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Opportunities in the 5G Buildout

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INTRODUCTION

The fundamental demand for advanced telecommunications is embedded in our DNA. People want and need to communicate. Whether by prehistoric cave drawings, messenger pigeons in the Middle Ages, or radio waves since 1896, the drive to improve the speed, breadth and affordability of communications has spawned countless industries and defined generations.

Our focus is on the latest iteration of the evolution: 5G or the Fifth Generation of mobile telephony.

To truly understand where telecommunications are going, especially in the 5G era, one has to understand computing. When the internet added cheap, worldwide communications to the power of programming and data analysis on a personal computer, a new era was born. When that power was transferred to mobile phones, new industries were born. The concepts of "mobile" and "personal" are really the same. Mobile phones and personal computers are now functionally indistinguishable from each other.

In retrospect, it's interesting that mobile telephones and personal computers became available at about the same time. Telephony and computers have both been with us for a long time. The first (landline) phone call was made by Alexander Graham Bell in 1876 and the first programmable computer was invented by Konrad Zuse in 1938. But, the first true mobile phone handset, i.e., one that didn't have to be connected to a car, was a 2-lb device showcased on April 3, 1973 by Motorola. And, the first true personal computer, i.e., a stand-alone computer that was affordable to the average consumer, was the Altair 8800 developed by MITS in 1974. The Altair 8800 is the machine that inspired Bill Gates and Paul Allen to launch Microsoft in 1975. (Wikipedia has nice, short histories of mobile phones and personal computers.[1])

With each new advance in microprocessor and memory chip technology, the PC industry saw rapid development in hardware and software. When the internet became commercially available as the "World Wide Web" in 1990, the PC and telecom industries became inexorably linked. The internet became a must-have telecommunications service (remember those dial-up modems?) and the personal computer was the only way to get it. It also marked the beginning of the shift from voice communications on the telecom network to data communications.

These PC technologies helped mobile phones evolve from that first 2-lb Motorola handheld to the powerful smartphones of today. Like PCs, the use of mobile phones has shifted from its original intent as a tool for voice communication to a tool for data communication. Ericsson reported that mobile data traffic surpassed voice traffic on a global basis in December 2009.[2] Ericsson also reports that in 2018Q4, global mobile subscription penetration reached 104% or 7.9 billion mobile subscriptions, with 5.9 billion mobile broadband subscriptions and monthly mobile data traffic grew 88% YoY, the highest rate since 2013Q2.[3]

In this report, we seek to understand the business opportunities presented by the rollout of 5G in coming years. We first discuss the fundamental technology of mobile telephony, then review the various "generations" of mobile cellular communications leading up to 5G. We examine how 5G differs from 4G. We review the infrastructure work that needs to be done around the world to upgrade mobile communications from 4G to 5G. Finally, we review the various uses that 5G will enable in the near future, its anticipated uses in the more distant future and a preliminary investment strategy.

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OVERVIEW

How mobile phones work

Mobile telecommunications require one-to-one two-way communication from one mobile device to another mobile device or to a conventional land-line phone.[4] This is accomplished through the use of "cells", i.e., the geographic space surrounding a "base station", which is the collection of antennas, hardware and software that facilitates this two-way connection between a mobile device (phone, computer, etc.) in the cell to the telecommunications network. The cells are physically situated such that a mobile device will stay connected to the network seamlessly as it moves from cell to cell.

So, the communication path is from the sending mobile device, to an antenna situated in the nearest base station, to the network, to an antenna in the base station closest to the receiving mobile device, and then to the receiving mobile device. To allow for the largest possible cell size, antennas are installed in high places to provide for the strongest possible signals over the cell. These places are commonly atop individual stand-alone towers, in bell towers, atop telephone/utility poles, or the tops of tall buildings. Base stations are connected to each other and to the primary network via cables. When cable connections between towers are not practical, such as in rural areas, line-of-sight microwave radio transmission is used. Mobile providers will usually place their antennas together on the same tower.

The five generations of mobile telephony

As mentioned above, the PC and mobile phone industries are linked by history and by consumer use.

Early personal computers were large, complex machines with simple text-based screens that catered primarily to technology enthusiasts and academia. PCs became much more mainstream with the advent of the graphical user interface ("GUI"), such as Microsoft Windows and the Apple computer, which created a more intuitive, visual way to use the computer's applications. In turn, applications quickly came to market to take advantage of the GUI, such as spreadsheets, word processors and games. As microprocessor, memory, battery and screen technologies advanced, the PC industry became more mobile, introducing laptop and tablet computers. The first portable computer was made by Osborne Computers in 1981 and the first laptop by Grid Systems in 1982. The sale of laptops first exceeded that of desktops in 2005.[5] This indicates consumers' desire not only for mobility, but of the necessity of computers in everyday life.

> *"The first portable computer was made by Osborne Computers in 1981 and the first laptop by Grid Systems in 1982."*

The evolution of mobile phones from big and clunky to small and sleek echoes that of the PC. Over time, the technological advances for PCs were applied to the mobile phone market which allowed smart phones to act as computers. Early mobile phones were called "bricks" and handled only voice calls due to limitations of both the phone and the network. Text messaging became possible with phones that had simple multi-line text screens in a move to emulate email. "Smartphones" moved yet closer to the PC experience by adding larger screens, GUIs and the ability to handle larger quantities of data, such as pictures and video. Tablets lie at the intersection of smartphones and computers and were designed to be the single device for those who need a phone and a laptop, but don't want to carry both. But tablets have not caught on with consumers, and sales have declined steadily for many years. However, phones with larger screens have proven popular. Smartphones with foldable screens have recently launched, effectively doubling the size of current phone screens.

The need for faster, more reliable mobile communications networks has been driven by consumer demand for more and more data, as opposed to voice calls. The generations of mobile communications are summarized below. In general, technical specifications and standards for each generation of mobile technology are set worldwide by the International Telecommunications Union (ITU, www.itu.int) a United Nations specialized agency. While mobile service providers have largely abided by these standards, variations of the standard (most commonly, speeds that are not quite as high as the standard dictates) are often launched early in order to have bragging rights as first to market.

