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Future Internet Bandwidth Trends: An Investigation on Current and Future Disruptive Technologies

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Future Internet Bandwidth Trends: An Investigation on Current and Future Disruptive Technologies[*]

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Abstract / Executive Summary

New technologies sometimes result in disruptive changes to the existing infrastructure. Without adequate foresight, industry, academia, and government can be caught flat-footed. In this work, we focus on the trends surrounding home Internet bandwidth — the bandwidth required by end user applications at home. As building and managing last mile network infrastructure incurs substantial cost, the foresight of such trends is necessary to plan upgrades.

Using a bottom-up approach, we look at four potentially disruptive technologies, including millimeter wave wireless (mm-wave), the Internet of Things (IoT), Fog Computing, and Software Defined Networking (SDN). We examine use cases proposed by academia and industry, delve into the bandwidth requirements for proposed applications, and use this data to forecast future traffic demands for typical home users. Our projections show that bandwidth changes at end user devices will most likely be driven by two of the above technologies: millimeter wave wireless and Fog Computing. These technologies not only change the peak bandwidth, but also have noticeable secondary effects on bandwidth such as increasing upload bandwidth use, improving flash crowd tolerance, and increasing off-peak demand. While IoT and SDN are important, innovative technologies, they will not drastically alter the bandwidth usage patterns of ordinary users at home. We hope that the data and recommendations from this study can help business leaders and policy makers get an early jump on emerging technologies before they begin to shape the economy and society.

1 Introduction

Disruptive technologies, such as the steam power in the Industrial Revolution, semiconductor microchips, or the Internet, have transformed the way ordinary people live and work. These technologies are capable of creating opportunities for introducing new concepts, and creating pathways to altering the pre-existing infrastructures and pre-established orders. This work investigates the disruptive technologies that can potentially change the Internet *bandwidth* use of *end users* with a bottom-up approach. The technologies range from the fundamental physics in data transmission from one device to another, to the abstract, high-level programmability in a network.

This work investigates how bandwidth needs will change over the next 10 years. In particular, there are several distinctions that make our work unique in this space, and different from previous work [80, 86].

- *Providers know their users and deployment.*

  It is assumed that industrial leaders and policy makers are aware who the targeted users of their networks are. The question is then "what are the unknown unknowns?" For example, what new wireless technology can drastically change the bandwidth needs and usage patterns of users; what changes in the Cloud infrastructure can lead to much higher bandwidth and much lower latency; etc.

- *Focus on home users.*

  The focus of this work is not enterprise, business or academic users with super computation and storage power, but rather, ordinary home users. These users move relatively more frequently, own devices with limited capability, while still require satisfactory user experience.

- *Focus on bandwidth.*

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Bandwidth is the main focus of this work, instead of programmability and other factors. Different from the industrial or academic networks, home networks have different providers on the access link. To provide satisfactory user experiences, bandwidth is the major concern for both users and service providers.

- *Focus on technical need.*

  Only technical aspect, instead of economic, social or legal aspects, will be considered in this work. While the technologies in this work have a tremendous impact on the economy and society, these factors are out of the scope of this work. Any legal issues are also not within the scope.

- *Assume existing infrastructure exists.*

  New technology will only be adopted when appropriate given other choices in the marketplace. If building a service using existing technology makes sense from a legal, financial, and performance standpoint, there is no reason to adopt new technology to do so.

Finally, we would like to emphasize the last distinction in the above list. A blind-spot that comes up repeatedly by studies examined in this work is technology that could be done much more effectively with cloud computing infrastructure. Namely, the cloud provides inexpensive, medium latency access to effectively unlimited computation and storage capacity. Thus unless the latency, financial, or legal attributes of the cloud are not attractive for that application domain, the application will likely be done with existing cloud technologies.

This has the effect of bounding data intensive applications to the bandwidth needed, e.g., to run a VLC terminal. For example, assume that an application provides high resolution maps. Instead of distributing these high resolution maps to clients and having them select the area to display on the screen, we believe that these services would be built as web applications that are hosted in the cloud. Only the selected map area by clients will be transferred over the Internet, so that both traffic and latency will be reduced. This is a common practice used by most services today, and it effectively limits the amount of bandwidth needed that can saturate the user's output devices.

1.1 Internet Bandwidth and Disruptive Technologies

The growth in Internet bandwidth has historically been fueled by two factors. First is the natural growth in bandwidth as more user become online, new media formats are adopted, and users purchase devices with new capabilities. These factors are relatively well-known and predictable, due to the improvement in the capacity and affordability of processors, memory and disks, etc. The second factor comes from disruptive technologies that dramatically shift the bandwidth use pattern by shifting how users access the network. This includes technologies and applications discussed in this work, which have resulted in a ground-swell of use that was fundamentally different than previous expectations would have predicted.

This work will focus on a study of the likely future bandwidth use of four different emerging trends that may potentially be disruptive to Internet bandwidth consumed by end users. In particular, we will study the effect that the following technologies would have on peak network bandwidth:

Millimeter wave radio access (mm-wave). One major factor that is driving Internet bandwidth consumption is the move to from wired networks to wireless, such as WiFi and cellular services. While wireless technologies have brought significant flexibility to people's everyday life by allowing mobility, the scarce wireless spectrum is facing global bandwidth shortage [93], a fact exacerbated by the drastically increased number of wireless devices. By the end of 2013, there were one and a half billion smartphones in use [50], which means 22% of the world population owns a smartphone. According to the recent data released by the International Data Corporation (IDC), 87% of connected devices sales by 2017 will be tablets and smartphones [30]. One potentially disruptive effort by NYU WIRELESS [49] is looking to use new spectrum bands and other optimizations to increase wireless bandwidth by a factor of up to 1000 within the next few years. We will study the potential impact that these technologies will have on end user bandwidth.

Internet of things (IoTs). Over time, more and more consumer devices are becoming connected to the Internet. These not only include laptops and smartphones, but also power meters, washing machines, thermostats, refrigerators and light bulbs. As more daily devices become connected and bring more convenience to people's everyday life, this may also shift the use patterns of network bandwidth and result in a different bandwidth demand curve. We will study the likely impact of such a trend impacted by smart, networked things in daily life.

Community Cloud / Fog Computing. Recent development in Cloud Computing features centralized data processing and storage. Overlay networks and peer-to-peer systems, on the other hand, have demonstrated excellent growth potential because they can be directly deployed by end users. A community cloud will leverage a middle ground by embracing the distributed network nature while providing virtualized computation to requesting users. Since network operators need not deploy hardware or software, these systems can become widely deployed in a short time. In a similar vein, Fog Computing, as is advocated by Cisco [76], embeds cloud computing infrastructure in routers and switches directly connected to end user devices. By utilizing idle computing and network capacity on these edge devices, such systems possess the potential to unlock and pool these capabilities.

Software defined networking (SDN) for home networks. Technologies such as OpenFlow [51] are being touted in the data center as an easy way to more efficiently utilize bandwidth and provide additional programmability without repeatedly changing network hardware. There are efforts like US Ignite [68], Mozilla Ignite [42] and GENI [24] that are interested in seeing how this technology can transform consumer networks and applications. We will study possible consumer applications and deployment paths to understand their impact on bandwidth usage by end users.

1.2 Road Map

Through this work, our goal is to perform an investigation of disruptive technologies from an end-user perspective. Using this analysis policy makers can shift funding and national priorities, academic researchers can target future research to stay ahead of industry, and industry can have the agility to adapt to coming market, societal, technical and economical changes. The rest of this paper is organized as follows. Sections 2 to 5 introduce our study on the four disruptive technologies: mm-wave radio access, the Internet of Things, Community Cloud and Fog Computing, and Software Defined Networking. Finally, Section 6 concludes this work.

2 Mm-Wave Radio Access

2.1 Background

5G [3] denotes the next major phase of mobile telecommunications standards beyond the current 4G standard. According to historical data, new mobile generation has appeared approximately every 10th year since the first commercially automated cellular network, the 1G generation that was launched in Japan by NTT around 1980 [1]. It is suggested that a new generation of 5G standards may be introduced approximately in the early 2020's [83]. New mobile generations are typically assigned new frequency bands and wider spectral bandwidth per frequency channel. A comparison between 1G to 5G is given in [90], and the results are presented here in Table 1. As these previous generations of radio technologies have already resulted in substantial increase in the peak bit rate, it will be interesting to project how 5G plays a role in radio technology for even higher bandwidth. One effort by NYU WIRELESS [49] in 5G is looking to use mm-wave radio access and other optimizations to increase wireless bandwidth by a factor of up to 1000 within the next few years. This section provides our insight into the likely bandwidth of mm-wave, and how it will affect the end user data usage pattern.

2.2 The Usage of Millimeter Wave Spectrum

The development of wireless technology has led to changes in the way mobile and wireless network systems are used. Our vision is that the introduction of millimeter wave (mm-wave) technology, together with the emerging newer generation of wireless devices such as smartphones and tablets, and the wide variety of exciting applications, will lead to higher data rates and bandwidth use from denser crowds of users. This will also result in higher requirements on the end-to-end performance, service quality and user-experience. Compared to the current wireless and mobile networks, where the carrier radio frequencies are between 700 MHz and 2.6 GHz, mm-wave frequencies that are up to 90 GHz is one solution to 5G, which can be used for *both* wireless backhaul and access networks.

In 2009, researchers have proposed 5G as a user-centric concept instead of operator-centric as in 3G or service-centric concept as seen for 4G [81]. The following introduces some of the radio access technologies in 5G, as well as its advantages in handling higher data rate, increased data traffic, and more efficient use of radio spectrum.

2.2.1 Higher Bandwidth Allocations

The continued advances and discoveries in computing and communications, and the emergence of new consumer devices has resulted in ever-increasing demand on bandwidth and capacity. Although the service providers today promise to deliver high quality, low latency, content rich applications for mobile devices, the current carrier frequency spectrum has been limited to the very crowded range between 700 MHz and 2.6 GHz. The higher bandwidth use and traffic poses challenges to providing positive user experience and sustaining increased demands on bandwidth. This leads to a major cause of global bandwidth shortage. The global spectrum bandwidth allocation for all cellular technologies does not exceed 780 MHz, where each major wireless provider has approximately 200 MHz across all of the different cellular bands of spectrum available [92]. To support the ever growing data rate demands and exponentially increasing traffic volumes, higher spectrum availability and more advanced radio access technology is needed.

Generation	Time Period	Definition	Technology	Bandwidth	Features
1G	1980 – 1990	Analog	AMPS, NMT, TACS	14.4 Kbps (peak)	Wireless phones are used for voice only.
2G	1990 – 2000	Digital narrow band circuit data	TDMA, CDMA	9.6/14.4 Kbps	Allowing multiple users on a single channel via multiplexing; wireless phones are used for data and voice.
2.5G	2001 – 2004	Packet Data	GPRS	20 – 40 Kbps; 171.2 Kbps (peak)	Multimedia services and streaming starts to show growth. Phones start to support web browsing (very limited).
3G	2004 – 2005	Digital broadband packet data	CDMA 2000 (1xRTT, EVDO), EDGE	500 – 700 Kbps; 3.1 Mbps (peak)	Has multimedia and streaming services support; universal access and portability across different device types are possible.
3.5G	2006 – 2010	Packet data	HSPA	1 – 3 Mbps; 14.4 Mbps (peak)	Supports higher throughput and speeds to support higher data needs.
4G	2010 – 2020	Digital broadband packet; all IP; very high bandwidth	WiMax, LTE, WiFi	3 – 5 Mbps; 100 – 300 Mbps (peak); 100 Mbps (Wi-Fi)	Bandwidth is further increased to keep up with data access demand by various services; high definition streaming is supported; new devices with HD capabilities surface; portability is increased further.
5G	Likely from 2020	To be determined	LAS-CDMA, OFDM, MC-CDMA, UWB, Network-LMDS, IPv6, and many more	At least 1 Gbps	Provide very high bandwidth, efficient use of available bandwidth as seen through development of each new technology, affordable rates, higher peak bandwidth and reliability.

Table 1: The evolution of 1G to 5G: capabilities of each technology and features that can be supported [90].

