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Communications of the Association for Information Systems

Volume 27 Article 43

12-2010

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Recommended Citation
Pope, Michael Brian and Shim, J. P. (2010) "The Looming Bandwidth Crunch—Legitimate Crisis, or Cyberspace Chicken Little?," *Communications of the Association for Information Systems*: Vol. 27 , Article 43.
DOI: 10.17705/1CAIS.02743
Available at: https://aisel.aisnet.org/cais/vol27/iss1/43

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Communications of the Association for Information Systems

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The Looming Bandwidth Crunch—Legitimate Crisis, or Cyberspace Chicken Little?

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Abstract:

Global Internet usage has fueled much of the technological innovation seen during the first decade of the twenty-first century. Unsurprisingly, this has led to a commensurate increase in consumption of bandwidth, the measure of how much information the Internet can transmit. However, bandwidth is not an inexhaustible resource. Wired communications require physical infrastructure, requiring considerable investment and construction to expand, and wireless communications require sections of electromagnetic spectrum, which has grown much more crowded. This article examines the current bandwidth situation in light of networking trends and events as of 2010. Findings indicate that, although there is no immediate bandwidth crisis, one may eventually come, especially in the wireless spectrum, and, although technological innovation may provide a considerable hedge against the crippling implications of such a shortage, care must be taken to manage growth in bandwidth usage to maintain it at acceptable levels while accounting for the needs of all concerned parties.

Keywords: Internet, bandwidth, peer-to-peer, social networking, wireless, networking, spectrum, backbone, Internet Service Provider (ISP), FCC

Volume 27, Article 43, pp. 803-818, December 2010

Communications of the Association for Information Systems

I. INTRODUCTION

The old tale of "Chicken Little" speaks of an anthropomorphic, inexperienced chicken being struck on the head by an apple and interprets this as the sky falling. After attempting to convince his contemporaries of his claims that the world is coming to an end, one of his more experienced peers points out that it is indeed fruit. The younger realizes the importance of having learned a valuable lesson. Today, it seems as though a similar situation may be happening with bandwidth consumption for new technologies in the United States and around the world. However, the evidence is far more complicated, and possibly more condemning, than a mere apple to the head. Bandwidth could be said to be the lifeblood of our current economy. As broadband access becomes commonplace, even for lower-end connections, greater demands are being placed on our sources of that very lifeblood—namely, the cable that has been laid over the years, and the electromagnetic waves that are used to carry information where cables do not run. This scheme has worked across several different mediums for nearly a century. Considering how far we have come with this combination of technologies, it would seem that we have managed to do quite well with it.

However, it is questionable as to whether or not it can remain this way. Although we can lay more fiber optic cable with time and money, many frequencies are difficult for us to use for wireless purposes [Wells, 2006], and transmissions interfering with each other on the same frequency cause problems for all involved with current technology. This has only become more concerning as wireless has evolved from a broadcast, one-way medium to a ubiquitous, duplex phenomenon in which millions of customers use both reception and transmission facilities available in their personal electronic devices. Such features are very useful—and require the ability to transfer data in a wireless manner over the very same spectrum that millions of other users' devices need. As of 2010, there have been concerns as to a potential shortage of these spectrum allocations. Of course, these concerns may be exaggerations. But even if they are not, the Internet backbones—the basic lines that consist of the core of the Internet—may be reaching overload. Despite the prospects of new cable, if the companies cannot or will not add more, a bandwidth shortage will be just as real as if the spectrum were completely clogged.

Just as concerning regarding basic day-to-day functionality is the potential for the Internet to operate in a crisis. Indeed, we already have some examples of how the Internet operates—or rather, fails to operate under these circumstances. Large-scale news stories have strained it, such as Internet access during news coverage of the 2009 death of Michael Jackson, which, while not threatening core Internet infrastructure, did cause some popular websites to go down, including parts of Google's infrastructure, when the search engine giant thought they were under a massive attack from the sheer number of hits [Pittman, 2009]. An older, but very relevant example exists in the terrorist attacks of September 11, 2001, wherein major news sites were forced to essentially disable their main websites wholesale and put up a very abbreviated, simplified version—even requiring Google to put up a cached version of these pages, advising users to seek information from television or radio sources [Wiggins, 2001]. Perhaps more concerning are the prospects of situations that would have an extended strain on the infrastructure, such as those that might accompany a flu pandemic [Pearce, 2009]. Should such a situation last for over a year, it could cause considerable increases in bandwidth demand, given that telecommuting would be considered as a solution for the social and economic implications. Extreme congestion or outright collapse could require difficult choices to be made, such as shutting off bandwidth-intensive sites, causing innovation to stagnate, assuming that the attempts would be successful in maintaining basic economic functionality [Thibodeau, 2007].

Considering the gravity of this situation, it behooves us to determine whether this is actually the case, and examine the existing research into the problem to determine the veracity of this difficult problem. This article attempts to examine the bandwidth situation, using the insights of the literature and knowledge base, combined with the timeliness of industry publications, in the face of the ever-changing technological marketplace. Also, the authors seek to provide information and guidance regarding the bandwidth shortage—whether it exists, and if so, its severity and disruptive potential.

II. BACKGROUND AND HISTORY

Although as of 2010, attention has only recently focused on some aspects of the problem, such as those presented by the explosion of smartphones, concern regarding bandwidth shortages is not new. Although it would likely be difficult to pinpoint when concerns of general Internet bandwidth shortages began, an early, very large-scale example occurred during the Atlanta Olympics of 1996 [Goldsmitz and Stanford-Clark, 1997]. At the time, noteworthy Internet pioneer Robert Metcalfe asked whether or not the Internet infrastructure could survive the massive strain that the Internet connectivity of the Olympics, now online for the first time [Metcalfe, 1996]. Fortunately, the infrastructure survived and remained robust; however, it did expose the concerns, and the structure of the network systems used to permit the groundbreaking connectivity has since been the subject of academic papers for large-scale network planning [Balakrishnan et al., 1998]. However, changes were already beginning to happen to bandwidth consumption—around this time, America Online (AOL), a prominent Internet Service Provider (ISP), stopped charging for hourly access for its dial-up modem service to compete with smaller ISPs which were already offering raw Internet access with no metering. Even though the bandwidth available over such a link is limited, the door was open for unlimited access by the general Internet public.