The Generations of Wireless Technology

1G	1979 Japan Nordic countries	Analog (i.e., limited capacity and quality) signals; first came to the US in 1983.
2G	1991 Finland	Digital signals; in 1993, IBM introduced Simon Personal Communicator, the first smartphone – a touchscreen personal digital assistant with telephony features. Text messaging offered by some providers. First access to the mobile web in 1996 in Finland. First mobile-specific web service, i-mode, offered by NTT DoCoMo in 1999.
3G	2001 Japan	Use of packet switching (which is how the internet works) instead of traditional circuit switching. Frequency range 400Mhz (Megahertz)-3GHz (Gigahertz). Speeds up to 2 Mbs (megabits per second) indoors, 394 Kbs (kilobits per second) outdoors. This speed allowed audio streaming pioneered by RealNetworks. First came to the US in 2002.
4G	2009 Stockholm Oslo	First internet protocol networks (IP, exactly how the internet works) with speeds up to 100 Mbs to 1 Gbs (gigabits per second); Frequency range 700Mhz-3Ghz.
5G	April 2019 South Korea 2019 Japan & US	Speeds up to 20 Gbs; latency (signal delays) < 1 millisecond vs 30-40 ms for 4G; Frequen-cy range 30-300Ghz; higher system capacity, massive number of device connections.

How 5G differs from 4G

As can be seen, speed improvement has been the driver from one generation to the next. This is accomplished by using increasingly higher radio wave frequencies and increasingly wider frequency bands. 5G will operate in the 30-300 Gigahertz frequency band ("millimeter" wavelengths) as opposed to 4G's 700-2600 Megahertz band. To date, cell towers could be up to 40 kilometers (25 miles) apart, since radio waves in the 4G range can penetrate solid objects. However, millimeter waves can be interfered with by solid objects and even rain, so 5G base stations must be no more than about 1 km (0.6 miles) apart.

To achieve higher capacity, 4G uses MIMO (multiple-input, multiple-output) technology. This involves splitting a large chunk of data into smaller pieces that are sent simultaneously over the same frequency band, thus increasing the capacity. This is accomplished by using multiple transmitting and receiving antennas along with software to strategically split and reconstitute the signals; the number of separate pieces of data being sent is limited by the lesser of the number of transmitting or receiving antennas. 5G will have to use MIMO to an even greater extent ("massive MIMO"), thus increasing the number of antennas being used in 5G on two counts: more antennas in each cell, and more cells, since 5G cells are roughly 40 times smaller. Practically, in cities, it's possible that antennas will need to be placed on each floor of a high rise in order to effectively access a nearby base station. A compensating factor is that 5G antennas can technically be 10-100 times smaller than 4G antennas, depending on the frequencies employed.

It is important to remember that the transition from 4G to 5G will occur in stages. 5G will initially use 4G to initiate a cell phone connection. So, the 4G infrastructure will still be used extensively. And, as a practical matter, it won't make sense to have a plethora of 5G antennas in sparsely populated areas. So, 4G and 5G will most likely co-exist for a long time. Also, the early versions of 5G will likely operate at below 6GHz, which will operate 25-50% faster than 4G. As more 5G cells are put into place and 5G-enabled devices become available, the 5G network will be upgraded and higher speeds will be achieved.[6,7]

"...in cities, it's possible that antennas will need to be placed on each floor of a high rise in order to effectively access a nearby base station."

And, true 5G may never be fully achieved in all locations. Even now, current high-speed mobile service is labelled "4G LTE (long term evolution)", or simply LTE, because it is does not strictly adhere to the 4G standard. Often the upload or download speed is not quite up to the 4G standard, but it is still a many-factor improvement over 3G. This will undoubtedly occur with 5G, where speeds may be 5-10 times current levels, but not up to the 20 times improvement specified by the 5G standard. "5G NR (new radio)" is already being used as a name for the first 5G-like services being developed. Regardless of the name, expect speeds at least 10 times faster and latencies 10 times lower than LTE.

5G and Wi-Fi

When describing 5G as high speed internet access limited to a small cell, it sounds a lot like wi-fi. From a customer perspective, there is no difference. When your phone automatically switches from the cellular network to wi-fi in a coffee shop or at home, you still have all your phone's functionality at the same speed. The primary difference is that wi-fi is unlicensed radio spectrum, i.e., it is free to use. But, as such, devices that use this spectrum must be low power, i.e., cannot transmit over a broad area.

The Wi-Fi Alliance, the non-profit organization that promotes wi-fi standards and certifies wi-fi products (www.wi-fi.org), plans to maintain this parallel path with 5G development. All wi-fi operates at either 2.4Ghz or 5Ghz frequencies. The current wi-fi standard (802.11ac or Wi-Fi 5) operates on 5Ghz and delivers speeds of 210Mbps to 1Gbps. The next wi-fi standard (802.11ax or Wi-Fi 6) calls for speeds up to 4 Gbps. So, early 5G deployments will look almost exactly like wi-fi.

A quick word about safety

There have been reports over the years of brain cancer and other maladies being caused by electromagnetic waves from cell phone antennas being held close to the skull. The energy of electromagnetic waves increases as frequency increases, so there has been renewed concern about 5G. The frequencies used in all cell phones are in the non-ionizing range, meaning that the waves are not strong enough to break down chemical bonds but are strong enough to pass through the body. However, results from studies of the effect on cell phones waves on the body have been inconsistent. The National Cancer Institute has published a summary of historical tests and results as of January 9, 2019.[8] As stated in its report: "The only consistently recognized biological effect of radiofrequency radiation in humans is heating. The ability of microwave ovens to heat food is one example of this effect of radiofrequency radiation. Radiofrequency exposure from cell phone use does cause heating to the area of the body where a cell phone or other device is held (e.g., the ear and head)." One mitigating factor is that the phones are not held close to the head as before: data use is greater than voice use, and the increased use of earbuds and earphones keep the phone away from the head. While the risk of harm from 5G is most likely very low, if we are going to be surrounded by 5G signals from our phones and a plethora of devices around us, more research and monitoring needs to be done.

INFRASTRUCTURE

In the building of the telecommunications infrastructure, the benefit will continue to go to those network, construction and equipment companies that are already involved in the buildout of 4G.

Network construction

First, let's consider the telecommunications network itself. In the major markets, except China (see discussion on China below), the mobile carriers are the ones responsible for building the infrastructure. So, the telecom companies themselves are the ones to watch.

South Korea launched its 5G service on April 3, 2019 through all three of its mobile carriers: SK Telecom (17670-KR), KT (30200-KR) and LG Uplus (32640-KR). In the US, Verizon launched its 5G service the same day in parts of Chicago and Minneapolis. Both are claiming they were first. It is too early to know how the services are doing.

In the US mobile market, the major players are Verizon (VZ-US), AT&T (T-US), T-Mobile (TMUS-US) and Sprint (S-US). Besides Verizon, the others will be launching 5G in 2019. As of May 20, 2019, the FCC has indicated that it will approve the $26.5B merger between T-Mobile and Sprint, thus potentially creating a third major player in the 5G market. To obtain approval, the companies promised to commit to a three-year buildout of a 5G network and to not raise prices during this buildout.