Different from the current wireless solutions, mm-wave utilizes the *unused* wireless spectrum at much higher frequencies. Therefore, it will not compete with the existing wireless spectrum allocation that is already crowded. According to a recent research study by NYU WIRELESS [94],

> *"The main differences of 5G compared to 4G will be the use of much greater spectrum allocations at* untapped *mm-wave frequency bands, longer battery life, lower outage probability, much higher bit rates in larger portions of the coverage area, lower infrastructure costs, and higher aggregate capacity for many simultaneous users in both licensed and unlicensed spectrum (e.g. the convergence of WiFi and cellular). The backbone networks of 5G will move from copper and fiber to mm-wave wireless connections, allowing rapid deployment and mesh-like connectivity with cooperation between base stations."*

Mm-wave carrier frequencies allow for larger bandwidth allocations, which means higher data transfer rates, increased data capacity, and much lower latency. Furthermore, given the increased bandwidth, both base-station-to-device links, and the backhaul links between base stations will have greater capacity to accommodate increased data traffic.

2.2.2 Massive Dense Networks and Advantages

One important advantage of using mm-wave is the reduced cell size. As seen in Figure 1, a low radio frequency corresponds to larger wavelength, and large coverage area. In contrast, radio technologies using higher carrier frequencies have much smaller cell coverage. For example, the carrier frequency of 4G is between 2.4 to 2.6 GHz, which requires 9 times the site density to match the cell size in 800 MHz. Because of the much higher carrier frequency and short wavelength, mm-wave, which operates up to 90 GHz, has much smaller coverage range compared to other radio technologies.

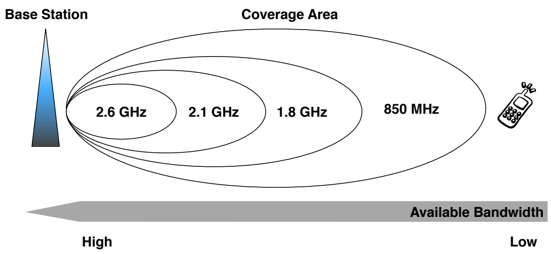

Figure 1: Radio frequency and cell size in current wireless and mobile networks.

Spatial reuse and flexibility. The reduced coverage is beneficial for the current operators, who continue to reduce cell coverage areas to exploit spatial reuse. As mm-wave proliferates, the cost per base station will drop, making wireless backhaul essential for flexible, quick deployment, and reduced ongoing operating costs. Mm-wave supported base stations will become more plentiful and densely distributed over the urban area. Currently, there are 28 GHz and 38 GHz bands available for operation, with spectrum allocations of over 1 GHz of bandwidth.

Closer spectral allocation. Instead of the disjointed spectrum allocated to many cellular operators today, the mm-wave spectrum will have spectral allocations that are relatively much closer together. Having the frequency allocation as of today's radio technologies, the resulting coverage distances of cells vary largely over three octaves [94]. With closer band allocations, the mm-wave spectrum makes the propagation characteristics of different mm-wave bands much more comparable and *homogeneous*.

Traffic offloading, energy efficiency and environmental factors. Small cells offload traffic from base stations by overlaying a layer of small cell access points. Such a mechanism decreases the average distance between the access points and end users, resulting in lower propagation losses and higher data rates and energy efficiency [96]. Moreover, as opposed to the common myth in the wireless engineering community that rain and atmospheric absorption make mm-wave spectrum useless for mobile communications, the study in [94] shows that mm-wave can overcome these issues.

2.2.3 Radio Penetration and Propagation Characteristics

Understanding the characteristics of the new radio technology itself is critical. In particular, radio technologies can behave differently when indoor as compared to outdoors. These characteristics will serve as a guidance for researchers, industry practitioners and service providers to plan the wireless network, set up access points and cellular base stations, etc.

Indoor penetration and reflection. According to the study in [94], common building materials such as tinted glass and brick pillars that are typical exterior surfaces of urban buildings, have high penetration losses with mm-wave transmissions. Therefore, building penetration of mm-waves will be difficult for outdoor transmitters. This will lead to high isolation between outdoor and indoor networks. On the other hand, common indoor materials such as clear non-tinted glass and drywall have relatively low penetration losses. This suggests that repeaters or access points may need to be installed for handoffs at entrances of commercial and residential buildings. Furthermore, the indoor penetration loss does not greatly depend on the transmitter-receiver separation distance, but mostly depends on the number and type of obstructions.

The reflection coefficient is also studied in [94]. On the surface boundary of different materials, a larger reflection coefficient indicates that more radio signals are reflected back and thus cannot penetrate. The research found that the outdoor materials have larger reflection coefficients for tinted glass and concrete, as compared to clear non-tinted glass and drywall. The high penetration loss through outdoor building materials and low attenuation through indoor materials suggest that RF energy of mm-wave can be contained in intended areas.

Urban propagation. The authors of [94] also studied the radio propagation in different urban scenarios, e.g., Brooklyn, Manhattan and Austin, Texas. The 28 GHz radio was tested in New York City, whereas the 38 GHz radio was tested in Austin. The measurement was conducted for signal acquisition, path loss, outage probability around transmitter sites, etc. Although New York City shows higher signal cluttering and path loss compared to Austin, the measurement results showed consistent 200 m cell radius, within which signal outage does not occur. Furthermore, by aligning base station antenna orientation, the path loss experienced by mm-wave is identical to today's 700 MHz to 2.6 GHz bands.

2.3 Typical Use Cases

As one of the important trends and foreseeable future needs of mobile and wireless networks, it is expected that 5G will bring forward traffic volume explosion in new application areas. From an end user's point of view, the end user bandwidth usage will be drastically changed by the mm-wave technology of 5G in four aspects, from (1) very *high* data rate, and hence, much lower *latency*, to (2) lower *energy cost*, and by (3) very *dense* crowds of users with a massive number of devices. The following are some of the typical use cases in these four aspects, demonstrating such dramatic change in network bandwidth usage pattern.

2.3.1 Very High Data Rate

Traditional wireless 3D videos and remote collaboration applications face significant challenges when the connections become wireless. Today's wireless technologies are not capable to provide, at reasonable costs, the high data rate and capacity requirements posed by these applications on the access and backhaul wireless networks.

To meet the demand of high-definition, real-time video streaming, access network end users should be able to experience sustainable data rates of around 70 to 140 Mbps, from the end user device to the base station or access point. Such a requirement is particularly prevalent in home networks with large screens and displays of high resolutions. The calculation of this data rate requirement is given in Section 2.4.1 and Appendix A.2. With the current wireless network, such as LTE, the peak download rates up to 299.6 Mbps and upload rates up to 75.4 Mbps depending on the user equipment category [41]. However, in the near future, different applications need to be aggregated or pooled for various purposes, such as the flash crowd situation (Section 2.3.3), or virtual reality applications (Section 5.4.2). As seen, the bandwidth requirement in those application scenarios will very likely to reach or exceed hundreds of Mbps, or even several

Device	iPhone 4	iPhone 5	Galaxy S III	iPad	Laptop PC	Digital Photoframe	Desktop PC	Set-top Box	Xbox 360	Plasma 42" TV
Cost ($/year)	$0.38	$0.41	$0.53	$1.36	$8.31	$10.34	$28.21	$30.20	$40.24	$41.13

Table 2: Annual electricity cost ($/year) of in-home energy consumption (e.g. charging phones and keeping computers and TVs plugged in): smartphones and tablets use much less energy [27].

Gbps. With mm-wave, the bandwidth provided can easily meet such requirement in the future by supporting data rate of at least 1 Gbps (Section 2.2.2).

For practitioners and service providers, the backhaul infrastructure is equally important as the user experience. Whether in a residential apartment or in a corporate building, it is highly desirable to have a high speed connection, such as optical fiber, available on each floor and across different floors. However, for reasons of flexibility, installation simplicity and cost, the amount of cabling and rewiring should be avoided or minimized. For the transport backhaul, the installation of building's communication network should be quick and with small impact on the building structure. As in Section 2.2, mm-wave radio can be used as both the access and backhaul network. As a result, installation and maintenance of backhaul network becomes smooth without troublesome configurations. Even in case of building emergency, such as during an earthquake or a hurricane, wireless backhaul is less likely to totally collapse. The ultra high speed provided by mm-wave will come to the rescue of hundreds of lives.

Very Low Latency. The high-speed, high-bandwidth last hop and backhaul wireless connections result in very low latency. This provides opportunities for real-time monitoring of events, such as traffic emergency. Everyday devices, like smartphones and embedded sensors, can collect and analyze data in emergent events and provide feedback in real time. Mm-wave technologies hence enable a lot of ultra-low-latency applications for the Internet of Things (IoTs). These applications will be detailed in Section 3.

2.3.2 Very Low Energy Cost

Today's end user devices feature rich content and diverse applications, often operating over wireless network connections. Study has shown that if a smartphone is plugged into the wall, it consumes a negligible amount of energy compared with other household electronics [27]. Table 2 shows the annual electricity cost of smartphones and tablets compared to other home electronic devices about their in-home energy consumption. However, to deliver a total of an hour of video to a smartphone or tablet each week, over a year it adds up to higher power consumption than two new Energy Star refrigerators [27]. Therefore, it is desirable that as little energy as possible is required to maintain the uptime of these devices. As in Section 2.2.2, mm-wave uses small cell size with small coverage range, which decreases the average distance between the infrastructure, base station and end devices, resulting in lower propagation losses and higher energy efficiency.

In February 2013, a project named 5GrEEn started, whose focus is on the design of Green 5G Mobile networks [5]. The project goal is to develop guidelines for the definition of new generation network with particular care of energy efficiency, sustainability and affordability aspects. There are also other green 5G wireless initiatives. For example, some of the world's biggest telecoms firms joining forces with the UK government to fund a new 5G research center [4]. Their goal is to offer testing facilities to operators keen to develop a mobile standard that uses less energy and radio spectrum. With more relevant projects launching, 5G will become a wireless technology that is even more energy efficient.

2.3.3 Very Dense Crowds of Users

In our daily life, we can expect that wireless networks provide connections with both high data rate and low latency. However, there are special events, such as sports games or concerts where a huge number of people gather in a relatively small space. People can exchange multimedia content with their smart devices both within the event location or transmit the content outside. With today's wireless solutions, service providers experience difficulty in providing a service with good quality in these situations. The difficulties are mainly caused by the extreme crowdedness, or the huge number of user devices, that requires very peculiar infrastructure deployment. Meanwhile, such services have to be provided for very limited time intervals, adding constraints and overhead from a cost perspective.

The potential solution is provide the service operators or event organizers the possibility to offer rich wireless communication services at lower deployment cost and energy consumption than with today's solutions. Additionally, one has to offer a reliable and extremely huge bandwidth service to a multitude of users temporarily located in an already deployed area, such as a stadium or a sport facility. 5G mm-wave technology can achieve these requirements with its dense deployment, low cost of base station installation, and higher spatial reuse for increasing system capacity (Section 2.2.2).

2.4 Conclusions: Potential for 1,000 Times the Capacity of 4G

The uncrowded, license-free mm-wave frequencies can provide 50 to 100 times more user capacity than that is readily available. When combined with other optimizations, mm-wave is expected to increase wireless bandwidth by a factor of up to 1,000 than current 4G within the next few years [59]. According to recent measurement, current mm-wave already supports a bandwidth of *at least 1 Gbps*, the bandwidth that can sustain the most demanding applications such as high-definition video streaming. Such bandwidth demands are calculated in this section.

2.4.1 Case Study: Bandwidth Requirement of Future Retina Display

With the increasing number of personal and home devices, increased data created, and the resulting content-rich applications, video streaming in particular, has become the application that requires the highest amount of bandwidth. Yet, video streaming is becoming much more widely used by end users for both work and leisure.

Video streaming is directly related to display technologies, where the pixel density [54], display size, color depth [13], frame rate, among other factors, determine the bandwidth requirement. The latest buzz word in the current display technology is the "Retina Display", a brand name used by Apple for the LCD display that has a high enough pixel density that the human eye is unable to notice pixelation at a typical viewing distance [58]. This term was first invoked by Steve Jobs in 2010, where a magic number 300 pixels per inch (ppi) was mentioned [39]. At the pixel density of 300 ppi, if a device is held between 10 to 12 inches from one's eye, the resolution of the device display outweigh the ability of human eye to resolve the differences between the original pixels.