Indeed, the general public responded with innovation previously undreamt of. Their access to the Internet increased in both quality and quantity, permitting applications that fifteen years ago would seem improbable, if not impossible. Coupled with increasing computational power, advances such as Video-On-Demand (VOD) systems have become possible, which may in some cases be displacing conventional television, bolstered by increased accuracy for advertisers aiming for a particular demographic [Mei et al., 2007].

The Internet is, in fact, rapidly displacing traditional communication—to the extent that it alarms some firms and organizations solely providing these services. Voice over IP (VoIP) is a relatively new technology that attempts to use the Internet as a substitute for the telephone, through services such as Skype, and potentially many other facilities. Some technology giants, wanting users to remain with conventional telephone service, have attempted to prevent adoption of VoIP—including, surprisingly, Apple with its iPhone [Van Buskirk, 2010]. The thought that a customer could get worldwide voice service by reallocating some of their bandwidth—of which, if the connection is broadband, would be relatively trivial—is not a comforting one to companies coveting this income, which may one day be drained away entirely by unmetered, flat-rate bandwidth, as opposed to long-distance charges or an additional flat rate. Complicating the situation are considerations by the FCC to move the entire traditional telephone service system to IP-based communications [Gelinas, 2010]. The Post Office has faced tougher challenges as well; with the advent of e-mail, it finds itself with decreasing revenues and budget problems as far fewer people conduct business or otherwise communicate via standard postal service [Jagow, 2009].

Through all of this, there were concerns that the collapse of the Internet was near. This is not a unique or new concern—in fact, it was considered before the Internet was even well known to the general public. As early as 1984, Internet pioneers examined the phenomenon of “congestion collapse” [Nagle, 1984]. In principle, this idea is very much related to bandwidth concerns and could be considered a basic definition of wired bandwidth fears. Its effects can be summed up simply—the network locks up due to overwhelming traffic. These concerns persist today, coupled with concerns of other aspects of potential harbingers of Internet doom. As an example, concerns as of 2009 over ever-increasing Internet traffic combined with a lack of infrastructure upgrades have led some to believe that significant Internet degradation will occur in the near future [Tuazon, 2009].

However, despite all of this, innovation continues, and it is continuing to be the centerpiece of communication in the modern world. It has also shown itself to be resilient and capable of surviving considerable challenges. Thus far, it has survived all doomsday prophecies. Even when it may have stumbled, it has not stayed down for long. As an example of its resiliency, one can look at the legendary “Eternal September,” which was brought about by an unrelenting tide of new AOL users ignorant of basic Internet culture disrupting the then-important Usenet system [Carraway, n.d.]. However, although Usenet has diminished in influence, it also illustrates that even in the face of potential disruption, the Internet can innovate around damage, such as forum sites now commonly used and open to the public in place of Usenet groups. While this does not deal with hardware bandwidth, it does deal with the bandwidth of human attention and intellect, and illustrates the ability of the Internet to adapt to potential damage. More direct examples include those involving techniques such as “traffic shaping,” or prioritizing traffic by type, in order to preserve network integrity, although side effects from these techniques are not without controversy [Nagle, 1984; Hardesty, 2008].

With all of this, it might be tempting to say that our bandwidth remains abundant. Some have stated in the not too distant past that we may in fact have an outright bandwidth glut [Bush, 2005]. Considering the rapid increase in home broadband speeds, it might seem that this had merit. However, this assertion is controversial [Lee and Jones, 2001], and if it ever existed, many contend that it is no more [Malik, 2006]. Nevertheless, despite statements of potential doomsday scenarios, the Internet remains available today, save for occasional outages, such as the particularly severe Slammer worm that caused worldwide outages by exploiting unpatched servers [Moore et al., 2003].

Although wired communications may be solid, there is another medium that depends on it, but needs more in order to function—wireless services. Wireless services depend on the allocation of the electromagnetic (EM) spectrum in order to send information. EM signals are emitted at the speed of light in order to convey the message to its destination, where it is detected and converted into the intended message. They are physically identical to light in that they consist of waves of photons, and are differentiated by their frequencies, giving them different characteristics, such as radio waves. Wireless communications are considerably more complicated than wired communications, as all transmissions must share the same medium—the air. While wired signals are generally constrained to the path preordained by their physical structure, wireless signals will necessarily transmit until they are physically stopped or until they decay to the point of uselessness. Further complicating matters is the fact that each wireless message needs a frequency that it can control for the duration of the transmission or reception. Otherwise, the transmissions will interfere with one another, crippling both. Due to this sensitive state of affairs, regulation has been necessary in order to keep the wireless spectrum viable. In the United States, this is primarily the responsibility of the Federal Communications Commission (FCC), which allocates ranges of frequencies for specific purposes, and within these frequencies licenses specific operators to transmit. Through this, the wireless spectrum has remained useful and versatile. Despite the efforts of the FCC, physics remains a fundamental limitation in terms of how much of the spectrum is useful to us, triggering debates as to the appropriate allocations of parts of the spectrum—which causes problems due to the influx of two-way communications devices becoming common for the public, and as a result necessarily constrains transmissions and runs up against limits of how many messages can be sent or received using these services at a single time within a given area.

Messages over wireless services will only increase in number. The Internet continues to grow, along with computational power and complexity, which in turn tends to lead to more sophisticated messages, meaning that, as the number of nodes increase, the demands of these nodes will also increase. This is consistent with the networking effects used to describe the Internet previously in the literature, such as Metcalfe's Law, which states that a communications network greatly increases in value with the addition of every connected node [Robertson, 2004]. Even government itself is encouraging increases in consumption, such as FCC's attempts to create nationwide broadband access [Singel, 2010]. Ultimately, bandwidth is a resource that is going to continue to be tapped as long as there is demand, and with innovations such as IPv6, a version of the Internet protocol capable of assigning up to 2^{128} potential addresses—or 665,570,793,348,866,943,898,599 addresses per square meter of the Earth [Hinden, 1996]—it is unlikely to abate. As such, the question becomes whether or not we can continue to satisfy that demand.

III. THE CASE FOR A CRISIS

There is no end in sight for bandwidth demands. By 2001, sports began to become somewhat more participant-oriented with the ability of viewers to express their opinions of the game strategy [Rivenburgh, 2002]. Nearly a decade later, vastly more sophisticated options are available, with services, such as YouTube, proliferating and pushing bandwidth demands even further, both in number of users served and in richness and size of content.