Japan is also scheduled to launch in 2019 through its three carriers: NTT DOCOMO (9437-JP), KDDI (9433-JP) and Softbank (9984-JP).

"growth in data means growth in fiber cables"

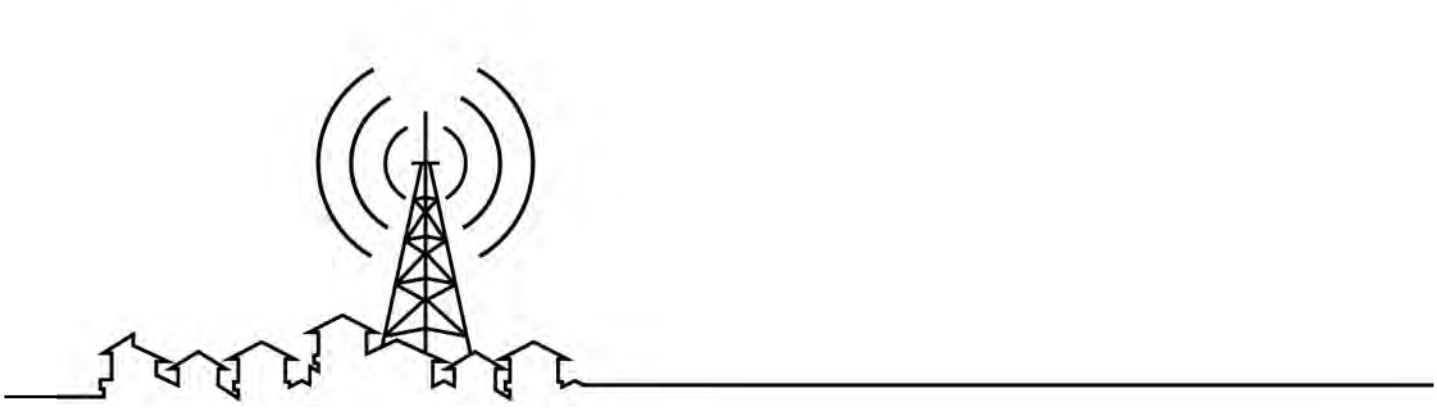
The "backbone" of the network is optic fiber that carries signals around the world. While the current optic fiber networks should be able to carry the bulk of data traffic in the short term, growth in data means growth in fiber cables. The top five providers of optic fiber (with 2018 market share) are Corning (GLW-US, 17%), Yangtze Optical Fibre & Cable (6869-HK, 14%), Hengtong Optic-Electric (600487-CN, 11%), Furukawa Electric (5801-JP, 10%) and Fiberhome Telecommunication Technologies (600498-CN, 7%).[9]

Towers

The towers that hold the base stations and antennas tend to be owned by independent companies. Towers are expensive, require local government approval, and cities require mobile equipment to be as hidden as possible. So, telecom providers rent space on towers for their antennas and base stations. The largest of these, in terms of numbers of towers owned and operated, are Crown Castle (CCI-US) and American Tower REIT (AMT-US).[10] Remember that 5G will still rely on 4G, so towers will still be needed. However, 5G antennas will need to be placed closer to the source of sending and receiving devices, which will most likely be mobile phones and devices closer to the ground or in buildings. So, while 5G equipment will certainly be placed on existing towers, there will not be a new demand for towers as they currently exist during the 5G buildout. There will be many smaller clusters of 5G antennas installed in strategic locations closer to street level, and tower companies will most likely own and operate these "small cell sites." So, the sharing of cell sites will continue, and tower companies will see growth in the buildout phase.[11] The CTIA (the wireless industry's trade association, www.ctia.org) reports that there are currently 154,000 towers in the US and there will be over 800,000 small cells deployed by 2026.

> *"5G antennas will need to be placed closer to the source of sending and receiving devices"*

One trend to watch is 5G in the home. In October 2018, Verizon launched "5G Home" which uses 5G to bring internet service into homes, essentially creating ultrafast wi-fi. It is available in limited areas of Sacramento, Los Angeles, Houston and Indianapolis. While this current version does not use industry standards, it's possible that if this type of internet service becomes prevalent and industry standards are used, every home can be a small cell site. This could be the best way to bring 5G service to the less densely populated suburbs.



Rural access

Getting 5G into rural areas is important for the future of agriculture and to address the general digital divide, i.e., the lack of access to information in rural areas of developed countries and in underdeveloped countries. This is a high priority for China (see next section) and has a high priority in the US and other developed countries as it pertains to autonomous robotic farming (discussed below).

There are two ways the delivery of high-speed internet is envisioned for rural areas. The first is the old-fashioned way: to run fiber optic cable along utility lines or other right of ways, such as railroad tracks. 5G base stations would be installed along the cable path as needed. Of course, this would be highly impractical, if not impossible, in trying to reach very remote areas.

The other method is to use low-earth orbit (LEO) satellites in a "megaconstellation" configuration, i.e., hundreds of satellites in coordinated orbits around the earth so that any point on earth has constant communication with one of those satellites. "Ground stations" would need to be installed at regular points around the earth to provide a connection between the internet network and the satellite network. Then 5G base stations would need to be installed as needed. OneWeb (private) is the first company to start the construction of a megaconstellation with its launch of six satellites in February 2019. These are the first of 650 total that are planned to be in orbit by 2021.[12] Amazon plans to launch a 3,236 satellite system and, in partnership with Lockheed Martin (LMT-US), is also developing "AWS Ground Station," a cloud service for ground station companies.[13,14] Facebook and SpaceX also have plans for megaconstellations.

At present, satellite internet is available commercially from ViaSat (VSAT-US) and HughesNet (sub of Echostar SAT-US). Download speeds are 25-100 Mbps with upload speeds of 3Mbps and latency is about 550 ms. This is due to the satellite orbits being high (36,000 km) and just over the equator, so signals take a long time to reach earth. LEO satellites will be 1,200-2,000 km high and will surround the earth, thus reducing the inherent latency. Planned speeds are 500Mbps in initial phases and

Rural access (cont.)

2.5Gbps in later phases, however latencies will still be in about 25 ms. This is not up to 5G standards but is equivalent to current mid-level cable internet service. With a higher density of satellites and improved transmission technology, it's possible that 5G-like service can be achieved.