According to a survey, the most popular TV screen size in the US in 2013 is 40 inches diagonally [69]. At the 2006 Consumer Electronics Show (CES), THX recommended that the optimal seat-to-screen distance is by multiplying the diagonal screen size by 1.2 [52]. This gives a distance of 48 inches from a 40-inch screen. At this distance, a pixel density of 62.5 ppi is required so that pixels are indistinguishable to a person with perfect vision viewing at the screen. The calculation of this pixel density can be found in Appendix A. With an aspect ratio of 16:9, a 40-inch screen in diagonal has a size of 683 square inches. With 62.5 ppi, such a display has about 2.67 million pixels. With 3 bytes per pixel, and 8 bits per byte color depth, this gives 64 Mb per frame, and a 30 frames per second refresh rate gives a raw data rate of 1.92 Gbps. With a reasonable compression ratio[1], 38.5 Mbps to 64 Mbps will be the resulting bandwidth required. Another possible factor is 3D TV. 3D TV is achieved by recording images as seen from two perspectives and sending two video streams [2], thus doubling the above calculations. This means a single uncompressed high-definition 3D video stream could require as much as 3.84 Gbps of bandwidth, and the compressed video stream only requires 77 Mbps to 128 Mbps bandwidth.

Note that, however, many other high-definition devices do not require such high bandwidth, as shown in Table 9 in Appendix A. For example, iPhone 5 pixel density is 326 ppi, but only has a total number of 727,040 pixels due to a much smaller screen size. With the same parameters as above, iPhone 5 only requires a bandwidth of 10 Mbps with a compression ratio of 50:1. Under similar conditions, a 15-inch MacBook Pro with Retina Display requires a bandwidth of 75 Mbps after compression.

2.4.2 Conclusions from Case Study

From the above calculation, mm-wave will be able to support the most demanding applications on the most up-to-date devices. Even when 40-inch Retina Displays come to exist in future homes, mm-wave can support the *raw* data transmission of high-definition videos (at around 1.92 Gbps without compression). Additionally, mm-wave will also help develop smaller, smarter cells with devices that cooperate rather than compete for spectrum. As a result, the end user bandwidth usage will be drastically changed to have very high data rate, much lower latency and energy cost, by very dense crowds of users with a massive number of devices. In face of the exponential wireless data growth and bandwidth demand, the mm-wave technology of 5G has the potential to spur and accelerate the deployment of *"more powerful, bandwidth-intensive, ubiquitous and more affordable wireless applications and services, and the support of more versatile, robust and rich-multimedia wireless networks"* [45].

3 Internet of Things (IoT)

In Section 2.3, we stated that mm-wave has paved the way for the Internet of Things (IoTs). The IoTs itself is a disruptive technology that can potentially change the Internet bandwidth use of end users. While the mm-wave technology of 5G focuses on physical transmission

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[1] Compression ratios to maintain excellent quality [64]:

10:1 for general images using JPEG;

30:1 for general video using H.263 and MPEG-2;

50:1 for general video using H.264 / MPEG-4 AVC.

of data bits over the wireless medium, IoT is a technology that uses mm-wave and other wireless solutions for everyday purposes.

3.1 Background

The phrase "Internet of Things" started life as the title of a presentation made by Ashton at Procter & Gamble (P&G) in 1999 [65]. It was an idea that was proposed for adding Radio Frequency Identification (RFID) techniques in P&G's supply chain. The original idea of Ashton was as follows:

> *"Today computers — and, therefore, the Internet — are almost wholly dependent on human beings for information. Nearly all of the roughly 50 petabytes (a petabyte is 1,024 terabytes) of data available on the Internet were first captured and created by human beings — by typing, pressing a record button, taking a digital picture or scanning a bar code. Conventional diagrams of the Internet include servers and routers and so on, but they leave out the most numerous and important routers of all: people. The problem is, people have limited time, attention and accuracy — all of which means they are not very good at capturing data about things in the real world."*

The unique idea of the IoT emphasizes the fact that both human and the environment are physical, whereas "things" can be extremely logical and can capture abstract and repetitive information that humans are not good at capturing or remembering. To enable "things" to record and capture facts about both the human and the environment, object identification, sensor and connection capability are the basis. In essence, the IoT refers to uniquely identifiable objects and their virtual representations in an Internet-like structure [33]. With the subjective recording and monitoring by these "things", people can know when supplies were fresh or past their best, and whether they needed replacing, repairing or recalling, etc. As a result, people *"would be able to track and count everything, and greatly reduce waste, loss and cost"* [33]. However, the research into the IoT is still in its infancy. Therefore, there are not any standard definitions for this research other than a few survey articles [15, 91].

3.2 IoT Technologies: Sensors, RFID, Bluetooth, and Many More

Internet of Things is also sometimes called the Internet of Everything, the Industrial Internet or Machine to Machine (M2M). It is true that RFID, sensor and similar technologies have enabled computers and similar devices to observe, identify and understand the world without the limitations of human-entered data. However, according to Helen Duce [74], it is also clear that challenges still exist:

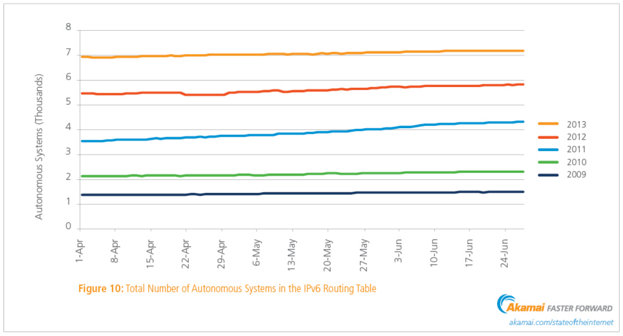

Figure 2: Total number of autonomous systems in the IPv6 routing table (Source: [6]).

> *"We have a clear vision — to create a world where every object — from jumbo jets to sewing needles — is linked to the Internet. Compelling as this vision is, it is only achievable if this system is adopted by everyone everywhere — Success will be nothing less than global adoption."*

The targeted smart systems of the IoT are the ones that are able to take over complex human perceptive and cognitive functions and frequently act unnoticeably in the background. Despite the fact that the IoT is to provide extreme convenience to people, several technologies need to be improved and several challenges need to be addressed by people before the IoT achieves a global adoption.

3.2.1 Unique Addressability

According to a survey by Cisco [15], there are 8.7 billion connected objects globally in 2012, 0.6% of "things" in the world. Driven by reduced price and rapid growth in M2M connections, by the end of 2013, this number will exceed 10 billion. It is estimated that the total number of connected things will reach 50 billion by 2020, or 2.7% of things in the world. Given such a large number, a globally unique addressing scheme is needed to identify the large amount of objects.

The original idea of Ashton was based on RFID-tags and unique identification through the Electronic Product Code (EPC) [21]. However, this has evolved into objects having an IP address and URI, which are much more

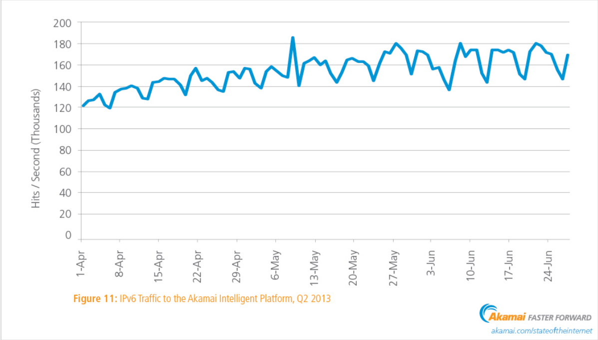

Figure 3: IPv6 traffic to the Akamai Intelligent Platform, Quarter 2 2013 (Source: [6]).

generic. In particular, because of the extremely large address space, the next generation of Internet applications using Internet Protocol Version 6 (IPv6) with a much larger address space is able to communicate with devices attached to virtually every man-made object. To help put this number in perspective, the 128-bit IPv6 address space provides 6.5×10^{23} addresses for every square meter of the Earth's surface [36]. The pressing need for IPv6 is also due to the fact that the number of available IPv4 addresses continued to decline in 2013, as Regional Internet Registries continued to allocate and assign blocks of IPv4 address space to organizations within their respective territories [56]. According to the quarterly survey by Akamai [6], both the number of IPv6 autonomous systems (Figure 2) and IPv6 traffic (Figure 3) have been increasing. Note that the traffic in Figure 3 has a weekly cyclic pattern.

Although IPv6 will be able to scale to the large numbers of objects envisaged, the lack of its backward compatibility [8] makes it difficult for general and timely adoption by the public. Meanwhile, from the aspect of the Semantic Web, great efforts have been made on enabling *all* things, not just those electronic or RFID-enabled, addressable by the existing naming protocols, such as URIs [67]. A consistent and unique addressing scheme is thus the prerequisite of the IoT and its relevant technologies.

3.2.2 Sensor Networks

In the modern Internet, everyday objects in the surroundings can potentially be the proactive information collectors, or be both the generator and consumer of information. These objects range from the devices that have existed in technological world for many years, such as vehicles, toasters or fridges, to objects external to the technological environment, such as garments or perishable food. They can even be plantations, woods or livestock. By embedding data storage, networking and computational capabilities in all such things, it will be possible to provide a qualitative and quantitative advancement in a wide range of sectors, including health care, logistics, and entertainment, etc. In fact, one of the most essential elements in the IoT is wireless sensor networks (WSN) [91].

The fact is that sensor network is not as a new concept as the IoT. The sensor network and related research existed a long time before the IoT was introduced. However, sensor networks were used in limited domains to achieve specific purposes, such as environment monitoring [84], agriculture [77], medical care [85], event detection [95], etc. The benefits of connecting both WSN and other IoT elements are not only remote access to heterogeneous information systems. The integration of WSN and the IoT is also a fact supported by several international corporations and standardization organizations, such as IBM [29], Internet Engineering Task Force (IETF) [89, 38], social networks and blogs [79], etc.

In order to allow WSN to become an intrinsic part of the IoT in a secure way, several challenges must be considered. The most important challenge is the integration of security and privacy mechanisms [88]. First, the growing data demand will require stronger security models employing context related security, which in return will help the citizens to build trust and confidence in these novel technologies rather than increasing fears of total surveillance scenarios. The sense of security will also be the most important incentive for wide adoption by users. Second, data privacy must be considered. The information available regarding a particular user will not only consist of the personal data, but also of any data generated by the objects surrounding this individual. It is necessary to clarify the data ownership and how the user data will not be used without user consent.

3.2.3 RFID and Bluetooth

Besides sensor networks, RFID and Bluetooth related communication technologies will also be the cornerstone of the IoT. Today, almost every smartphone is equipped with certain kind of short range radio communication such as Bluetooth, or more specifically near field communication (NFC) specifically designed for reading RFID tags. While RFID was initially developed with retail and logistics applications in mind in order to replace the bar code, developments of active components will make this technology much more than a simple identification scheme. For example, 10 million daily travelers of the public transport system in Paris have already access to an electronic ticket using a ticket system, Navigo, based on RFID [46].

Similarly, Bluetooth has been used by people for around 15 years, as a means of allowing devices to talk to each other cheaply and wirelessly over short distances. Although Bluetooth has tended to stay largely in the shadows in the past, the recent rapid growth in the use of mobile and sensing technologies has re-enabled its applications from health and agriculture, to business and electioneering [70]. One important reason is that Bluetooth targets lower transmission ranges and data rates than WiFi, and as a result has lower cost and lower power consumption. Recent advancements in Bluetooth technology make it the best way to free data from even the smallest devices, able to operate for months or years on button-cell batteries [14].

3.3 Typical Use Cases

3.3.1 Retail and Logistics

Replacing bar code with RFID tags in retail is the first large scale application of the IoT. There are multiple benefits by using RFID tags over bar code. First, for retailers, item identification will be unified throughout the supply chain, from the producer, to the storage and check out. Sales aisles equipped with RFID readers can issue refill orders automatically to the retailer's storage once any items are sold out. For consumers, the long lining up at check-out can be avoided.