The bandwidth situation has the attention of many academics and practitioners, as well as portions of the government. Millions have already been spent by state governments in order to study and attempt to overcome the problem, and officials familiar with the situation have advocated further spending at the local, state, and government levels [Rolfes, 2007]. Considering the push to provide broadband to most of the country, helped in part by movements by the FCC to fund such endeavors [Gross, 2010], it will only get more severe, adding to increasing demands from existing users.

These demands include not only the sheer magnitude of user requirements, but also the particular form that these requirements take. Some protocols and services require substantially more bandwidth than others, even though this effect may be non-obvious. Peer-to-peer is a prime example, and perhaps the most concerning one. Peer-to-peer networks have raised concern as to future congestion problems [Hardesty, 2008], especially since only three years ago, it was estimated to comprise 37 percent of all Internet traffic [WebProNews Staff, 2007], and this has likely increased in terms of absolute bandwidth consumed. But the causes are not as one might expect, however. While some users use peer-to-peer applications aggressively, contributing to the problem, a more fundamental difficulty lies in the way that peer-to-peer systems are constructed. Logically, a peer-to-peer network is akin to a partially connected mesh, which is a form of network topology that has no inherent central structure; rather, nodes connect to one or more other nodes, often in an ad-hoc fashion, and all assist in routing. This can be an effective network strategy. However, over the Internet, this can cause problems [Ripeanu et al., 2002]. Although the specifics may depend on the exact nature of the implementation, the worst-case example will have all traffic passing through these nodes. In turn, the entire mesh must be "mapped" over the public Internet, which can cause a great deal of redundancy, as well as involving numerous intermediary routing nodes that have nothing to do with the actual transaction and are expending bandwidth simply to keep the logical mesh running. In a worst-case scenario, this may be totally naïve to actual network geography, requiring numerous node hops in order to get to a node that could be contacted via much more efficient means. Figure 1 illustrates the problem. Note the path not taken that would potentially be much more efficient for all parties involved, as well as the general complexity—even though it is merely an example, it shows how convoluted a P2P network as small as four nodes can become when mapped onto the Internet topology.

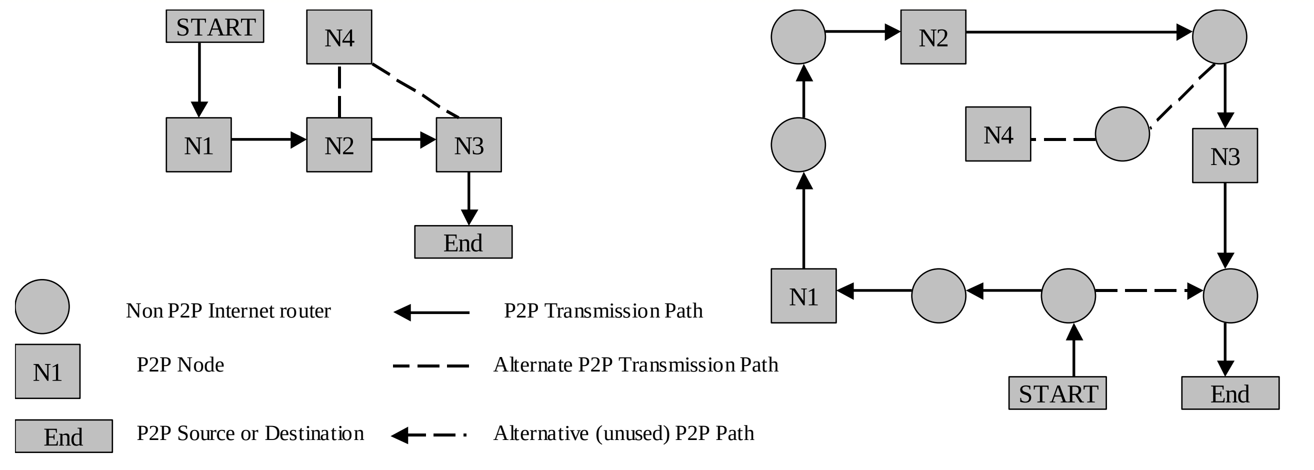

Figure 1. Example Logical Mesh Topology with a Physical Mesh That May Be Used to Convey It for a Peer-to-Peer Network

Although some systems work in a different manner, such as using more direct methods for actual bulk data transference, the problem nevertheless exists, and problems exist with other methods, including the aforementioned overarching problem of sheer bandwidth demand from these systems.

By far, the most pressing aspect of any potential bandwidth crisis involves the prospects of wireless technology, which has faced increasing demand since innovations such as the cellular phone became commonplace, resulting in current strains on EM spectrum allocation. Spectrum consumption levels are, in fact, such a major concern that the standard, over-the-air television system has been forced to convert from traditional analog signaling to digitally-based technology. High-Definition Television (HDTV), although carrying numerous technological benefits, ultimately attributes its adoption in the United States due to this lack of available spectrum. HDTV signals take up considerably less spectrum space, allowing much of what was once allocated to television to be reallocated for other purposes, such as data-based transmission and emergency services [dtv.gov, n.d.]. This has caused considerable hassle for both broadcasters and viewers alike, and the fact that such a fundamental broadcast method has to go through such a fundamental change should be an indicator of the potential gravity of this situation, particularly as it is not possible to continue reallocating spectrum forever. Television is not the only medium that is affected. In April 2010, Apple iPads were barred from being imported into Israel, due to concerns that the iPad's wireless features would be incompatible with other wireless systems [Washington Times, 2010]. As the spectrum gets more crowded, other frequency overlap problems are likely to arise. The situation can rather easily be surmised visually. Figure 2 is the current FCC spectrum allocation chart, which illustrates how crowded it is, and how little room there is for new technologies—or old technologies, for that matter—to work with.