Megaconstellation projects are multi-billion dollar and multi-year efforts. It is not clear that any of them will be profitable. But there is a social responsibility aspect to this effort. So, they will undoubtedly proceed as they all have deep-pocketed backers. SpaceX and Amazon (affiliated with Blue Origin) benefit from having access to low-cost space launches. Amazon has the benefit of having satellite-related cloud services but developing similar cloud services with Microsoft or Google would not be difficult.

The companies that are in the ground station business are either well-established governmental stations or are startups, such as RBC Signals (US), Infostellar (Japan), Kongsberg Satellite Services (Norway), Leaf Space (Italy), Swedish Space Corp (Sweden), Atlas Space Operations (US) and BridgeSat (US). Two major stations in Singapore are owned by SingTel (Z74-SG). There will be a need for many ground stations all over the world. And, like the symbiosis between tower companies and mobile carriers, it makes sense for these ground stations to be privately owned and to lease capacity to satellite internet service providers. There will undoubtedly be consolidation and possibly a rollup of the smaller companies.

China's role in 5G

The Chinese market is unique. First, it is the largest mobile market in the world. At the end of 2017, there were 1.4 billion Chinese mobile users, compared to roughly 400 million in the US. Secondly, as is the case with all major Chinese industries, the government controls the development of the market. China has historically taken outside technology and perfected the ability to manufacture it inexpensively through cheap labor. But, in May 2015, the government launched "Made in China 2025", a strategic plan that calls for China to be more than just a low-cost manufacturer. It calls for China to be a leader in developing and producing high value products and services, especially 5G and all the industries touched by 5G.

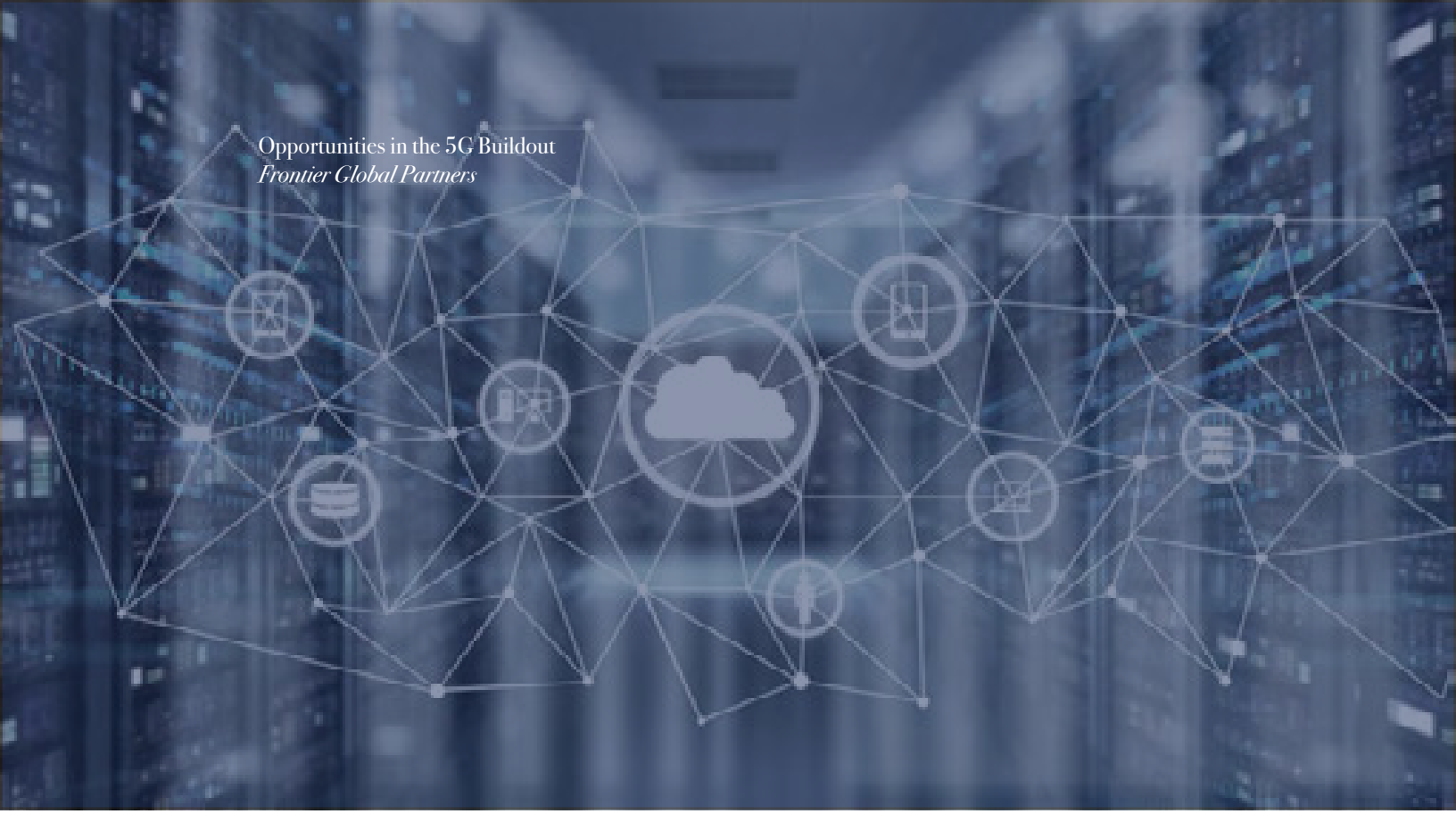
At the same time, China is completing its buildout of 4G in order to connect the whole country, especially rural areas. So, it's highly likely that much of China will be 5G-ready as 5G rolls out. China has three mobile providers: China Mobile (941-HK), China Unicom (762-HK) and China Telecom (728-HK). While each of these is involved in building the infrastructure for its own purposes, the Chinese government is trying to level the playing field by consolidating infrastructure building through the three mobile companies and two companies that are owned by the government: China Communications Services (552-HK), the builder and manager of network infrastructure, and China Tower (788-HK), the builder, owner and manager of wireless telecom towers. The Chinese government is the majority shareholder in all these companies.