Similarly, the IoT innovation in logistics allows improving efficiency and enabling new features. For example, in the retail warehouse, orders can be automatically passed on to the wholesaler whenever any items are out of stock. On a intelligent farm, for instance, RFID tagged cattle can be automatically monitored for health conditions, so that whenever one is sick or pregnant, an alert message is sent to the farmer. As a result of IoT innovations, products can be shipped automatically, and the manufacturers and farmers will have a direct feedback on the monitored product or livestock, leading to saved time, energy, resources and the environment.

However, security and privacy concerns are the biggest hurdle in adopting the IoT from the standpoint of consumers. For example, the privacy of a consumer can be intruded in case a purchase has been made for medical products. Farmers also need to protect themselves from competitors who may read their stock quantities and the health conditions of livestock. Meanwhile, the IoT technologies normally do not change the industry or production fundamentally, but rather, increase the efficiency production, manufacturing, sale, etc [74]. The low data rate and low update frequency of the IoT also will not dramatically change the end user bandwidth pattern. For IoT devices, bandwidth needs are typically low as they collect and send out brief bursts of data infrequently. For example, on a farm, the data generated by a cattle is 200 Mb per year. From these aspects, we can expect that much work remains before the IoT can gain wide adoption among consumers.

3.3.2 Food, Water, Health Care and Intelligent Home

Through labels embedded with microchips, food producers and retailers can easily track the origin of food, its location and the temperature and humidity of its surroundings. These factors are critical in the transportation and storage of fresh vegetables, fish and sea food. Furthermore, an IoT system to monitor water quality can be developed using similar concepts. The system can warn people in real-time if the turbidity and PH level has exceeded a safety threshold [35].

The IoT technologies have also been used in health care [97], where sensors can monitor the patient behavior and symptoms in real time and at a lower cost. This allows doctors and physicians to better diagnose disease, especially chronic illnesses, and prescribe tailored treatment. Patients can have their conditions monitored continuously as they go about their daily activities. As a result, early warning can be issued to avoid or reduce hospitalization and treatment costs [34]. With the recent prevalence in smartphones, many embedded sensors on these devices carried by people on a daily basis can now be utilized for telehealth and telemedicine [53], applying the low-energy sensors to individuals with Type-2 Diabetes [57], etc.

The IoT technologies have created the concept of Intelligent Home. As an example, microchips can detect the expiration of foods, signal need for new supplies of food, detergents, maintenance, etc. With such intelligent chips embedded in a refrigerator, not only the ambient conditions and food quality can be monitored, an automated dinner recipe can also be dynamically created given the food in fridge that is still in good condition, and the amount of nutrients needed for a particular meal. Further, intelligent control of electric power in the house will allow simple tasks such as switching on and off lights, and more complex ones such as fine-grained management of electric heaters in order to set the ambient temperature [34, 74].

3.3.3 Enhanced Situational Awareness

The typical scenario in this case is the massive deployment of sensors and actuators, which transmit data occasionally and have very low energy requirement. Applications are enabled by sensor network technologies (Section 3.2.2). The deployed devices report collected data to an infrastructure. For example, a large number of sensors are spread out over large agricultural areas to measure the fertility of crops and humidity of soil, to help the farmer optimize the right time for harvesting and fertilizing. Sensors can also be deployed on the surface of a wind mill, reporting vibrations and other measures that may give an early indication of material damage or suboptimal usage. In short, a large number of small devices collect data of interest, including data that is environment related (temperature and humidity), or the wear and tear of critical equipment, even the occupied tables and chairs in a restaurant.

The devices mentioned above create great convenience in people's everyday life. Their sizes are relatively small, and their structures are relatively simple. On the other hand, many of these devices are deployed at places that are difficult for human access, and thus these networks prefer minimal maintenance. This directly translates to the requirement for long battery life. Section 2.3.2 describes the support that mm-wave can provide to small and smart devices in terms of low energy cost. With 5G and mm-wave proliferation, the applications using sensors will benefit tremendously.

3.3.4 Transportation and Traffic Safety

The most demanding use of the Internet of Things involves the rapid, real-time sensing of unpredictable conditions and instantaneous responses guided by automated systems. The automobile industry, for instance, is beginning to use the different sensing devices in vehicles to gather environment information and provide intelligent traffic information services [98, 99] utilizing Vehicular Ad Hoc Networks (VANETs).

VANETs are new applications of sensor networks that use different sensing devices in vehicles to gather environment information and provide intelligent traffic information services. Information exchange among vehicles on the move will enable the provisioning of traffic safety hints to the driver or warnings about the road status, including road constructions, weather conditions, road hazards, etc. In foggy or rainy weather, when road visibility is low, a vehicle could signal to the driver the direction and velocity of any moving vehicles nearby, in order to avoid accidents. Such interactions among vehicles are vehicle-to-vehicle (V2V) communication [99]. Additionally, vehicles communicating with centralized infrastructures can receive real-time updates about road information that is relatively far away. As a result, vehicle traffic can route through less crowded area, increasing traffic efficiency and reducing fuel emissions. This is vehicle-to-infrastructure (V2I) communication [100]. Infrastructure can also offload part of the V2V traffic and provide higher speed. Finally, vehicles can collect safety relevant information directly from road pedestrians and cyclists so as to avoid running into road users. This can be achieved through communication to the smartphones, tablets or any sensor tags carried by road users. Such communication is vehicle-to-device (V2D).

All the above V2X communication requires very low latency, for both safety and efficiency reasons. The mm-wave technology of 5G again is the enabler of these IoT applications. It provides much lower latency than the current wireless solutions (Section 2.2.1), a direct end result of very high data rate by using mm-wave (Section 2.3.1). The small cell coverage also guarantees less contention among vehicles sharing the same road side access point. As a result, both periodic and event-driven broadcast traffic in the above V2X scenarios can be delivered both with low delay and low loss rate. When an accident happens, public safety agencies can detect imminent collisions and inform vehicles so as to take evasive actions. In addition to these applications with demand on very low latency, public transit system can also benefit from the IoT technologies, e.g., Navigo based on RFID [46] in Section 3.2.3.

3.4 Conclusions: Providers, Manufacturers and Consumers

In conclusion, technology trends such as support from wireless solutions (mm-wave in Section 2), cloud and mobile computing, Big Data, increased processing power, etc., are the driving force of IoTs. The dramatically increased end-user bandwidth and capacity at lower costs, the rapid growth of cloud, social media and mobile computing, and the ability to analyze Big Data and turn it into actionable information, have realized more value from the connectedness of things.

3.4.1 Created Values

According to a study by the Progressive Policy Institute, the impact of the Internet of Things on the US growth rate could raise the level of US gross domestic product by 2%–5% by 2025 [10]. However, such a fact and created intelligence reflect the projected heavy use of the IoT in manufacturing, rather than consumer-oriented services. Cisco's analysis also showed that most of the potential value created by IoTs, 66%, or $9.5 trillion, comes from transformation based on industry-specific use cases, such as smart grid and smart buildings. The other 34%, or $4.9 trillion, is produced by cross-industry use cases such as the future of work (telecommuting) and travel avoidance [22]. In the above examples given in Sections 3.3.1 to 3.3.4, consumers typically benefit from the added features of the IoT, such as greater labor efficiencies and eliminated waste. Furthermore, the security and privacy concerns are prevalent among end users, since the data captured from product purchase, health care and vehicles

Standard	Data Rate	Est. # of Devices (Bil.)			Est. Global Peak Traffic (per hour)			Est. Per-user Peak Traffic (per hour)		
		2012	2013	2020	2012	2013	2020	2012	2013	2020
IEEE 802.15.4 (Zigbee etc.)	≤ 250 Kbps	8.7	10	50	151 Gb	173 Gb	865 Gb	107 B	120 B	560 B
RFID (various standards)	26 – 424 Kbps				256 Gb	294 Gb	1,470 Gb	181 B	204 B	952 B
IEEE 802.15.1 (Bluetooth)	≤ 1 Mbps				604 Gb	694 Gb	3,470 Gb	428 B	482 B	2.25 Kb
IEEE 802.11 (WiFi)	2 – 3 Mbps				1,812 Gb	2,082 Gb	10,410 Gb	1.28 Kb	1.45 Kb	6.74 Kb
Total		—	—	—	**2,823 Gb**	**3,243 Gb**	**16,215 Gb**	**1.996 Kb**	**2.256 Kb**	**10.502 Kb**

Table 3: IoT device types, the expected data rates, the estimated device numbers, the **estimated global peak traffic per hour**, and the **estimated per-user peak traffic per hour**. The data rate listed for IEEE 802.11 WiFi is for IoT applications, rather than normal WiFi data communications. The estimated peak data traffic per hour is calculated as follows: assume the estimated number of devices are equally divided by the four categories, and the device data collection rate is once *per hour*. The peak data traffic calculation uses the highest data rate. For example, for RFID that has data rates from 26 Kbps to 424 Kbps, the highest rate 424 Kbps is used (peak rate). Note that the calculated data traffic corresponds to the worst case for all categories, and is the global data without dividing into regions. The estimated per-user peak traffic per hour is calculated by assuming 20% of of the world population owns the particular category of devices. The world population by the end of years 2012, 2013 and 2020 are 7,057, 7,195 and 7,717 million [72].

are all related to each individual and contain sensitive information.

3.4.2 Data Rates and Bandwidth

The data transfer rates are also vastly different either from the manufacturers or consumers point of view. The IoT technologies in Section 3.2 all have low data rate. For instance, the data rates of RFID vary from 26 Kbps to 424 Kbps. In sensor networks, nodes equipped with IEEE 802.15.4 transceivers operate at a maximum raw data rate of 250 Kbps [31], and Bluetooth operates at a rate no more than 1 Mbps [70]. Even in an intelligent home network, security surveillance cameras require 2 to 3 Mbps of data transfer rate. Furthermore, the data update rate for these small devices are also infrequent, e.g., sales items sold out, food supplies replacement, hazardous road conditions and accidents, etc. Despite the pervasive connectedness of things, the bandwidth usage from individual end-users will not be drastically changed.

At the manufacturers or public agencies where data from millions of devices are aggregated, the data rate will be drastically different. At the data aggregation point, compression and filtering can be done by the manufacturers or agencies to reduce redundant data. Therefore, the total data volume can be reduced. However, at individual homes, the low data rate and low update frequency are not expected to change the bandwidth patterns of end users and consumers. The complete list of IoT device types and their expected data rates are shown in Table 3. The table also shows the **estimated peak data traffic per hour**, which is calculated as follows. Assume the estimated number of devices are *equally divided* by the four categories, and the device data collection rate is *once per hour*. The peak data traffic calculation uses the *highest data rate*. For example, for RFID that has data rates in the rage of 26 Kbps to 424 Kbps, the highest rate 424 Kbps is used. Note that the calculated data traffic corresponds to the *worst case* for all categories, and is the *global data* without dividing into regions. Even with the worst-case calculation, it can be seen that the peak data traffic is not significant. Use WiFi as an example, which has a total global data traffic of 10,410 G per hour by 2020. If dividing this traffic equally among the three regions: Americas, Asia Pacific, and Europe/Middle East/Africa, then peak data traffic is 3,470 G per hour, or 0.96 G per second from each of the three regions without subdividing into countries or smaller regions. From an end user perspective, by the end of 2020, the world population will reach 7,717 million [72]. The total peak traffic generated by IoT devices is 16,215 G per hour in 2020. Assuming 20% of the population owns the IoT devices in Table 3, dividing the total peak traffic by this population and we get a per-user peak rate at 10.5 Kb per hour in the worst case from all IoT devices. Therefore, even with the tremendous increase in the things connected to the Internet, from an end user, the peak IoT traffic is not high and can be supported by any current service provider. With a higher percentage of population owning IoT devices, the per-user peak rate will be even lower.