Even if all of these concerns do not hold—and that is a difficult assumption, as some are unavoidable physical truths with current technology—it might be beneficial, if not essential, to consider scenarios that might occur should a bandwidth overload manifest itself, even if it should not be immediately crippling or even congesting. Unforeseen scenarios may end up damaging the backbone, for instance, and the results would only be all the worse if it were due to a large-scale crisis, or have an extensive effect that it might cause interference on an extended basis. Although it may be difficult to imagine most realistic natural disasters causing such a scenario, it is worth considering more unusual events, such as those presented by solar storms, which are believed to have the potential to disrupt electronics and communications, interfering with both transmission of information and generation of power [National Research Council, 2009]. This phenomenon was, in fact, known as early as 1859, when telegraphs experienced severe disruption due to unpredicted and extreme solar events [Bell and Phillips, 2006]. The actual disruption that a massive solar storm would cause remains unknown, but it is not out of the question that otherwise unanticipated events might cause similar problems, even if we insulate ourselves from space threats. An example of this might be a terrorist attack that jams communications over a wide area for an extended period of time. In any of these scenarios, although parts of the grid might well be unaffected, these may collapse as a result of being asked to shoulder the burden of an already overloaded system. While disaster preparedness is not within the scope of this article, it illustrates how conservation of existing bandwidth is important to preserving connectivity and how quickly a strained infrastructure could be pushed to the breaking point by an unexpected event beyond the control of its operators.

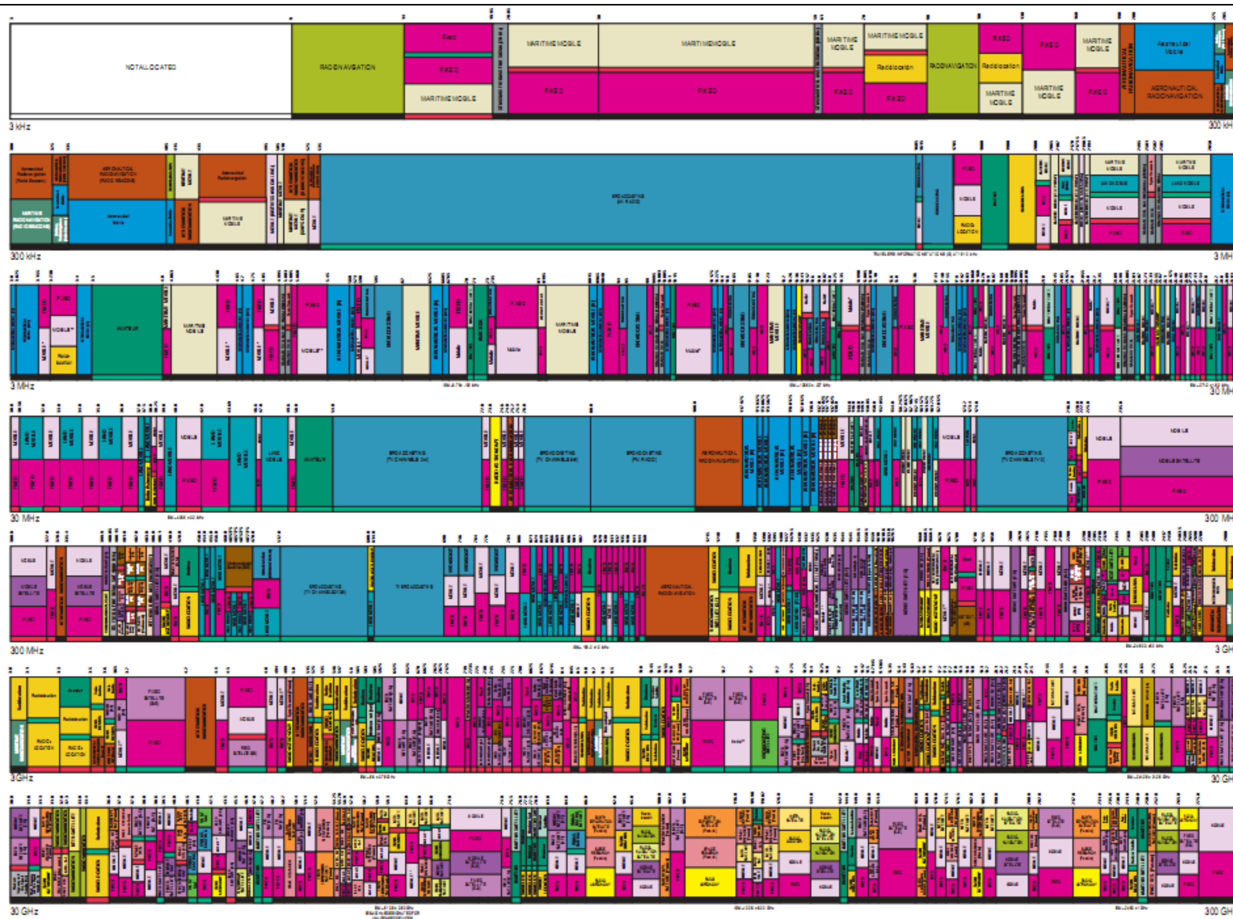

Figure 2. Current FCC Wireless Spectrum Allocation Chart [FCC, 2010]

Compounding this situation may be a slow, steady breakdown in the general courtesy between network operators. For a long time in Internet history, even if the behavior of users was questionable, many site administrators in key positions on the Internet played by certain unwritten rules to try to keep things civil and manageable for the common good. With the corporatization of the Internet, it is arguable that this has decayed significantly. The aforementioned VOD service is a key example of this. Video is an extremely bandwidth-intensive medium. YouTube traffic is believed to have consumed 10 percent of worldwide bandwidth used in the second half of 2009 [Dawson, 2010]. This is obviously a tremendous strain, and while other video sites are not as large as YouTube, they too feel considerable strain under the weight of the requirements of their service. A solution that has been studied thoroughly has been one that would help the providers, but put greater strain on the Internet as a whole—peer-to-peer sharing of videos being viewed [Huang et al., 2007]. This technique, though doubtlessly beneficial to video providers, would come at a cost to the Internet at large, in a way that is highly similar to those methods employed by peer-to-peer file sharing systems.

Academic bandwidth demands grow as well. The Large Hadron Collider, one of the world's largest scientific endeavors, transmits about fifteen petabytes per year [Heath, 2008]. While this project is an extreme example, it illustrates the increasing needs of science and technology, and, as more sophisticated experiments become more commonplace, many will require use of the Internet, as most will not be able to afford a private infrastructure. This is but an example of the increasing importance of—and demands on—global Internet bandwidth as a vital resource for future endeavors of all kinds.