Network equipment

A base station consists of antennas, a connection to the network (or to another base station that has a connection to the network) and a base transceiver station, which is a specialized computer that processes and routes the incoming and outgoing signals from the antennas and the network. Today, network equipment manufacturers are one-stop shops, providing the equipment, along with network management and data storage services. Most of the equipment being sold now is 4G equipment that is 5G-enabled. This allows the equipment to be used immediately and then converted to 5G with a simple turnkey process. The leading mobile network equipment providers are (with 2017 market share) Huawei (private, 28%), Ericsson (ERICA-SE, 27%), Nokia (NOKIA-FI, 23%), ZTE (763-HK, 13%) and Samsung (5930-KR, 3%).[15]

China-based Huawei is the largest seller of telecom equipment in the world. However, Huawei has been accused of placing rogue hardware on its circuit boards that allow the Chinese military to spy on the users of those boards, which are major corporations, other governments and internet service providers around the world. While Huawei has denied these accusations and maintains its independence from the Chinese government, this has not stopped the US government from banning the sale of Huawei equipment in the US and putting pressure on other governments to do the same. Germany is ignoring the US ban, while Australia and Great Britain have instituted bans of their own. In the company's earnings report for FY2018 on March 29, 2019, overall sales increased 19.5% YoY, but networking sales decreased 1.3%. This decrease was most likely affected by the ongoing trade wars as much as the ban itself. However, this situation may allow other companies to take market share from Huawei in the 5G buildout.

On May 17, 2019, the Trump administration banned the use of Huawei telecom equipment in the US, citing national security reasons. American companies were initially banned from selling telecom equipment to Huawei but were later given a 90-day window to supply and service equipment already sold to Huawei; a ban exists on new sales. On May 20, 2019, several US companies announced that they would honor the ban. Google will not support new Android phones made by Huawei and will restrict its access to the Google Play app store. Major US companies, including Intel, Qualcomm, Xilinx and Broadcom announced their compliance with the order, thus cutting off the primary supply of chips to Huawei's telecom, phone and PC businesses. A resolution of the trade war between the US and China will undoubtedly involve the lifting of this ban. Given the importance of China's 5G aspirations, this will either accelerate settlement discussions or, in a very lengthy delay, permanently rearrange the global supply chain for almost all finished electronic equipment. The latter is worthy of further research but is outside the scope of this report.



Cloud platforms

Cloud platforms (or simply, "the cloud") will be an integral part of the 5G network. The two major players are Amazon Web Services ("AWS", AMZN-US, launched in 2006) and Microsoft Azure (MSFT-US, 2010). Google Cloud (GOOL-US) is a distant third. In China, Tencent (700-HK) Cloud is a leader. Cloud platforms are large collections of computers, data storage systems and redundant internet connections that reside in data centers around the world. Cloud customers can run commercial software (such as Microsoft Office) or their own proprietary software in an on-demand environment, i.e. computing resources, storage and internet bandwidth can be increased or decreased as needed instantaneously, thus alleviating the need for owning and maintaining internal data centers. Even AI software is available as a module on all major cloud platforms. This value proposition has made cloud services a standard way of operating for any internet-based company and the corporate and governmental transition from closed systems to cloud or hybrid closed/cloud systems is well underway. Both are still experiencing high double-digit growth after initial triple-digit growth. Azure revenue was $3.3B with 73% YoY growth in 2019Q3 and $3.7B with 64% YoY growth in 2019Q4, its latest release.[16] AWS revenue was $7.7B with 41% YoY growth in 2019Q1 and $8.4B with 37% YoY growth in 2019Q2.

"This value proposition has made cloud services a standard way of operating for any internet-based company"

Data storage

Lots of data requires lots of data storage. This is especially true in this early stage of artificial intelligence models, where massive amounts of data are needed to develop the models. (For more discussion on this, see Appendix I.) The storage standard is currently NAND flash memory in solid state drives, termed "all flash storage arrays." These arrays are usually bundled with data management software and other related services. Of course, these are widely deployed in cloud platforms. However, for those industries that require absolute security of information, such as healthcare, private storage systems are deployed for active use and backup. The leaders in this field are NetApp (NTAP-US), Hewlett Packard Enterprise (HPE-US), and Dell EMC (sub of Dell, DELL-US). Of course, this is a highly competitive area and there are a number of interesting smaller companies: Kaminario (private), X-IO (subsidiary of Violin Systems, private), Tegile (sub of Western Digital, WDC-US), and Pure Storage (PSTG-US). Consolidation has been rampant in this area and will continue.

Security

Securing the 5G network will be of utmost importance. With so many connected devices, the network becomes that much more vulnerable. This was illustrated in 2016, when the Mirai virus[17] turned IoT devices, such as home cameras and Ring doorbells, into "bots" that were used to perform large-scale coordinated distributed denial-of-service attacks.[18] Mirai did this by simply scanning a wide variety of internet addresses and looking for devices that were still using the default administrator password. Every device maker is hardening its own built-in security. And, security at each point on the network is also being hardened via hardware and software. Security exists primarily as either a firewall, i.e., sophisticated hardware and software platforms that stop rogue traffic from entering the internal network at the point of contact with the internet, and/or as virus protection, software that detects and removes viruses from a device before it can infect the device. In a highly distributed network, as 5G will be, both modes will be required. Protection is needed in the devices and network equipment, on the network, and in the cloud platforms.

Leaders in this field are Cisco (CSCO-US), Symantec (SYMC-US), Palo Alto Networks (PANW-US), Check Point Software (CHKP-US), McAfee (private), and Trend Micro (4704-JP). There are many smaller, but also well-known companies such as FireEye (FEYE-US).

Our attention now turns to the uses of the 5G network. With 5G, the fundamental nature of the telecommunications network will not change – it remains based in internet protocols. What will change is the hardware, software and services that use the network. Backward compatibility, i.e., using old hardware and software on the upgraded network, will be supported, and there will be 4G service in parallel with 5G for the foreseeable future. But, adding new 5G-dependent functionality requires new software, which will not work on old hardware. So, a new upgrade cycle is expect-ed over 2020-2021.

SMARTPHONES

Customers will interact with the 5G wireless network primarily through smartphones. In fact, smartphones will also be the primary way customers control "Internet of Things" devices (discussed below) that connect to the network.

4G caused a revolution. By fully integrating the internet with the mobile phone, smartphone penetration increased and whole new industries were born: picture sharing (Instagram), ride hailing (Uber), augmented reality (Pokemon Go). These existing services will be enhanced by 5G. It is not yet clear if these will be changed at all. However, new industries will undoubtedly be created.

The top 10 smartphone makers (with global market share at the end of 2018) are: Samsung (5930-KR, 19%), Apple (AAPL-US, 14%), Huawei (private, 14%), Xiaomi (1810-HK, 8%), Oppo (private, 8%), Vivo (3454-TW, 7%), LG (66570-KR, 3%), Lenovo (includes Motorola, 992-HK, 3%), Nokia (NOKIA-FI, 1%) and Tecno (subsidiary of Transsion Holdings, private, 1%).[19] As mentioned above, the Huawei ban will severely hamper Huawei's smartphone business and may have uncertain effects on the global supply chain. However, phones built outside the US and China will be largely unaffected and will benefit from Huawei's slowdown.