4 Community Cloud and Fog Computing

4.1 Background

From the emerging 5G mm-wave and the Internet of Things, today's growing mobile traffic, multimedia data, and end-user diversity has lead to an increasing demand for applications that are generated by end users and processed by edge devices. Such an increase is the result of higher broadband adoption and wireless penetration, higher application demand and affordable storage de-

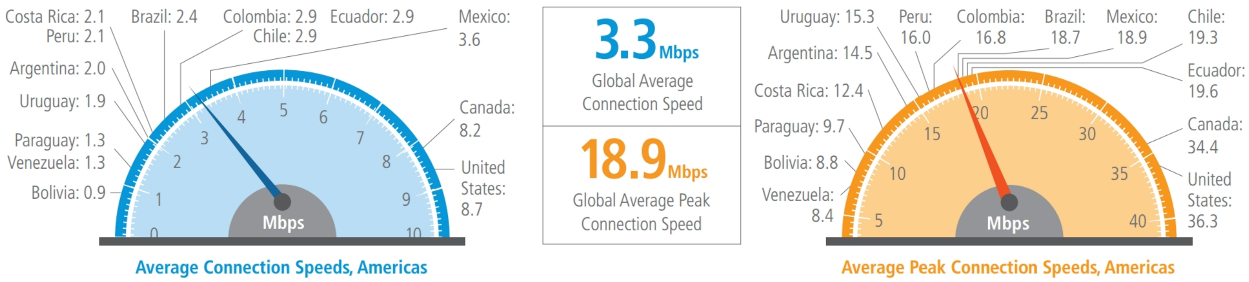

Figure 4: Internet broadband bandwidth. Examples are shown for the Americas (Source: [7]).

vices. As a result, *much lower latency* is required by users who can afford higher bandwidth and larger storage.

4.1.1 High Bandwidth and Wireless Penetration

The quarterly state of the Internet report from Akamai [6] reported data on average and average peak connection speeds — the latter provides insight into the peak speeds that users can likely expect from their Internet connections. The global average connection speed has kept increasing in 2013, growing to 3.3 Mbps in the second quarter. The average peak connection speed, on the other hand, represents an average of the maximum measured connection speeds across all of the unique IP addresses seen from a particular geography, therefore it is more representative of Internet connection capacity. According to [6], the global average peak connection speed increased in the second quarter of 2013 to 18.9 Mbps. Figure 4 shows this data with the distribution of both the average and average peak speeds in Americas. For both average and average peak connection speeds, the US and Canada ranked the first and second in this geographic region.

In the wireless and mobile network domain, both data and voice traffic, especially data traffic, have increased tremendously over the past 5 years, as shown in Figure 5. The data are not only from smartphones, but also laptops, tablets, and other devices that connect to the Internet through mobile networks. The figure represents the world total mobile traffic in 2G, 3G, and 4G/LTE networks, not including WiFi, and Mobile WiMax. As seen in the figure, the mobile data traffic has been growing exponentially. We can expect such an increase will continue in the future. Such high bandwidth will allow mobility to become the norm in user everyday communication.

Note that the reported bandwidth in Figures 4 and 5 are different from IoTs in Section 3. The applications in Section 3 have a strong focus on the monitoring the environment, everyday product, etc., to improve the quality of human life. The applications in this section have a strong emphasis in computation, storage (Section 4.1.2), and live data streaming (Section 4.1.3), and target at improving application responsiveness and enhancing user experience.

4.1.2 Higher Computation and Affordable Storage

With higher broadband penetration and more devices online, the requirement for computation and data-intensive services are getting higher at network edge. The traditional Cloud Computing data center with homogeneous compute, storage, and networking resources featuring remote batch processing can no longer meet device heterogeneity, exponential demand and real time latency requirement. Take storage as an example: Disk space has increased dramatically and has outgrown the wide-area bandwidth such that, with 3 TB stored data, it requires 278 days to transfer it over a 1 Mbps broadband connection [87]. The Cloud-based solutions have a tough time keeping up with both storage and computation requirements. Instead, programmable edge network devices such as switches and home routers, which are able to expose performance issues related to cross traffic, wireless network, and end-host configuration, will be crucial in the near future.

4.1.3 Real-Time Applications and Lower Latency Requirement

According to the bi-yearly research study published by Sandvine, a Canadian broadband management company, real-time entertainment (comprised mainly of streaming video and audio) continues to be the largest traffic category on virtually every network in 2013 [25]. It is expected that this continued growth will lead to the emergence of longer form video on mobile networks globally in to 2014. Table 4 is a summary of top 3 peak period applications in regions including North America, Europe, Latin America and Asia-Pacific. The data in Table 4 are reported for wired access networks in [25]. The

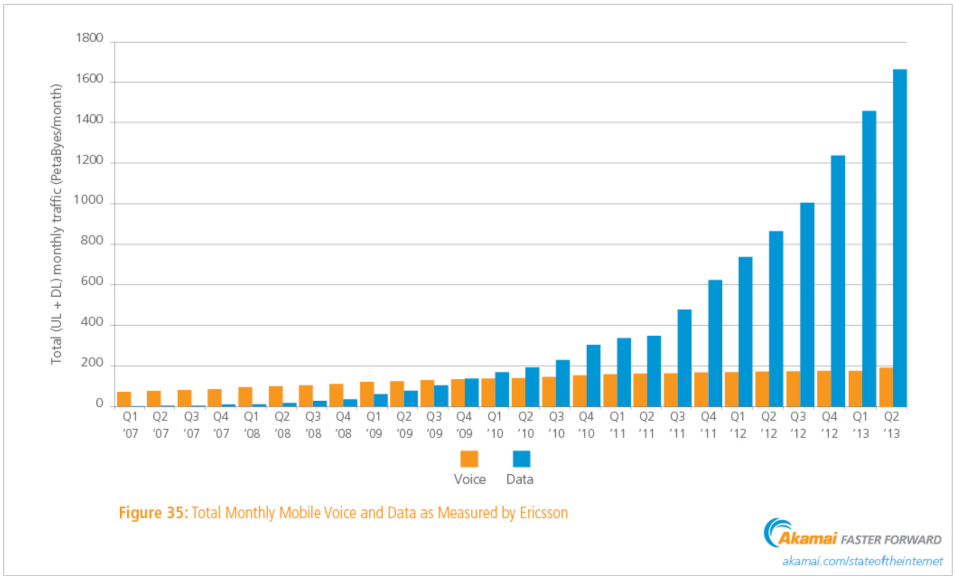

Figure 35: Total Monthly Mobile Voice and Data as Measured by Ericsson

Figure 5: Total monthly mobile voice and data as measured by Ericsson (Source: [6]).

Region	**Upstream**		**Downstream**		**Aggregate**	
	Application	Share	Application	Share	Application	Share
North America	BitTorrent	36.35%	NetFlix	31.62%	NetFlix	28.18%
	HTTP	6.03%	YouTube	18.69%	YouTube	16.78%
	SSL	5.87%	HTTP	9.74%	HTTP	9.26%
Europe	BitTorrent	48.10%	YouTube	28.73%	YouTube	24.21%
	YouTube	7.12%	HTTP	15.64%	BitTorrent	17.99%
	HTTP	5.74%	BitTorrent	10.10%	HTTP	13.59%
Latin America	BitTorrent	29.70%	YouTube	36.82%	YouTube	33.29%
	YouTube	14.70%	HTTP	20.01%	HTTP	18.10&
	Facebook	8.55%	BitTorrent	7.63%	BitTorrent	11.14%
Asia-Pacific	BitTorrent	35.72%	YouTube	31.22%	YouTube	23.30%
	QVoD	14.10%	BitTorrent	14.25%	BitTorrent	21.18%
	YouTube	6.65%	HTTP	10.48%	HTTP	8.08%

Table 4: Top 3 peak period applications, wired access networks. Across all regions over the globe, BitTorrent, the traditional peer-to-peer application continues to be the dominant application in the upstream, taking around 1/3 of the upload share among the rest of YouTube, NetFlix, HTTP, Facebook, etc. (This is a summary of data reported in [25]).

report on mobile networks in these regions can also be found in [25]. From Table 4 it is clear that across all regions over the globe, BitTorrent, the traditional peer-to-peer application continues to be the dominant application in the upstream, taking around 1/3 of the upload share among the rest of YouTube, NetFlix, HTTP, Facebook, etc. Note that all these applications mainly feature real-time data streaming, the application category that requires very low latency.

While P2P has existed for decades, using P2P in traditional Cloud is a rather new concept. P2P has little or no infrastructure, and runs directly on end user devices. Cloud Computing, on the other hand, frees the enterprise and the end user from the specification of many details. This bliss becomes a problem for latency-sensitive applications, which require nodes in the vicinity to meet their delay requirements [76]. Today's network infrastructures are not totally as ad-hoc as P2P, but rather a mix of P2P and infrastructure, such as WiFi access point, cellular tower, etc. Such a mixed infrastructure is close to the end user, while still has dedicated devices for control that is within the proximity to end users.

It is known that geographic location accounts for almost 94% of network latency [82]. Applications behave differently depending on their location to the service infrastructure. Utilizing devices in the vicinity — switches and routers in the same network as end hosts — for data storage and computation offloading is thus a natural solution for reducing user perceived latency. Such a concept is Fog Computing [76], which is essentially *everything-as-a-service*.

With the dramatically increasing bandwidth at network edge (Section 4.1.1), much more powerful computation and affordable storage (Section 4.1.2), and the real-time applications like YouTube, NetFlix and BitTorrent that require very low latency (Section 4), there will be an ever-increasing interest and demand in Fog Computing services discussed in this section.

4.2 Characterization of Fog Computing

Many applications today require nodes in the vicinity for computation and storage resources to meet their delay requirements. Newly emerging Internet deployments, such as the Internet of Things (Section 3), require mobility support and geo-distribution in addition to location awareness and low latency. A new infrastructure is needed to meet these requirements: a platform called Fog Computing first proposed by Cisco [75, 76]. Fog Computing is so named simply because the fog is a cloud close to the ground. Compared to Cloud Computing that relies on centralized data centers, Fog Computing has the following unique characteristics.

4.2.1 Geographical Distribution and Location Awareness

In contrast to the centralized Cloud, the services and applications in Fog demand widely distributed deployments. Such geographical distribution will facilitate the applications that require low latency, such as streaming high definition videos to users carrying mobile devices through proxies and access points positioned inside lecture halls on a campus, or in buildings in a residential area. Applications with low latency requirements will benefit the most from the more flexible, down to the ground infrastructure of Fog. For data storage, on the other hand, if replicating file systems across nearby devices, the device diversity makes correlated failure less likely, and device proximity avoids the wide-area bandwidth bottleneck. However, because user devices are highly dynamic and can be online and offline any time, replication must be fast and light-weight.

4.2.2 Very Large Number of Nodes

As a consequence of the wide geo-distribution, not only a larger number of end user devices will be serviced by the Fog infrastructure, more edge routers and access points will become part of the Fog infrastructure for both service orchestration and data delivery. For example, large-scale sensor networks that monitor the environment, and the Smart Grid are both examples of inherently distributed systems with a large number of deployed nodes. These systems require both distributed computing and storage resources. In this regard, Fog Computing shares the same characteristic as the Internet of Things that are composed of millions of end devices. The difference is that Fog Computing includes both end user devices and their last hop routers and access points, which belong to the infrastructure side of the Fog platform.

4.2.3 Support for Wireless Access and Mobility

It is essential for many Fog applications to communicate directly with mobile devices, and vice versa. Therefore, the support for mobility techniques is critical, especially when mobile device users are moving across different home network, campus network that are usually behind Network Address Translators (NATs) and firewalls. One technology that can provide stable services that support device mobility is Zenodotus [73] developed within the Seattle project [60]. As an open Community Cloud computing platform itself, Seattle operates on a wide range of resources such as laptops, servers, phones and wireless routers, which are donated by users and institutions. Zenodotus enables a stable URL despite users moving between Fog virtual machines. It can be used to deploy services supporting smooth mobile handover and load balancing, which are crucial for latency-sensitive applications such as video multicast.

4.3 Typical Use Cases

4.3.1 Offloading Mobile Computation and Storage

Mobile devices with battery and power constraints will benefit from offloading local computation to network devices nearby. While computation offloading has been shown to be effective using remote Cloud data centers, Fog Computing provides much lower latency via the orchestration on routers and switches that are typically one hop away from end devices. Irrespective of user location or device type, Fog users can access applications with higher performance, reliability and security. Furthermore, low latency access to nearby computing resources substantially encourages more offload processing without impacting user perceived latency. For data storage, because Fog user devices are highly dynamic and mobile, data replication must be fast and light-weight. For example, once replication is complete, a replica can be used offline and later merged into other replicas. Similar techniques must also be used to ensure high levels of security and performance isolation.