IV. CAVEATS TO A CRISIS

The case for an impending bandwidth crisis is strong, and there are many issues that have yet to be overcome. However, we must not be too hasty to believe that this is the entire story. There are a number of other issues to consider, including the interests of telecommunications providers.

Metered Internet largely faded out in the 1990s, much to the chagrin of time-billed ISPs like AOL [Odlyzko, 2001]. Those days are long gone, but potential profits combined with control over resources allowed for businesses to determine their own price points. Internet usage has climbed far above the consumption rates of that era—and, as

AOL demonstrated with its own experience, can explode in an unmetered environment [Bourreau, 2001]. The potential business justification for such rates—resource restrictions—may still be there. Placing a premium on bandwidth consumption would offset the costs of scarce throughput via physical cables or wireless linkages, and would help to explain why unlimited (or at least, mass) consumption must be charged for, albeit likely in consumed throughput as opposed to time.

Concerns for a bandwidth crisis also seem to be used to fuel the debate over Net neutrality, the concept that an ISP should not charge different rates for different customers for the same consumed bandwidth, among other regulatory matters important to Internet organization [Hogendorn, 2007]. There have been concerns that current law would allow the ISP to profit from multi-tiered levels of service from different networks, encouraging use of its own content and potentially severely limiting the capabilities of competitors and other Internet companies to provide service. Legislation and regulations intended on enforcing Net neutrality are designed to force an ISP to use nondiscriminatory practices, charging and treating all network traffic equally. This has created a great deal of public debate and concern regarding the future of the Internet as a free and open medium. Large telecommunication corporations are largely against Net neutrality, in no small part so they can influence their customers into using their services and not those of competitors. In public, one of their justifications for this is stratification of service in order to better control bandwidth overuse. While there is likely a case to be made for it, exaggerating a bandwidth shortage would strengthen their position in terms of preventing Net Neutrality, giving them an incentive to exaggerate the actual extent of the situation at least long enough to pass legislation that would solidify their position.

Technical limitations are more difficult to overcome, as they certainly exist, especially in terms of physical limitations. Of these, the actual hard-wired connection is the most easily solved problem—in fact, it may already be solved. An abundance of unused fiber optic cable—so-called “dark fiber”—exists, installed by the telecommunication companies in the 1990s in anticipation of what was then called the “Information Superhighway” [Corbato and Cotter, 2005]. This inactive capacity represents a great deal of potential throughput. There has been debate that this abundant dark fiber does not exist [Lee and Jones, 2001], but there is enough that it is actually being sold to private companies, such as Google [Hansen, 2005] and is otherwise bought and sold as a commodity, making these claims ring hollow [Benston and Hartgraves, 2002; darkfiberpricing.net, 2010]. As such capacity lies fallow, it is possible that a so-called looming bandwidth crisis, at least so far as the backbone is concerned, may be at least partially artificial scarcity.

Political concerns aside, there are, of course, the physical and technological limitations. One cannot, for instance, change the speed of light. However, we are still some distance from being constrained by that fundamental limit. Wireless transmissions continue to become more sophisticated, using an increasing number of frequencies and tapping into parts of the spectrum thus far unrealized—for instance, developments as of 2007 have made advances toward utilizing a surprising source of wireless transmission, that of modulation of optical light [Langer and Grubor, 2007]. This would permit, for short-range transmission, a high-speed medium for data transference, likely supplementing existing short-range wireless systems. They also carry a number of other benefits, such as a lack of regulation, as well as a lack of direct electromagnetic interference from outside sources. This would be particularly useful for Personal Area Network (PAN) applications, which are becoming more common as personal electronics interact with one another.

For applications that cannot take advantage of short-range solutions, technology is opening new possibilities by making more frequencies accessible for data transmission, meaning that, while usable bandwidth is finite, we still have room to grow yet, and also have room to grow to make more of it usable [Wells, 2006]. Innovations as of 2010 are enabling large portions of higher segments of the spectrum, such as 70 or 80 GHz, to be useful for transmission. An abundance of medium-range cell phone towers may overcome problems certain high-frequency signals may have with direct long-range transmission. In densely populated areas, relatively short ranges could be immensely valuable, not only due to the higher density of receivers, but also the increased demand for these services in the area. Signals with high frequency but poor propagation, such as those above 100 GHz, may be usable with the implementation of error-correction technology at the cost of throughput—a worthwhile trade when the alternative might be no signal at all.

Another strategy is continued optimization of allocation of the available spectrum. Steps toward this, both in terms of reallocation and technological changes such as spread-spectrum transmission schemes, have already been taken and implemented, and there are yet greater potential improvements. More sophisticated techniques are being developed, such as those involved in the “Open Spectrum” approach, which attempts to determine positions in the spectrum not in use at a particular time and utilize them, with more decentralized methods being developed to allow more practical computation of a high-quality result and to make computation of the complex mathematics involved in such a strategy more practical [Peng et al., 2006].

Even with the existing physical limitations, there are possible remedies. One comes from a surprising source—peer-to-peer distribution, which loses many of its disadvantages when it is no longer required to be run over a different physical topology and can form its own network via wireless links. This new topology is called a *mesh*, where nodes are intended to be interlinked with one another instead of going through dedicated backbone or core nodes, such as with topologies like stars [Zeng et al., 2007]. A so-called partially connected mesh assembled in an ad-hoc manner can be a very effective way to network nodes. If the network is wireless, cumbersome cabling is not required, and it can autonomously assemble itself simply by transmitting and receiving credentials and establishing a connection as soon as nodes are in range. If a mesh network is established, backbone infrastructure will not need to be used at all, as each node in the network directly connects with one another, forming a sort of bucket brigade, taking up spectrum space for a much shorter range as calls and data are handed off [Frenzel, 2005]. One well-known example exists in the One Laptop Per Child project, which uses mesh technology to help entire classrooms access scarce Internet resources, relaying signals between the laptops to reach the Internet proper [OLPC, n.d.]. This approach has its problems, most notably security, but these can be addressed to some extent as well, such as the use of a robust encryption scheme. Another alternative is compression; more sophisticated compression would, by its very nature, require less airtime than information transmitted that is not compressed well or at all. Considering the advances in mobile device processing, as well as the possibility of customized chips explicitly designed to speed compression, there are a number of alternatives available in this arena.