Samsung's Galaxy S10 5G phone was used in South Korea's launch. Motorola had two phones available on Verizon's launch: The Moto 3Z and the Moto Mod 5G. And, there are a host of other phones set to launch when 5G becomes more widely available later in 2019.

Of course, this is a highly competitive market and is subject to the whims of consumer tastes. Sales of smartphones have slowed considerably in recent quarters due to slowdowns in national and regional economies, especially China. This slowdown is expected to continue while the trade war between the US, China, and the EU persists. Trade agreements will eventually be reached, but the timing is uncertain. However, the number of mobile and smartphone users continues to grow, so the 5G buildout is continuing. It's possible that the 5G upgrade cycle will help increase smartphone sales growth in 2019.

While it is difficult to pick a winner in 5G phones, the crowded field is an early indication of the high projected consumer demand for 5G. As has been the case in earlier generations, the winner has often been determined by a radical new design or a killer feature, e.g., the iPhone's sleek design or the high-resolution camera. The most radical new design feature unveiled so far is the foldable screen, such as the Samsung Galaxy Fold. However, recent problems with the screen breaking under normal use makes this questionable as a killer feature. The killer feature will most likely be 5G itself and the applications ("apps") that 5G enables.

Smartphone Components

Again, while picking a smartphone winner is difficult, another strategy would be to bet on smartphones in general by examining what all of these phones have in common. All phones consist of a screen, a camera, memory, a microprocessor, an antenna, a battery, microphones, a GPS receiver, various other sensors, and software. Many of these components are commodities, figuratively and literally. We will examine the products as well as any materials that may be required, except steel and plastic.

- Displays

The most obvious feature of a phone is the display. As discussed, display size is a selling point, along with the expectation for high resolution, brilliance of color and impact resistance. The major display manufacturers are: Samsung (5930-KR), LG Electronics (66570-KR), Tianma Microelectronics (50-CN), Japan Display Inc (6740-JP), AU Optronics (2409-TW), Sharp (6753-JP) and Foxconn Technology (2354-TW).[20] The screens are made of specialized, high impact resistant glass, such as Gorilla Glass, invented by Corning. As one might expect, there are many competitors, including the optical glass fiber companies mentioned above, as well as LCD television display companies. Glass is made of silicon. As a commodity, silicon is the second most abundant element on Earth, after oxygen. So, there is no commodity risk.

- Digital Camera Sensors

The quality of the camera is also a major selling point. The camera is actually a sensor on a chip that translates the millions of light impulses captured while taking a picture into digital signals. While there is some debate as to whether the race to add more and more pixels to a camera is worthwhile,[21] a high-quality camera is an essential part of a smartphone. The major digital camera sensor makers are: Sony (6758-JP), Omnivision Technologies (private), Toshiba (6502-JP), SK Hynix (660-KR), and Samsung (5930-KR).[22]

- MEMS Devices

Micro Electro-Mechanical Systems are devices that have microscopic mechanical functionality etched onto a chip and integrated into an electronic circuit. This allows the device to be compact. For a smartphone, the most common MEMS are microphones, accelerometers, which measure forces, such as gravity, and movement; gyroscopes, which indicate the physical orientation of a phone; and Global Positioning System (GPS) receivers, which indicate a phone's location and is used for mapping. Gizmodo has a nice overview of these devices.[23] While these are marvelous feats of engineering, these technologies have been in existence for decades. They are used in many consumer and industrial applications and are mass-produced commodity items. So, there are literally thousands of IoT sensor manufacturers. The major manufacturers in the general IoT sensor market are: Texas Instruments (TXN-US), TE Connectivity (TEL-US), STMicroelectronics (STM-US), Broadcom (AVGO-US), and NXP Semiconductors (NXPI-US).[24]

- Microphones

As video recording has become a more important feature of smartphones, capturing higher quality sound has also become a focus. Current smartphones contain three or four microphones. The Apple iPhone X contains four MEMS microphones supplied primarily by GoerTek (2241-CN), Knowles Electronics (KN-US), and AAC Acoustic Technologies (2018-HK). In turn, Infineon Technologies (IFX-DE) provides chip technology for GoerTek and AAC microphones.[25]

- Antennas

5G requires a 5G-specific antenna, which was for some time thought impossible. So, one of the winners here will be Qualcomm (QCOM-US), which launched its QTM052 5G mobile phone antenna in July 2018. These are combined with Qualcomm's Snapdragon X50 5G modem and the latest integrated Snapdragon System-on-Chip Mobile Platform. The company's recent patent lawsuit settlement with Apple, along with Intel's exit from this sector, puts Qualcomm in an enviable position. On July 25, 2019 Apple announced it would buy Intel's smartphone business for $1B. While this will undoubtedly reduce Apple's reliance on Qualcomm, it will likely take many years for Apple's modems to be of the same quality as Qualcomm's.

- Silicon chips

We have discussed the chip industry in our reports on Samsung (5930-KR, memory chips), Siltronic (WAF-DE, silicon wafers) and Shin-Etsu Chemical (silicon wafers). In brief, the memory and processor chip markets currently have a glut of product due to a period of undersupply, followed by a period of oversupply due to weak global demand, attributable in part to the trade wars. This oversupply is predicted to last until late 2019 as inventories are worked down, subject to global economic conditions.

- Batteries

While battery life will always be a concern, it is quite easy to recharge a phone battery. Many stores, such as Starbucks, even offer smartphone charging stations at each table. However, the process of seeking a cell signal is energy intensive. Also, many apps will be constantly accessing GPS and other sensors. This will be offset somewhat when cell sites are closer to the phone, i.e., easier to connect to. But we are not at that stage yet.

"It is with batteries that the underlying commodities are a concern."