4.3.2 Enhanced Video Multicast Services

Video streaming consumes a substantial portion of the bandwidth on end user networks. To provide better user experience, there are many existing encodings and

IP Traffic (PB per month)	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Allc. IPv4 /8 Prefix [28]**
North America	14,439	18,788	23,520	28,667	34,457	40,672	36
Europe	11,127	13,274	15,735	18,515	21,840	25,646	35
Latin America	3,397	4,321	5,201	5,975	6,682	7,415	9
Asia-Pacific	13,906	18,212	22,953	28,667	35,417	43,445	45
Middle-East and Africa	701	1,049	1,483	2,013	2,659	3,465	4
Total	**43,570**	**55,644**	**6,8892**	**83,837**	**101,055**	**120,643**	**129**

(a) Overall IP traffic in different geographic regions (Source: [78]).

Aggregatable IP Traffic (Gbps)	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Avg. YoY Growth Rate**
North America	154.74	201.35	252.06	307.22	369.27	435.87	23.11%
Europe	122.65	146.32	173.45	204.09	240.74	282.69	18.18%
Latin America	145.62	185.23	222.95	256.13	286.44	317.86	17.05%
Asia-Pacific	119.22	155.36	196.78	245.77	303.64	372.47	25.62%
Middle-East and Africa	67.61	101.18	143.04	194.16	256.46	334.20	37.83%
Total	**609.84**	**789.44**	**988.28**	**1,207.37**	**1,456.55**	**1,743.09**	**23.42%**

(b) Aggregatable IP traffic per IPv4 /8 prefix in different geographic regions, by assuming that IP traffic is equally divided among the allocated IPv4 /8, and each month has 30 days.

Table 5: Overall IP traffic and aggregatable IP traffic per IPv4 /8 prefix in different geographic regions, 2012 to 2017.

codecs with different screen sizes and loss rates. Participants who are connected to the same networking device may desire different codecs, and thus cannot participate in the same multicast stream. In Fog, router and switches can receive a single incoming stream and re-encode it for each individual user. With close proximity to streaming devices, video services can dynamically apply different codecs and network optimization techniques to adapt to the changing conditions and capability of a network.

4.3.3 Improved Network Diagnosis

The primary challenge with network administration is understanding the communications from the viewpoint of end users. However, this is difficult due to network path asymmetry, network components such as firewalls and NATs, ICMP filtering, and other complications of the modern Internet. Fog provides more effective probing that replicates the behavior seen by the actual end user. For example, a network administrator can relay TCP communications through the user's last hop to observe the exact web browsing behavior experienced by the user.

4.3.4 Other Use Cases

Many applications require both Fog localization and Cloud globalization [76], particularly for data analytics. Fog devices and routers provide direct access to end user data, with both localization and context awareness. These data are the major sources of applications such as emergency dissemination, protection, and real-time data streaming and control that require fast and reliable processing, typically in the range of milliseconds. The data from this layer can also be filtered or aggregated before sent to higher layers. On the other hand, data analytics and reporting that require more data and computation intensity can be processed at centralized Cloud data centers. These data centers collect raw or semi-processed end user data, and produce results in the time scales of seconds to minutes, or even hours. Therefore, a combination of both Fog and Cloud Computing infrastructure will benefit an even wider range of applications.

4.4 Conclusions: Changing the Business Model

The current Cloud Computation model is Business-to-Business, where infrastructure resources are bought from corporates like Akamai and L3, and such resources are hosted by other corporates for a certain service. Such model, very much similar to the transactions between a manufacturer and a wholesaler, or between a wholesaler and a retailer, is not agile. Fog Computing breaks this model and provides services directly to the end users, much similar to the Business-to-Consumer model. Fog Computing can potentially utilize the resources on edge routers, especially home routers, given the fact that these routers simply forwards traffic between the Internet and home users. Abundant resources on these devices are just being idle. If these idle resources would be harnessed, applications and services could easily obtain an open and distributed data center with low latency from the end users. There will be legal issues, however, which are outside the scope of this effort.

Table 5(a) lists the global IP traffic in different geographic regions, from both wired and wireless networks. The number of allocated IPv4 /8 prefixes is calculated from [28][2]. Table 5(b) shows the aggregatable IP traffic per IPv4 /8 prefix, by assuming that the IP traffic

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[2] These prefixes are mainly for ordinary users, not including the prefixes allocated for administrative purpose, prefixes for private IP addresses, and reserved prefixes.

is equally divided among the allocated IPv4 /8 prefixes, and that each month has exactly 30 days. Overall, North America has the highest amount of aggregatable traffic each year, whereas its average year-over-year (YoY) growth rate is just about the global average 23.42%. In contrast, Middle-East and Africa has the lowest aggregatable traffic but the highest average YoY growth rate, such that its aggregatable traffic will surpass Europe in 2016, and surpass both Europe and Latin America in 2017.

From the data shown, it is easy to see that each /8 prefix has several hundred GB of data per second in total (or aggregatable). The data in Table 5 underestimates the number of prefixes allocated for private addresses, however, it provides a reasonable estimation. By partitioning data further, e.g., among the /16 prefixes, the amount of aggregatable data is still large. For example, if the data from North America in 2017 is equally divided among the $2^8 = 256$ subnets, each subnet will have 1.7 Gbps data from all the end users. By aggregating and offloading this 1.7 GB data from end users to their one-hop router every second, 6,120 GB data per hour will experience reduced latency, i.e., only from the local device to the edge router, which is equivalent to 4.4 PB data per month.

Essentially, Fog Computing represents a combined model of Cloud Computing and Content Distribution Network (CDN), but at a much lower cost. As a result, end users will benefit from more affordable service and improved application experience.

5 Software Defined Networking (SDN)

Software defined networking (SDN) allows network administrators to manage network services through abstraction of lower level functionality. This is done by decoupling the system that makes decisions about where traffic is sent (the control plane) from the underlying systems that forwards traffic to the selected destination (the data plane) [61].

SDN appeared as a result of the limitation of today's networks. In today's Internet, the data plane and control plane of protocols are drastically different. Unlike the data plane that is highly modular and reusable from application layer to physical layer, protocols on the control plane tend to be defined in isolation, with each solving a specific problem and without the benefit of any fundamental abstractions and modularity. As a result, the networks today are becoming increasingly complex. For example, while existing networks can provide differentiated QoS (quality of service) levels for different applications, the provisioning of those resources is highly manual. IT must configure each vendor's equipment separately, and adjust parameters such as network bandwidth and QoS on a per-session, per-application basis. Because of its static nature, the network cannot dynamically adapt to changing traffic, application, and user demands.

5.1 Characterization of SDN

SDN features the physical separation of the network control plane from the forwarding plane, and where a control plane controls several devices [62]. In this unique space, SDN has the following characteristics and features.

Directly programmability and flexibility. Network control is separated from forwarding functions, and thus directly programmable. Because of the capability of high-level control, network traffic and forwarding policies can be dynamically adjusted and changed.

Open standard. Control commands and instructions are implemented by open standard. Vendor specific device controls are masked from network operations. Therefore, networks become openly programmable instead of proprietary.

Better user experience. Due to the high flexibility and elasticity, an SDN infrastructure can adapt to dynamic user needs. For example, video streaming applications of a video content provider will be able to detect the changing available bandwidth in the network in real time. Whenever the bandwidth degrades, the applications automatically adjust to lower video resolution.

More detailed characteristics of SDN can be found in [63].

5.2 US and Mozilla Ignite

With this new trend in software-defined networking, a few projects and challenges have been put forward by government, open source communities and public sectors. US Ignite and Mozilla Ignite are two important open challenges. They are both driven by public interest in new technologies and by practical use. The motivation of these projects are: average person is generally not interested in understanding how network technologies make things like ultra-high-speed networks possible, but is instead more interested in discovering the applications that might help them live, work, learn or play better and more efficiently.

The US Ignite initiative fosters the development of next-generation applications that provide transformative public benefit using new technologies including software defined networks, cloud computing and gigabit to end-users [68]. Mozilla Ignite [42] is an open innovation challenge hosted by Mozilla and the National Science Foundation as part of the US Ignite initiative. The goal of Mozilla Ignite is to develop applications that show the full potential of next-generation networks, without the constraint of network speed, latency, and program the entire network, from clients, servers to all the middle boxes in between. Both the US Ignite and Mozilla Ignite promote the programmability on high bandwidth networks, and building new classes of applications leading to tremendous public benefit by taking advantage of deeply programmable, slice-able networks. In addition to the US and Mozilla Ignite, the Global Environment for Network Innovations (GENI) [24] is another project sponsored by the National Science Foundation that provides global programmability for researchers and practitioners. Several Mozilla Ignite projects, as listed below, utilize the platform resources provided by GENI.

5.3 Typical Use Cases

5.3.1 Public Safety (Emergency Response)

This use case corresponds to the detection, observation, and assessment of situations requiring intervention by emergency responders and depends on high-quality "live" data. To get first hand, real-time emergency data, the smartphone application is installed on the phones of people in the national guard, military reservists, etc [55]. Example use scenarios include events occurred during and after Hurricane Sandy, earthquake and tsunami on the Pacific Northwest, etc. In such a use case, the demands of routing potentially large numbers of live video streams, e.g., from such on-site smartphone cameras in an arbitrary location to specific control sites, requires the features of programmable networks to manage bandwidth allocation and possibly multicast distribution of the data with minimal latency.

5.3.2 Remote Collaboration and Learning (via Video Conferencing)

These use cases aim at promoting remote collaboration and learning, and sparking interest in Science, Technology, Engineering and Math (STEM) learning through engaging real-time simulations and rich media content [12]. Scientific datasets can be very large and complex, and analysis benefits greatly from worldwide review. Therefore, high speed networks provide the necessary headroom to reduce latency. Providing tools and allowing users to collaborate in real-time on datasets will reduce time to produce results significantly. In real-time collaboration and learning, the rich media environments require high bandwidth by default. The programmability of SDN therefore controls the networked rich media and enables the environment to become collaborative, allowing users to contribute large amounts of data without affecting their experience negatively.

5.3.3 Health and Energy

Telemedicine [9] and telehealth [37] are future applications that require high bandwidth, high security and high programmability. In the case of telemedicine, the bandwidth requirements for the necessary quality of multi-point encounters (between patient, doctor and guardian) is huge. The bandwidth requirements for multi-point and real time transmission is 100 Mbps or less, from the data calculated in Table 6 to Table 8 for typical current applications, and around 150 Mbps for applications involving 3D videos. Furthermore, the data transfer between access points, to health information exchange networks and entities for reporting has to be highly encrypted to preserve user privacy. In telehealth use case, data sharing is critical. GENI and OpenFlow allow the exploration of real-time data sharing with different routing methods for multi-point and broadcast sessions with recording ability. As a result, more people can participate in each health exercise session, broadcasting a training session will experience lower latency with higher resolution, feedback between participants and cloud based computing analysis for assessment are provided in real time.

5.4 Conclusions: Bandwidth Requirement vs. SDN

While the concept and ideas of SDN is new, the above open challenges are somewhat like solutions looking for problems. All the awarded Mozilla Ignite projects are listed in Tables 6 and 7, and the funded US Ignite projects are in Table 8. The rational for NSF and Mozilla Ignite projects are "building applications for the future", where a bandwidth of up to 1 Gbps is available. Our analysis shows that the application use cases in Section 5.3 can all be deployed in the current network, and SDN will hardly change the bandwidth usage patterns of end users. In Tables 6 and 7, we provide our suggestions of alternative solutions using the current technologies and Internet bandwidth.