Changes in the infrastructure itself may help, as well. More numerous nodes combined with shorter transmission lengths may ease pressure on the spectrum. While expensive, each shorter-range station would combine with the others to support a much greater number of users than could otherwise be serviced. Other remedies may be used where this may be insufficient, such as those in business districts of major cities. Smarter packet arrangement could use router processing hardware in order to optimize packet transportation, such as with traffic prioritization. While it is arguable that this might conflict with Net Neutrality principles, traffic shaping technology can likely be used to boost network efficiency regardless of these concerns. In conjunction with the aforementioned compression, this might be a very powerful tool, allowing for the highly compressible nature of voice data [Pan, 1993] to allow smarter usage of the telephone system and allowing it to coexist more peacefully with wireless Internet capabilities. While these tactics are almost certainly already being deployed, it is likely that more can be done as processing hardware continues to decline in expense.

V. TWO VIEWPOINTS—IS THERE A MIDDLE GROUND?

Considering the drastically differing viewpoints, it might seem as though there is no way to reconcile the two divergent arguments. The fact that both require radically different courses of action does not help—a critical bandwidth shortage might cripple future innovation, and may result in extensive, and expensive, infrastructure changes and interruptions. In the case of an inability to develop or deploy technological solutions, the "digital economy" may find its growth stunted badly for a considerable length of time. In the case of a bandwidth glut, care must be taken to avoid a bandwidth shortage, but focus can be placed on other areas, such as using that bandwidth in a better manner—in fact, it may be possible to use this excess bandwidth to conserve other scarce resources. For instance, instead of processor-intensive compression algorithms being used, less intensive compression could be used, or in an extreme case, raw data could be transferred, greatly reducing the strain on CPU power, which would be particularly helpful for streaming media applications. The fact that there seems to be no definitive indicator makes this a quandary that seems to be unlikely to be resolved soon, if ever.

However, there may be "compromise" between these two extremes, one that may be more hopeful than an impending failure of wireless and wired bandwidth alike, but still serious nonetheless—an impending, future shortage. Overall, Internet bandwidth growth has remained well over 50 percent per year over the last several years, with particular areas showing a great deal of growth, such as linkages between the United States and Latin America in 2008 [Kim, 2008]. In 2009, John Donovan, CTO of the powerful telecommunications company AT&T, stated that over the preceding twelve quarters, wireless data growth had risen by a total of 4,932 percent [Bhupendra, 2009]. In just the last half of 2009, cell phone data plan usage is believed to have grown by 72 percent [Dawson, 2010]. Much of this growth has been due to innovations such as the iPhone, and with numbers like this, and the exploding popularity of powerful smartphones following in the iPhone's footsteps, it seems likely that this explosive increase will continue, given the considerably higher computational power available to mobile users and the resulting Internet connectivity now available [Shim et al.,2007]. Under these conditions, corporations have been feeling the heat from the increased demand. It is likely that innovative solutions will be employed to help alleviate this pressure before long, as well as adding spectrum capabilities to newer handsets and devices. Nevertheless, as there are fundamental limits to the effectiveness of many frequencies for transmitting information [Wells, 2006], and with the difficulties of having different messages attempt to share a single frequency, it is quite possible that they will not continue to compensate forever. Exotic solutions such as those related to quantum computing may exist, but these are surely decades off at the very least as they require greater understanding of fundamental physics, leaving us an impending problem that we can see rapidly moving toward us.

The outlook for wireless technology seems particularly dire. It is possible that technical challenges may emerge that will severely impede improvements, causing a sharp decline in the ability to proliferate sufficient bandwidth. Economic fluctuations may impact the availability and price of rare materials used in electrical components [Hsu, 2010], impeding future innovations in networking infrastructure components, including energy-efficient systems that are in demand to process new traffic [Berry, 2009]. Not only would this affect bandwidth over the wired backbone, it may be particularly severe in terms of wireless components which may have a particularly high demand for power efficiency given the nature of their application. Although large receiver stations may be well fed with power, smaller and more numerous repeaters and access points, for instance, may not be so fortunate. Signs of strain are already visible, with some providers, including AT&T, considering more expensive wireless data plans in the near future [Finley-Price, 2009]. The reallocation of traditional television spectrum goes further to solidly demonstrate the truth of the "bandwidth crunch" we may be facing. As such, we may eventually have to face some difficult choices in terms of the use of the available spectrum.

Wired bandwidth, fortunately, is less of a problem, but it is a problem nonetheless. Dark fiber is already laid down, the extensive infrastructure costs already paid for. While at this time, dealing with dark fiber may be fairly easy, at some point new lines will simply have to be laid down (possibly sooner rather than later if concerns about dark fiber scarcity are true), and with them, data centers will need to be built, equipped, and staffed. These may run into some problems similar to those found in wireless technology, such as the availability of base materials for building up-to-date equipment [Hsu, 2010; Berry, 2009]. Although it is fortunate that these are not the most expensive parts of constructing networks, telecommunications companies are already embroiled in the parts that are, the so-called "last mile"—in this case, in its most extreme form, deploying direct fiber linkages to home customers, a trend which is increasing [Green, 2005]. Their resources are already invested in these developments. This brings another problem, in that such increases in bandwidth provide a far more direct—and far faster—connection to the Internet, increasing bandwidth demands even more. Ultimately, the worst part of the problem is that the entire Internet, including wireless, depends on the backbones that hold it together, and, if these are saturated, congestion collapse at these points will cause the Internet to slow to a crawl, if not fail outright.

In addition to physical issues, there are others that may arise. Technology itself may be a limiting factor. Although fiber optic cable can carry information at the speed of light, processors are limited by more conventional circuitry. As such, limitations to chip technology apply to communications speed as well. Furthermore, processors are necessary in order to compress data to make it smaller for transmission and uncompress the packets after receipt. Limitations to chip-making technology apply here, too, as they limit the maximum speed at which the information can be transformed. Social and societal issues abound as well, including the swelling middle class in some large countries such as India and China, who demand Internet access, and the ever-present threat of cyber war, which may damage portions of the Internet for days, weeks, or longer and has already had at least one high-profile instance occur, in the form of a massive cyber attack against Georgia during Russian military operations against the country [Markoff, 2008].