Currently, all rechargeable batteries use lithium ion technology. The major manufacturers of lithium batteries are: Samsung SDI (subsidiary of Samsung, 5930-KR), Toshiba (6502-JP), and LG Chem (51910-KR). Other lithium ion battery producers are focused on the electric vehicle market, such as Tesla (TSLA-US), A123 Systems (private), eCobalt Solutions (ECS-CA), BYD (2594-CN), Contemporary Amperex Technology (300750-CN), and Johnson Controls (JCI-US).[26]

It is with batteries that the underlying commodities are a concern. The demand for batteries in the auto and smartphone markets has put pressure on markets for lithium and cobalt, the two principal metals used in lithium ion batteries. Lithium is plentiful but located in areas where extraction is difficult. This has caused significant volatility in the price of lithium. Lithium prices reached an all-time low in February 2016, an all-time high in January 2018, and are currently 33% below that all-time high, having dropped 5.4% year-to-date. The search for new, easier sources of lithium is yielding positive results.[27]

While lithium is located primarily in Australia, China, Chile, Argentina and North America, over 60% of the world's cobalt supply comes from the politically unstable Democratic Republic of Congo (DRC). Global cobalt reserves are 50% in DRC with the other 50% dispersed throughout the world. So, this commodity supply risk will persist indefinitely.[28] However, it is possible to substitute iron for cobalt.[29] A lithium-iron battery does not currently have the same power or longevity as a lithium-cobalt battery, but research is continuing to reduce or replace cobalt. The major lithium miners are: Tianqi Lithium (private), Jiangxi Ganfeng Lithium (2460-CN, 1772-HK), Albemarle (ALB-US), Sociedad Quimica y Minera de Chile (SQM-US), and Livent (LTHM-US).[30] Major cobalt miners are: Glencore (GLEN-LN), China Molybdenum (603993-CN, 3993-HK), Fleurette Group (private), Vale (VALE-US), and Gecamines (private).[31]

Smartphone software

After display and camera, the most important features of smartphones are the applications (or apps) that are available for the phone and its operating system. With Microsoft exiting the phone market and Blackberry having virtually no market share, there are essentially just two smartphone operating systems available: Apple iOS and Google Android. Android is the most popular OS to date. When apps are developed, they are generally released on both operating systems. However, while iOS is uniform across all Apple iPhones, the Android OS is different for each Android smartphone maker, making Android app development trickier.

Smartphone apps

Apps built for Android are available mainly on the Google Play site and the individual phone makers' sites. However, apps built for iOS are available only through Apple's App Store and customers can only pay via Apple's iTunes payment system. Customers in Google Play can pay in different ways. As of 2019Q1, there were 2.1 million apps in Google Play and 1.8 million in the App Store.[32] To sell apps, Apple charges developers a $99 annual fee plus 30% per sale and 15% for annual subscription renewals. Google charges developers a $25 one-time fee plus and, same as Apple, 30% per sale and 15% for annual subscription renewals. Global app revenue in 2018 was $46.6B in the App Store and $24.8B in Google Play. Total mobile gaming revenue was $54.7B and non-gaming revenue was $16.6B.[33]

The Supreme Court recently agreed to hear Apple Inc. v. Pepper, a case that accuses the App Store of being a monopoly. Also, on March 15, 2019, Spotify filed an antitrust complaint with the European Commission. If Apple loses these cases, it may have to allow iOS apps to be obtained from other stores or may have to spin off the App Store. That potential negative for Apple would be a positive for app developers. As of May 16, 2019, the top 10 free iOS apps on the iTunes charts were (in order, games bolded) **Tomb of the Mask**, **Go Fish!**, **Hello Stars**, Instagram, Snapchat, Messenger, Facebook, **Bumper.io**, **Fortnite** and Google Maps – Transit. The top 10 paid iOS apps were **Minecraft**, **Heads Up!**, PlantSnap, **Plague Inc.**, Human Anatomy, Facetune, **Bloons TD 6**, Sky Guide, Dark Sky Weather and **Pocket City.** Google Play does not have a similar overall statistic, instead categorizing by Top Free Apps, Top Paid Apps, Top Grossing Apps, Top Free Games, Top Paid Games, and Top Grossing Games.[34]

Gaming apps

It is no surprise that the most popular apps are games and 77% of app revenue derives from games. The global gaming market in 2018 is estimated at $138B with the mobile gaming market being $70B, or 51%.[35] Much like the fusion between PCs and smartphones, 5G promises to bring a console-quality gaming experience to the mobile phone. This will tempt console game developers to port their popular franchises to mobile platforms. Blizzard Entertainment (sub of Activision Blizzard ATVI-US) plans to port Diablo Immortal, the latest version of its popular multi-player game, to mobile.[36] This follows the success of Epic Game's (sub of Tencent Holdings, 700-HK) 4G mobile port of Fortnite: Save the World, a four-player game.

"The global gaming market in 2018 is estimated at $138B."

Using Google Play's lists of Top Grossing Apps and Top Grossing Games, we recognize the top app companies, excluding Google-related apps, as Sirius XM Holdings (SIRI-US, Pandora), IAC/InterActiveCorp (IAC-US; Tinder), AT&T Warner Media (T-US, HBO), Walt Disney (DIS-US, ESPN), Netflix (NFLX-US), Bumble (private), BIGO Technology PTE. Ltd. (private, BIGO Live), King (sub of Activision Blizzard ATVI-US, Candy Crush), Moon Active (private, Coin Master), Tencent Games (sub of Tencent Holdings 700-HK, PUBG Mobile), Playtika (sub of Caesars Interactive Entertainment CAR-US, Slotomania Slots Casino), Playrix (private, Homescapes), Peak Games (private, Toon Blast), Gram Games Ltd (sub of Zynga ZNGA-US, Merge Dragons!), Small Giant Games (sub of Zynga ZNGA-US, Empires & Puzzles), Century Game (private, Guns of Glory).

Gaming apps (cont.)

If we focus on the most recent quarter, the top gaming app companies in 2019Q1 were Delightworks (private)/Aniplex (sub of Sony Music Entertainment 6758-JP, Fate/Grand Order), Tencent (700-HK, Honour of Kings, QQ Speed), King (ATVI-US, Candy Crush Saga), mixi (2121-JP, Monster Strike), Bandai Namco (7832-JP, Dragon Ball-Z Dokkan Battle), NetEase (NTES-US, Fantasy Westward Journey), Nintendo (7974-JP, Pokemon Go), and GungHo Online (3765-JP, Puzzle & Dragons).[37]

On May 16, 2019, Microsoft and Sony announced a strategic partnership where both companies would use Microsoft's Azure cloud platform to co-develop game streaming services that will "enhance customer experiences in their direct-to-consumer entertainment platforms and AI solutions." The AI collaboration centers around integrating Sony's advanced image sensor technology with Microsoft's AI platform. This took the industry by surprise, as Microsoft's Xbox and Sony's PlayStation are fierce competitors in the game console market. This just underscores the importance of the cloud and AI in developing the next generation of games.