5.4.1 Bandwidth Requirement

The most demanding application today is high-definition video streaming, including those in Section 5.3, where emergency response, remote collaboration and learning all leverage live video streaming. In Section 2.4 we estimated the bandwidth required by the of the most up-do-date home devices with Retina Display. In Table 11 of Appendix A we provide an analysis of bandwidth requirements that are common in modern homes, with different screen sizes and various aspect ratios. As seen in the table, the bandwidth requirements are almost independent of screen sizes. The reason is that the pixel density is determined by the limit of human vision. The

Focus Area	**Project Name**	**Approach**	**SDN Concerns**		**Predicted Bandwidth Required**	**Who Will Use**
			Problem	Alternative Solution[3]		
Advanced Manufacturing	Remote process control using reliable communication protocol	Implementing reliable third-party control algorithms, e.g., 3D printing.	Reliable communication	Multi-path TCP with overlay	Between 38 to 74 Mbps	Manufacturers
	Simulation-as-a-service for advanced manufacturing	Remotely access a virtual desktop-as-a-service system for advanced manufacturing processes.	A simulation-as-a-service app based on cloud resource	Using thin-client protocols, e.g., PCoIP	Several tens of Mbps of network bandwidth supporting few tens of users	Manufacturers
	Cloud computing for collaborative advanced manufacturing	Using ultra fast, low latency networks to enable remote collaboration	To be agile in responding to customer requirements	Current cloud service with higher resources	Between 38 to 74 Mbps	Manufacturers
	Consumer 3D Content Creation	Post to and access a Flickr-like online repository for 3D images and videos.	Video, images, and published content do not exist for 3D	—	Between 77 to 148 Mbps	**End Users**
Emergency Preparedness & Public Safety	Real-time emergency response	Detect, observe and assess situations for emergency responders using live video and social media data.	Real-time detection and response	Centralized emergency operations center	Real-time, high-definition device communication at 10 to 18 Mbps	Emergency responders
	The Rashomon project: online multi-perspective chronologies	Tell the story of an event from audio and video simultaneously captured from many users.	Obtaining a comprehensive understanding of an event from many videos	Multiple-camera video streaming	Around 10 to 18 Mbps	**End Users**
	FloodCube: national flood information platform	Predict flood more precisely with real-time analysis of flood sensors and tailor alerts for individuals.	Flood warnings, forecasts, visualizations, mapping and weather info	Using sensors to derive information for scientists	Special sensors at 6 Mbps	Emergency managers and forecasters
Education & Workforce Technologies	engage3D video conferencing	Create engaging learning using 3D telepresence, streaming Kinect sensor data.	Extend video conferencing to 3D	Multiple-camera video streaming	Between 77 to 148 Mbps	**End users**
	High quality open source Web conferencing	Access high-quality, interactive education from classrooms throughout the country.	Regardless of location, all one needs is a browser	Google hangout and Skype	Between 38 to 74 Mbps	**End users**
	OpenPath	Engage in mobile, place-based, collaborative learning in real-time.	Web conferencing in a broader sense	Google hangout and Skype	Between 38 to 74 Mbps	**End users**
	Banyan – share collaborate & publish scientific research	Facilitate collaboration and version control for scientists and researchers.	Sharing data between geographically diverse users	Github in a Scientific context	Between 38 to 74 Mbps	Scientists and researchers
	Hyperaudio Pad and Language Course Creator	Learn, edit and remix media through simple text interface to audio/video.	Learning languages through transcripts	Interactive audio and video editing	Between 38 to 74 Mbps	**End users**
	PeerCDN	A peer-to-peer content delivery network (CDN) that will make the Web faster, more reliable, and help sites to reduce bandwidth costs.	Peer-based content delivery networks	Serving static content over a peer-to-peer network	Between 38 to 74 Mbps	**End users**
	Software lending library	Check-out software from the library using ultra fast low latency networks.	Lack of ubiquitous access to needed applications	Delivering software to users with high bandwidth	Between 38 to 74 Mbps	Students, inner city residents, entrepreneurs, researchers
	PlanIT Impact – 3D planning/design and impact assessment tool	Understand and participate in decisions in the community with data visualization and 3D tools.	To promote smarter decisions in city planning process	Interactive data sharing, audio and video editing	Between 38 to 74 Mbps	City planning agency
	Luminosity – a web app for astronomical analyses and visual	Collaborate on large data through web-based tools for scientists, researchers and citizens.	Need for interactive astronomical visualizations	Interactive data sharing, audio and video editing	Between 38 to 74 Mbps	Scientists and researchers
	CIZZLE (collaborative science learning environment)	Collaborate and learn in immersive 3D environments that users can update simultaneously	Sparking interest in STEM learning via real-time/rich media content	Interactive 3D data sharing, audio and video editing	Between 77 to 148 Mbps	Scientists and researchers

[3] An alternative solution does not require SDN technologies such as OpenFlow, but can solve the same problem with a current approach.

Table 6: Mozilla Ignite projects, approaches, alternative solutions and bandwidth requirement (Complete list of funded projects [43]).

Focus Area	**Project Name**	**Approach**	**SDN Concerns**		**Predicted Bandwidth Required**	**Who Will Use**
			Problem	Alternative Solution[3]		
Healthcare Technologies	KinectHealth	HD workout videos, calorie tracking via motion sensing and a data connection to workout buddies.	Achieve fitness with peers and trainers anywhere	HD video, motion sensing, data transfer all exist	HD video: between 38 to 74 Mbps; sensors: a few hundred Kbps (Table 3)	**End users**
	euMetrica – a remote monitoring and notification system	Monitor, alert patients and doctors with real-time, cloud-based analysis of health sensors.	Real-time preventative care via live variables	HD video, motion sensing, etc.	HD video: between 38 to 74 Mbps; sensors: a few hundred Kbps (Table 3)	Doctors and patients
	WeCounsel solutions, an online therapy innovation	Access and conduct counsel and therapy at a distance using high quality videoconferencing.	A distance treatment solution for therapists	Google hangout and Skype	HD video: between 38 to 74 Mbps	Therapists
	Brief+Case health	Coordinate medical diagnoses and treatment with multi-party telemedicine.	Lack support for parental remote participation	E-health / checkup program using video	HD video: between 38 to 74 Mbps	School telehealth programs
Clean Energy & Transportation	Optimizing public transit	Optimize public transit planning through real-time data analysis of variables such as weather and traffic patterns.	Real-time scheduling public transportation	Cloud based backend data processing	Vehicular comm.: 2 – 3 Mbps; sensors: a few hundred Kbps (Table 3)	Public transit agencies

Table 7: Mozilla Ignite projects, approaches, alternative solutions and bandwidth requirement (Continued, complete list of funded projects [43]).

larger a screen size is, the fewer number of pixels can be seen from a far-away distance. This is a trade-off among the screen size, distance to the screen, total number of pixels can be seen, and the bandwidth. Overall, the bandwidth requirements are almost independent of screen sizes, varying around **38 Mbps to 74 Mbps** for 2D high-definition displays depending on the compression ratio, and **76 Mbps to 148 Mbps** for 3D displays. Such a bandwidth requirement can be served by current network connections.

5.4.2 Conclusions from Case Study

While the Mozilla Ignite participants are drawn from the broader Internet community (Tables 6 and 7), the US Ignite projects have participants from academia (Table 8). Several US Ignite projects require transferring 3D video data. This can leads to bandwidth requirement higher than 100 Mbps (between 77 to 148 Mbps specifically). From Tables 6 to Table 8, the majority of the proposed applications can be deployed in the current network, as their bandwidth requirement is mostly under 100 Mbps. From these tables, there is no project that requires bandwidth higher than 1 Gbps, and used by ordinary end users, i.e., changing the end user bandwidth usage patterns.

Should services use uncompressed video? Overall, any bandwidth higher than 1 Gbps can potentially support raw data transfer, e.g., about 2 Gbps data rate calculated for the high-definition displays *before compression*. However, there is no substantiated need for uncompressed videos based upon current research. Current video compression techniques often employ perceptual model of human psycho-visual system, which can achieve *an immense compression ratio with an extremely little perceptibility of quality loss* [40]. In other words, videos can be compressed significantly with little visible quality loss, and such loss from the original video before compression often can hardly be noticed.

However, using uncompressed, raw data streams is challenging even when the full bandwidth is available. The processing power needed to manage huge volumes of data would make the receiver hardware very expensive [71]. For example, when recording an uncompressed video to a computer, the computer must act like a real-time operating system. Any significant program activity including background processes may disrupt, distort or stop the video recording. Hard disk drives have to be fast solid-state drives (SSDs) or RAID to be capable of the data rate of raw videos [66]. If recording an uncompressed video over a wireless connection, any slight or even short time disruption or bandwidth decrease will also disrupt the video recording. Even today's memory, disk space and network connections are more affordable, uncompressed videos can easily exceed their limit, and thus *diminishing the benefit of preserving more information over computation, storage and network resources*.

Environments needing more bandwidth. Bandwidth significantly higher than 1 Gbps can support futuristic application environment such as CAVE2 [47]. CAVE2 is the current highest resolution LCD-based virtual reality system, with a 36-node high-performance computer cluster, a 10-camera optical tracking system and requires a 100-Gbps connection [11].

For most current applications, including all of those in Section 5.3, existing home wireless bandwidths are more than sufficient.

Project Name	SDN Concerns			Predicted Bandwidth Required	Who Will Use
	Problem	Approach	Solution Details		
Disaster mitigation system [18]	Energy production, transportation and utilization are subject to failures and can have catastrophic impact of life and property.	Providing emergency response staff with training, planning, and real time guidance on effective strategies to protect the general public and first responders.	① Computational fluid dynamics to predict toxic plume evolution; ② Intelligent agent based model in intelligent traffic management systems; ③ Cognitive algorithms to analyze output to channel necessary information and guidance to the appropriate people.	Vehicular comm.: 2 – 3 Mbps; sensors: a few hundred Kbps (Table 3)	Emergency operations center and first responders
In-home health alert system [17, 44]	Health problems often require adults to live in assisted-care facilities to be observed by medical professionals. Adults cannot maintain their independence.	Using motion-sensing technology to monitor changes in residents' health.	① Motion sensors for activity monitoring, Kinect depth images for gait analysis, a hydraulic bed sensor for capturing quantitative pulse, respiration, and restlessness; ② Pattern recognition algorithms to look for changes in the sensor data patterns.	HD video: between 38 to 74 Mbps; sensors: a few hundred Kbps (Table 3)	Health care providers
Telehealth & wellness for senior citizens utilizing in-home Gigabit HD multi-point videoconferencing [19]	Commercial videoconferencing systems employ expensive bridges, limit the number of concurrent video conferences, and limit the quality of video.	Endpoints discover and exchange capabilities and determine the usable network bandwidth to negotiate parameters for the best quality video conference.	① By taking advantage of the Gigabit bandwidth, the endpoints can send reduced-compression video or uncompressed video that is higher quality. ② Layer 2 routing is used to increase effective bandwidth and GENI slices are used for enhanced privacy.	HD video: between 38 to 74 Mbps; (unsubstantiated request for uncompressed HD video at 2 Gbps)	Healthcare professionals and senior residents
Ultra high-speed bandwidth for performance improvements in radar networks for weather & aircraft surveillance [20]	Today's best-effort Internet used to transport data from radars to a variety of end users for decision-making can cause important information to be lost.	Connecting radars to ultra high-speed networks to improve hazardous weather warning and response and the identification and tracking of small, low-flying aircraft.	① Developing new detection algorithms that operate directly on uncompressed, high-bandwidth radar data; ② Using a test bed of high resolution, low-cost radar linked to emergency managers and National Weather Service forecasters.	HD video: between 38 to 74 Mbps; (unsubstantiated request for uncompressed HD video at 2 Gbps)	Emergency managers and National Weather Service forecasters

Table 8: US Ignite projects, approaches, alternative solutions and bandwidth requirement (Complete list of funded projects [48]).

6 Conclusions

This paper studied four emerging technologies from the standpoint of whether adoption would spur bandwidth growth at edge networks. Our conclusions are that several technologies, such as SDN and IoT, should not be expected to drive home user bandwidth. This result goes contrary to the substantial attention that has been foisted upon these technologies for this purpose.

However, the mm-wave technology of 5G will first lead to a ground-swell of network use that is fundamentally different than any previous expectations. Overall, this technology will behave differently in flash crowds and similar situations which may change usage patterns, increase bandwidth sharing between unknown parties, which may drive end user demand.

Furthermore, Community Cloud offerings as are found in Fog Computing, would dramatically reduce cost and latency for cloud applications. If adopted they would shift load to more fully utilize the heterogeneous edge devices. This will alter bandwidth to a much more balanced upload / download ratio while also increasing bandwidth utilization during off-peak hours.