Such problems should not be taken as indications of a hopeless quandary—rather, they should be taken as a call for innovation. Some of the technologies mentioned in this article, as well as many others, await improvement and implementation, and will surely increase the speed at which information can be processed. Though expensive, new cable can always be laid if demand is sufficient, and communications technology continues to improve, including the use of optical chips that help process fiber optic signals much more quickly by using the light that is used to convey the signals. As such, it may be that, while consideration must be given to the problem now, we may not yet be in a crisis or immediately facing one, particularly for wired communication.

VI. A POSSIBLE SCENARIO—SOCIAL NETWORKING

Although the picture painted seems to have dire portents for the Internet as a whole, it may be difficult to see the direct impact that such developments may have on innovation currently studied by IS researchers on the Internet, attributing much of it to gluttonous users saturating bandwidth with piracy and other unnecessary resource drains. In order to illustrate the problems that such a situation might cause, it is advantageous to provide a possible scenario where innovation might be stunted by a bandwidth shortage. One can be found in an area currently experiencing tremendous growth, social networking. Social networking, while it may seem like it is mostly text, actually has many different aspects to it, and many potential implementations, including some that may seem surprising, such as peer-to-peer–based networks [Pouwelse et al., 2008]. The nature of social networking and peer-to-peer systems are in many ways very similar, and the proposed system, Tribler, may be a glimpse into the future of social networking and peer-to-peer technology alike.

Although it is possible to circumvent some peer-to-peer problems at a cost of anonymity by direct connection for actual file transfers (which may be quite acceptable for social networks), it still requires, at the very least, control information to be passed between nodes in order to maintain the network. Many advantages that would otherwise speed a network may end up weakening it in a bandwidth crisis situation. An example of this is the traditional practice of caching, which would allow particularly popular pages to be accessed more quickly—and a practice that might drag down overburdened nodes under excessive strain. Efforts that would otherwise go to improving the features and richness of the network and its content would go toward streamlining it and improving its performance. Individual, private users would have to use their own bandwidth, which would likely be far scarcer than that in reach of entities with corporate funding. In the face of difficulties in conventional social networking systems, such as those encountered by Facebook regarding privacy concerns in 2010 [Shiels, 2010], alternative systems being developed, such as Diaspora [Grippi et al., n.d.], have some of these impediments, as they involve the usage of individual users' computers in order to disseminate their data. This would render them vulnerable to network difficulties in bandwidth scarcity situations if their information is more popular than anticipated. The problem becomes considerably worse when wireless devices are also considered.

Even centralized social networking systems may require considerable bandwidth. YouTube, for instance, is considered by many to be a social networking site, or at the very least having important social networking features [Lange, 2007]. Other social networking sites also incorporate rich media and may continue to incorporate resource-intensive media, such as "apps" in Facebook [Nazir et al., 2008].

Even more disruptive is the effect that a bandwidth shortage might have on moves for social networking sites to act as a "single sign-in" point for many other sites—sites that will necessarily carry authentication traffic for many other, heavily-used sites. This will require extremely reliable connections, withstanding high loads and external attacks, lest many other sites be crippled for lack of an ability to sign on. As such, even with a centralized model, bandwidth scarcity becomes an issue. Large sites would be burdened, and smaller sites and individuals would undoubtedly be crippled as attempts to innovate and start up new services as their cost becomes prohibitive, if not outright impractical.

As such, it is not difficult to see how social networking might be affected by a bandwidth crunch, and these are only a few examples of how it might happen. There are likely many other ways such a shortage would negatively impact this information systems field, including many ways we cannot yet predict. The problems are also far from isolated to social networking; as it is merely one aspect of the Internet, it is not difficult to imagine that many other aspects, such as video sites, would be affected. Even more distressing may be the opportunities we do not yet know about, that will never make it out of a laboratory or a personal project server, should the bandwidth not be available to make their potential manifest, resulting in a great loss for what could otherwise be revolutionary technology. One can only imagine what the Internet might have been like had Google never made it out of the garage where it began. Even worse, these technologies, being impeded or nonexistent, will not be able to interact, preventing the creation of even more fruitful products of innovation simply by being used together, conceptually if not literally.

VII. POSSIBLE SOLUTIONS—SHELTER FOR A FALLING SKY

While the scenario we portray may seem dire to some, it is not by any means insurmountable, provided that businesses and government use the innovation at their disposal wisely. In hopes of provoking thought along these lines, we offer several potential solutions that may provide some small measure of help, and when combined with many others, they may provide more comprehensive relief to the pressures presently facing the infrastructure.

Bandwidth charges. Although it is true that services such as AOL and CompuServe suffered greatly and eventually ceased to operate in their traditional manner after the advent of the Internet, it is important to note that their original pricing model was often based on time connected, not on actual bytes transferred. Furthermore, many Web hosts and other Internet services already charge for bandwidth use (or, at least, excessive bandwidth use above and beyond the terms of the service agreement). While time-related charges are likely to cause great backlash, bandwidth-related charges, so long as they are reasonable, may be less likely to incur the wrath of consumers. Additionally, it may be possible, using packet-inspection technology, to charge for overuse of certain kinds of bandwidth, such as video or audio. This problem has been explored at least to some extent in the literature [Yaïche, et al., 2000].

P2P multicast. Multicast IP services, such as the MBone [Eriksson, 1994], exist in order to permit large numbers of identical packets to be "broadcast" with reduced network overhead. It is possible that P2P systems could be engineered to use similar protocols. While it is unlikely that many file-sharing users would use this method, as many trade in infringed copyrighted material and, as such, wish to remain difficult to trace, it is possible that other uses of this technology might benefit from an infrastructure of this type, if it can be established.

Rich clients. The Internet has brought about a renaissance of thin client systems, depending on "the cloud" for storage and processing power, and slowly abdicating away application logic to remote servers in favor of client devices being little more than "smart" terminals. Services such as Google's GMail, for instance, rely a great deal on external connectivity, even when their primary function of communication is not being used. In situations like this, we believe it may be best for the user to utilize a more robust client, capable of doing much of its own processing and logic, leveraging the impressive enhancements of mobile phone technology that have taken hold over the last several years, thus freeing up valuable air time for traffic that is actually required.

