.[163] One could argue that in the early 1900s AT&T was willing to connect a central office to multiple power grids and install its own internal power generators because of this type of regulatory distortion. However, in our opinion, the Averch-Johnson effect has no standing here because AT&T was not regulated in the early 1900s.

AT&T was not regulated, in part, because it was a period of intense competition. Between 1894, when Alexander Graham Bell's patents expired, and 1907, AT&T's market share declined from 100% to a bit above 50%.[164] In light of the intense competition that occurred in the early 1900s, we also reject the proposition that AT&T was a flush monopolist able to dabble in excess redundancy. Indeed, competition at the early 1900s had the impact of compelling AT&T to improve its quality of service.[165] AT&T's president at that time, Frederick Fish, in letters to Bell Operating Company executives, frequently emphasized the need to improve the service: "We must give good service and must do everything that is necessary to have good service. Most of our opposition troubles are due, not so much to rates as to two other things, namely, bad service and not covering the field." Even where AT&T had successfully developed the market, poor service continued to endanger its position.[166]

We can offer two other hypotheses about the different policies regarding power redundancy. First, it is likely that the business case for redundancy is lower today because the commercial power grid is more secure, and, possibly, redundancy is currently relatively more expensive to obtain. Second, in the early 1900s AT&T's engineers likely had a greater influence on the investment decisions of their firm than do their peers within existing wireless companies. An engineering-driven firm may have focused more of its resources on power redundancy than do current wireless firms.

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[162] http://aboutus.verizonwireless.com/bestnetwork/network_facts.html accessed May 18, 2012.

[163] Averch, H., and L. L. Johnson. "Behavior of the Firm under Regulatory Constraint," *American Economic Review*, *52*(5), 1962, 1052-1069.

[164] U.S. Department of Commerce, *Telephone and Telegraphs, 1907*, table 10, p. 23.

[165] David Gabel, "Competition in a Network Industry: The Telephone Industry, 1894-1910," *Journal of Economic History*, *54*(September 1994), pp. 543-572.

[166] Id., pp. 544-5.

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