To policy makers or businesses that want to expand high bandwidth home networks, increasing the adoption of 5G mm-wave technology and Fog Computing would be the wisest course of action. Businesses that want to predict future bandwidth growth by home users, would be wise to watch Fog Computing and 5G adoption closely.

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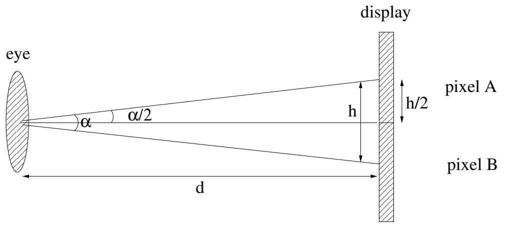

Figure 6: The physics behind retina (Source: [16]).

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A Appendix

A.1 The Physics Behind Retina

The term Retina Display is relative, as the definition follows the human eyes' perception of the sharpness of a display. Figure 6 shows an example of two pixels of a display in front of a human eye, where α is the angle at which the human retina will see two distinct pixels, d is the perpendicular distance from the eye to the display surface, and h is the distance between two district pixels in one dimension. From the figure, we have

$$\tan\left(\frac{\alpha}{2}\right) = \frac{h/2}{d}, \quad \text{or} \quad \alpha = 2\arctan\left(\frac{h}{2d}\right). \qquad (1)$$

Using equation (1), we can determine the angles at which two adjacent pixels can be perceived by human eye. For instance, at the *retina limit* mentioned by Steve Jobs [39], the pixel density is 300 ppi at a distance of 10 inches. This is equivalent to $h = 1/300$ and $d = 10$, thus giving $\alpha^* = 2\arctan\left(\frac{1}{6{,}000}\right) = 3.3 \times 10^{-4}$ radians, the angle at which the human eye can distinguish two pixels at a distance of 10 inches. In other words, any angle larger than 3.3×10^{-4} radians is distinguishable by human eyes at 10 inches from the display. We can thus calculate the values of α and compare with α^*. The data for current Apple devices, pixel density, α, resolution, etc., are shown in Table 9.

Note that the concept of Retina Display is relative, as seen in the data shown in Table 9. If holding an iPad at a normal distance of 15 inches, then $\alpha = 2.5 \times 10^{-4}$ radians, smaller than the minimum α^* of Retina Display. If holding the same iPad closer at a distance of 10 inches, $\alpha = 3.8 \times 10^{-4}$ radians and thus no longer meets the requirement of Retina Display.

A.2 Bandwidth Requirements by Common Home Displays

As in Section 2.4, the parameters required to calculate the digital bandwidth requirements for uncompressed video is [26]:

- *Video resolution.*

  This is measured by the number of pixels wide by the number of pixels high of a video stream. High-definition video is generally defined as having a resolution of at least 1280×720. However, there are also a wide variety of available video resolution formats. Depending on the screen size, certain criteria must be met in order for the pixels to be indistinguishable to a person with perfect vision, when viewing at a certain distance from the screen (Appendix A).

- *Frame rate.*

  This is the number of *still images* or frames per second (FPS) sent as part of the video stream [23]. Broadcast high-definition videos are transmitted at a rate of 59.94 FPS in North America, and 50 FPS

Device Type	Pixel Density (ppi)	h (inch)	d (inch)	α (radian)	Retina Display	Resolution	Total Pixels
iPhone 4/4S and iPod Touch (4th Generation)	326	1/326	10	3.1×10^{-4}	✓	960 × 640	614,400
iPhone 5/5S/5C and iPod Touch (5th Generation)	326	1/326	10	3.1×10^{-4}	✓	1136 × 640	727,040
iPad (3rd/4th Generation/iPad Air)	264	1/264	15	2.5×10^{-4}	✓	2048 × 1536	3,145,728
iPad (3rd/4th Generation/iPad Air)	264	1/264	10	3.8×10^{-4}	✗	2048 × 1536	3,145,728
iPad Mini (2nd Generation)	326	1/326	15	2.0×10^{-4}	✓	2048 × 1536	3,145,728
MacBook Pro with Retina Display 13”	227	1/227	20	2.2×10^{-4}	✓	2560 × 1600	4,096,000
MacBook Pro with Retina Display 15”	220	1/220	20	2.3×10^{-4}	✓	2880 × 1800	5,184,000

Table 9: Current Apple devices: device types, pixel density, resolution and retina display (Source of device types, ppi and resolution: [58]).

Device Type	Pixel Density	Total Pixels	Data per Frame	Uncompressed Data Rate	Compressed Rate
iPhone 4/4S and iPod Touch (4th Generation)	326 ppi	614.4 K	14.75 Mb	442.4 Mbps	8.85 – 14.75 Mbps
iPhone 5/5S/5C and iPod Touch (5th Generation)	326 ppi	727.04 K	17.45 Mb	523.4 Mbps	10.47 – 17.45 Mbps
iPad (3rd/4th Generation/iPad Air)	264 ppi	3.146 M	75.6 Mb	2.268 Gbps	45.36 – 75.6 Mbps
iPad Mini (2nd Generation)	326 ppi	3.146 M	75.6 Mb	2.268 Gbps	45.36 – 75.6 Mbps
MacBook Pro with Retina Display 13”	227 ppi	4.096 M	98.3 Mb	2.949 Gbps	58.98 – 98.3 Mbps
MacBook Pro with Retina Display 15”	220 ppi	5.184 M	124.42 Mb	3.732 Gbps	74.65 – 124.4 Mbps

Table 10: Bandwidth requirements for current Apple devices: device types, pixel density, resolution and retina display (Source of device types, ppi and resolution: [58]).

in Europe. However, we also need to account for possible *interlaced* video [32], which is a way of sending only half of the video frame at a time, either the odd rows or the even rows of the image. This effectively reduces the number of full frames sent per second by half, and thus cuts the bandwidth requirement in half. In the following, we assume the frame rate is North America standard with interlacing, or 30 FPS.

- *Color depth.*

  This is also referred to as bits-per-pixel or bpp, and defines how many colors can be represented by each pixel in the video. A color depth of 1-bit is monochrome, either black or white, while 8-bits can generate 256 colors. Most professional broadcast cameras have a color depth of 24bits or more per pixel, which is considered true-color with over 16 million color variations. However, some professional cameras use a technique called *chroma subsampling* to reduce the number of bits needed, and thus the bandwidth required, to achieve a full spectrum of color. For example, chroma sub sampling can reduce the bpp from 24-bits to 16-bits without a visible effect on video quality.

To calculate the bandwidth required for video transmission of a certain screen size, we have the uncompressed data rate as

$$(\text{No. of total pixels}) \times (\text{color depth}) \times (\text{frame rate}), \quad (2)$$

and data rate after compression as the result in equation (2) divided by the compression ratio.

A.2.1 Real Bandwidth Requirements by Apple Devices

Table 10 shows the required bandwidth for Apple devices given their pixel density. The ppi values are from Table 9. Current high-definition smart device displays, such as iPhone 5 in Table 10, has a total number of 727,040 pixels at 326 ppi. Due to a much smaller screen size and closer distance from eyes to the display, this gives merely 17.45 Mb per frame with a 24-bit color depth. 30 frames per second refresh rate thus leads to a raw data rate of 523.4 Mbps. As a result, an iPhone 5 only requires a bandwidth of about *10 Mbps to 18 Mbps* depending on the compression ratio.

A.2.2 Theoretical Bandwidth Requirements by Television Displays

Table 11 summarizes the theoretical bandwidth requirements of different screen sizes with Retina Display standard. As seen in the table, the bandwidth requirements are almost independent of screen sizes, varying around

Size (Market Share)	d	Pixel Density	Aspect Ratio	Resolution	Total Pixels	Data per Frame	Uncompressed Data Rate	Compressed Rate	Compressed 3D Rate
22 (0.52%)	26.4	114 ppi	4:3	2006×1505	3.02 M	72.45 Mb	2.173 Gbps	43.47 – 72.45 Mbps	86.94 – 144.9 Mbps
			5:4	1961×1562	3.06 M	73.5 Mb	2.205 Gbps	44.1 – 73.5 Mbps	88.2 – 147 Mbps
			16:9	2189×1231	2.69 M	64.56 Mb	1.937 Gbps	38.74 – 64.56 Mbps	77.5 – 129 Mbps
26 (0.42%)	31.2	96 ppi	4:3	1997×1498	2.99 M	71.79 Mb	2.154 Gbps	43.07 – 71.79 Mbps	86.14 – 143.58 Mbps
			5:4	1949×1559	3.04 M	72.93 Mb	2.188 Gbps	43.76 – 72.93 Mbps	87.52 – 145.87 Mbps
			16:9	2175×1224	2.662 M	63.88 Mb	1.917 Gbps	38.3 – 63.84 Mbps	76.6 – 127.68 Mbps
32 (13.33%)	38.4	78 ppi	4:3	1997×1498	2.99 M	71.79 Mb	2.154 Gbps	43.07 – 71.79 Mbps	86.14 – 143.58 Mbps
			5:4	1949×1559	3.038 M	72.93 Mb	2.188 Gbps	43.75 – 72.92 Mbps	87.5 – 145.84 Mbps
			16:9	2175×1224	2.662 M	63.88 Mb	1.917 Gbps	38.3 – 63.84 Mbps	76.6 – 127.68 Mbps
40 (59.39%)	48	62.5 ppi	4:3	2000×1500	3 M	72 Mb	2.16 Gbps	43.2 – 72 Mbps	86.4 – 144 Mbps
			5:4	1952×1562	3.049 M	73.17 Mb	2.195 Gbps	43.9 – 73.17 Mbps	87.8 – 146.34 Mbps
			16:9	2181×1225	2.67 M	64.12 Mb	1.924 Gbps	38.5 – 64.12 Mbps	77 – 128.24 Mbps
46 (10.49%)	55.2	54.3 ppi	4:3	1998×1499	2.995 M	71.89 Mb	2.157 Gbps	43.13 – 71.89 Mbps	86.26 – 143.78 Mbps
			5:4	1950×1561	3.043 M	73.04 Mb	2.191 Gbps	43.82 – 73.04 Mbps	87.64 – 146.08 Mbps
			16:9	2178×1224	2.666 M	63.98 Mb	1.919 Gbps	38.4 – 63.98 Mbps	76.8 – 127.96 Mbps
55 (15.32%)	66	45.5 ppi	4:3	2000×1500	3 M	72 Mb	2.16 Gbps	43.2 – 72 Mbps	86.4 – 144 Mbps
			5:4	1952×1562	3.048 M	73.16 Mb	2.195 Gbps	43.9 – 73.16 Mbps	87.8 – 146.32 Mbps
			16:9	2179×1225	2.669 M	64.06 Mb	1.922 Gbps	38.44 – 64.06 Mbps	76.9 – 128.12 Mbps
60 (0.10%)	72	41.67 ppi	4:3	2000×1500	3 M	72 Mb	2.16 Gbps	43.2 – 72 Mbps	86.4 – 144 Mbps
			5:4	1952×1562	3.048 M	73.16 Mb	2.195 Gbps	43.9 – 73.16 Mbps	87.8 – 146.32 Mbps
			16:9	2179×1226	2.67 M	64.11 Mb	1.923 Gbps	38.47 – 64.11 Mbps	76.94 – 128.22 Mbps

Table 11: Theoretical bandwidth requirements of different screen sizes with Retina Display standard (Size: diagonal screen size in inches; d: distance from human eye to screen in inches). Assuming 24-bit color depth, and frame rate 30 FPS.

38 Mbps to 74 Mbps depending on the compression ratio. The reason is that the pixel density is calculated according to equation (1), which is determined by the limit of human vision. This is a trade-off among the screen size, distance to the screen, total number of pixels can be seen, and the bandwidth.

Note that 3D printing (Table 6) works by slicing a 3D object into layers and processing the object by each layer. Therefore, the same bandwidth requirement in 2D applies to 3D printing at each layer, with extra computation and processing in the third dimension. Similarly, the technology used to produce 3D videos works by recording images as seen from two perspectives [2]. As a result, the bandwidth required will be at most twice as high as in 2D, which is between *76 Mbps to 148 Mbps* for the high-definition TV screen examples in Table 11.