Client delegation. By using techniques such as artificial intelligence and Bayesian methods, it may be possible to truncate the overhead of basic Internet data transmission by establishing a "client delegate" at the tele-communication company. This delegate would run as a process on the host machine. The delegate would intercept certain types of packets, such as Internet Control Message Protocol (ICMP) messages, and act on the behalf of the mobile user, thus preventing an actual transmission. Alternatively, several such packets could be cached and then loaded into a single meta-packet, thus reducing the overhead needed during the actual wireless transmission to and from the mobile device.

User-controlled throttling. Throttling techniques are a tactic employed by some ISPs to control bandwidth use [Goth, 2008]. However, it is arguable that it might be more productive to place throttling at least partially in the hands of the users. A base throughput that is acceptable for most basic connectivity, combined with a higher-throughput mode that charges per time in mode or bandwidth used might allow consumers to be more cost-conscious, as well as make certain that when they use higher throughput, they actually need it, as opposed to wasting it (or having it wasted for them) by things such as unwanted video ads popping up in their Web pages. Furthermore, if charges are related to the activity on the network, time of day, or day of the week, it might also encourage network usage during lower traffic periods, such as late at night, especially if bandwidth-intensive tasks and throttle controls can be automated.

Bandwidth repartitioning. Although many individuals run Internet servers from their home, most do not. As such, they are often not likely to have much use for their computer's connectivity when they are away from it. However, if the computer is left operational, it may be using bandwidth in wasteful ways. Companies might find ways to take advantage of this in a manner similar to user-controlled throttling—for instance, while at home, an individual may "trade" some of their home Internet bandwidth for mobile Internet bandwidth to their phone or laptop computer. While such a scheme might be cumbersome, experience would likely eventually erode this difficulty, and cost-conscious customers may be willing to adapt if the incentives are high enough.

VIII. CONCLUSION

As technology continues to advance rapidly, so too will the communication that utilizes it. With these changes will come greater demands on the media that convey the information thus produced. Media to convey data, like any other resource, are finite, and as our economy increases its dependence on data transference, a very legitimate question arises as to whether or not our prodigious growth will allow us to continue to expand our capabilities.

Unfortunately, the answer is unclear. Changes in complicated sociopolitical dynamics affect Internet usage, making it difficult to forecast its development beyond the fact that it will grow. Further, both sides of the debate have important points. Nevertheless, there are a few points that are worth emphasizing. Several of these are summarized in Table 1.

First is the nature of wired communications. Simply put, it is possible to lay new cable. It is expensive and may be difficult in places, but it can be done. In fact, we have not yet begun to truly tap the full capabilities of our infrastructure with a great deal of dark fiber already existing. If demand drives the need for further expansion, additional cable can be laid and facilities constructed to manage these new lines.

The second is the nature of wireless communication. Although only applicable within a particular given area, within that area everyone must use the same common resource for information transmissions. Although there are ways to work with this issue, and it may be possible to continue mitigating its effects, it is nevertheless impossible to deny that it exists. It will continue to influence our communications networks for the foreseeable future according to our current understanding of the scientific principles behind it, as well as our understanding of possible alternatives to the present EM-based systems that we use.

Third, and perhaps most important, is the fact that the Internet has not yet collapsed. Many have believed that it would fail, and in some cases it has suffered severe technical setbacks, but it still remains robust, vibrant, and growing, proving its tenacity in the face of challenges to its structure. If we simply stop or if corporate or government interests use this as an excuse to impose control and/or restrictions for additional power or money, the potential of

Table 1: Summary of Points For and Against Impending Bandwidth Crisis		
Infrastructure Type	**Crisis Likely**	**Crisis Unlikely**
Wired	Considerable expense in infrastructure upgrades	New lines can be added.
	Perpetual growth in bandwidth demand will eventually exhaust existing infrastructure.	Dark fiber—unused wired potential
Wireless	Usable wireless spectrum is limited.	Better use of short-range wireless can mitigate problems, especially in densely populated areas.
	Increase in mobile app usage	New frequencies can make more wireless spectrum available.
	Already big enough to require reallocation of traditional bandwidth uses	
Wired and Wireless	Constant increase in Internet usage	Many previous disaster predictions have not come to pass.
	Increasing population who can access the Internet	Supply-and-demand (e.g., “pay per byte”) may help regulate overuse.
	Video usage growing especially large-scale	Situation may be exaggerated for political purposes or profit.
	P2P use is especially demanding.	Advances in technology may make smarter use of bandwidth.
	New applications may require more bandwidth.	
	If bandwidth is scarce, a disaster may push it into a crisis.	
	Some technological solutions are at least decades away.	

the Internet will, without question, be badly hindered, and possibly will be for many years if the interference is overly extensive.

Fourth, the possibility exists that the Internet will never attain a true extended state of bandwidth glut or bandwidth scarcity. Analysis conducted in the early 2000s indicated that there was an effect similar to Cooper’s Law in terms of Internet growth, and that demand for the bandwidth would continue to increase into the future, doubling roughly once every year [Coffman and Odlyzko, 2000]. It also held that due to this, data transmission capabilities would continue to grow with demand. This would have a much more unstable growth curve compared to other communications systems, but, nevertheless, it would continue to grow. As such, it is unlikely that there would be a sudden incapacity for the Internet to continue to be used or expanded.

Another concern that arises is the processing power needed in order to properly copy, route, segment, process, and otherwise manage network transmissions. This may seem trivial compared to bandwidth limitations in terms of long-range media, at least for the moment. However, limitations have already been found in increasing processor efficiency, and these may not be overcome in the foreseeable future. Further, if, at some future point, it becomes advantageous to embed processor-intensive options into the backbone (such as an extension of the Internet Protocol that might include cryptographic authentication), pressure on processing resources may experience strain on top of existing bandwidth scarcity. While not an immediate concern, it illustrates that challenges will lie ahead. Nevertheless, all of these notes and observations are subject to one overarching truth—while it is possible that no bandwidth crisis yet exists, we still operate within finite boundaries. Careful choices and design may be necessary in order for us to continue our collective transition into the digital age with the full benefit of wireless communications and plentiful bandwidth. Finally, there remains one truth that, although Chicken Little was never forced to face it, even he could not escape had it come true—the sky has to fall only once.

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1. These links existed as of the date of publication but are not guaranteed to be working thereafter.

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Communications of the Association for Information Systems

ISSN: 1529-3181

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