Non-gaming apps

Non-gaming apps account for 23% of the mobile app market, or $16.6B. The top grossing nongaming apps in 2019Q1 were Tinder (dating, IAC-US), Netflix (entertainment, NFLXC-US), Tencent Video (video, 700-HK), iQIYI (video, sub of Baidu BIDU-US), Pandora (music, SIRI-US), YouTube (video, sub of Google GOOGL-US), Kwai (video, private), Youku (video, sub of Alibaba BABA-US), Line and Line Manga (messaging, Naver Corp 354210-KR).[38]

VIRTUAL REALITY AND HEALTH TECH

Augmented and virtual reality, e-commerce and advertising

Augmented Reality (AR) is the melding of the real world and imaginary world. Virtual Reality (VR) is the total immersion into an imaginary world. It was Nintendo's (7974-JP) and Niantic's (private) Pokemon Go that brought AR to the masses in 2016. Pokemon Go is still the leading AR game. Other popular AR games are Ingress (Niantic, private), ARrrrrgh (Warpin Media, private), Temple Treasure Hunt (MobiTech, private), Sharks in the Park (Geo AR Games, private), and dARk: Subject One (Combo Studio, private).[39]

Top VR games include Beat Saber (Beat Games, private); Rick and Morty: Virtual Rick-Ality (Adult Swim Games, Warner Media, T-US); Cloudlands VR Minigolf (Futuretown, private); Moss and Wipeout Omega Collection (both Sony PlayStation VR, 6758-JP).[40]

VR apps require a headset to get the full experience. The top producers of these headsets are: Oculus (sub of Facebook FB-US), Nintendo (7974-JP), Sony (6758-JP), HTC (2498-TW) and Lenovo (992-HK).[41] These are all full headsets for use with game consoles or in an industrial setting. VR glasses/goggles for use with smartphones are also available. Samsung has the Gear VR headset specifically for their own phones. Apple's AR/VR goggles for iPhones are set for a 2020 release date. There are many other models available for any smartphone, some of the most popular being Oculus Go (Facebook, FB-US), Google Cardboard (Google, GOOGL-US), and Merge VR Goggles (Merge Labs, private).

As mentioned before, it's possible that 5G and 5G-enabled apps will be the killer feature that stimulates smartphone sales and the smartphone upgrade cycle. It's highly possible that it will be AR and VR in free apps that will provide this motivation. Facebook's acquisition of Oculus is already an indication that this is where things may be going. By "free" apps, we are referring to the many apps that provide information or services and never require a payment to enjoy enhanced services. All of these obtain revenue from purchase fees or advertising fees. A full 79% of smartphones users have made a purchase using their phone within the last six months.[42] What AR could do is make advertising more compelling by presenting 3D sales experiences, or by answering questions via live video chat, resulting in greater click-through rates. And, once at a seller's website, AR and VR could provide a more engaging sales pitch, especially if a travel destination, food or drink is involved.

Here are some thoughts on how certain apps might benefit from 5G's higher bandwidth and lower latency:

• **Mapping** (Google Maps, Google Waze GOOGL-US, Apple Maps AAPL-US) – overlaying enhanced advertising and reviews along the directions route

• **Social media** (Facebook FB-US, Instagram FB-US, SnapChat SNAP-US, Twitter TWTR-US, LinkedIn MSFT-US) – sharing 3D pictures and videos, enhanced advertising, live virtual networking and socializing

• **Reviews** (Yelp YELP-US, Angie's List ANGI-US) – video reviews, enhanced advertising

• **e-commerce** (Amazon AMZN-US, Postmates private, GrubHub GRUB-US) – enhanced product advertising

• **Travel** (Trip Advisor TRIP-US, Expedia EXPE-US, Booking.com/Priceline,com/others BKNG-US) – enhanced pictures and videos of hotels, restaurants, tourist sites; video commentary; AR/VR virtual guided or non-guided tours

• **In-store shopping** – rather than looking for a store employee for help, shoppers could be helped by a virtual assistant directing them to desired products, while also suggesting alternatives and making them aware of sale items. These virtual assistants could be operated by a person in a back room, or mapping could be used to guide the shopper through the store to the correct shelf with automated shopping suggestions. Importantly, 80% of shoppers use a mobile phone inside of a physical store to either look up product reviews or compare prices.[43]

Health, wearable tech and medical technology

Physical and mental health is now a mainstream preoccupation. The awareness of "natural" and "organic" food has led naturally to devices and apps with which to easily monitor personal health.

Smartwatches (i.e., smartphones in watch form) play a key role in this trend. Smartwatch sales grew to $5B in 2018, up 51% YoY with unit sales up 61% YoY. Apple (AAPL-US), Samsung (5930-KR) and Fitbit (FIT-US) control 88% of the market, with the Apple Watch being the clear leader.[44] Besides functioning as a smartphone, it can track miles walked/run and measure heart rate, sleep cycle and perform electrocardiograms.

As far as apps go, there is no shortage of apps to help us exercise, monitor sleep, meditate, or eat better. Many are run by venture-backed startups. There is no clear killer app yet in this field. This is undoubtedly due to the lack of small, inexpensive sensors that can deliver hospital-quality measurements. Apple filed a US patent, "Portable Electronic Device Having an Integrated Biosensor" that envisions a sensor on a laptop that can perform more extensive measurements, such as blood pressure. If successful, it will not be long until we see such a sensor on a watch and the subsequent killer apps. In the meantime, certain strides are being made. Cyrcadia Health (private) and Nanyang Technological University in Singapore are developing early breast cancer detection technology through its ITBra, wearable breast patches that measure circadian temperature patterns, which are sent and analyzed by diagnostic algorithms.[45] Dias and Silva Vunha published a very nice overview of the vital signs that are being monitored by wearables and the current state of those technologies as of mid-2018.[46]

Every major technology company (e.g., Apple, Microsoft, Google), every major health system and hospital, every major pharmaceutical company, every major university, and every major government are developing medical technology, often in partnership with each other, especially in the application of artificial intelligence to improve the practice of medicine. Some are focusing on wearable tech, others are focusing on medical information and data management, some are exploring robotics. Robotics are a particularly interesting area and will be addressed below.

This whole area is still in its infancy, but shows great promise in lowering the cost, improving the quality, and increasing the availability of healthcare worldwide. The advantages 5G will bring to these efforts is the reduced latency in real-time communication. Even telemedicine will be improved. While telemedicine is simply video conferencing with a doctor, the ability to transmit high resolution images in real time will greatly improve the patient-doctor interaction.

Of equal importance in the health technology field is agricultural technology. 5G will certainly make "precision" robotic farming much more feasible. Eating healthy has become the new mantra for young and old alike. Beyond Meat's (BYND-US) highly successful IPO in a weak market attests to the popularity of plant-based meat substitutes. But the price premium associated with organic food is still a deterrent. Reducing the cost of production will certainly help this market, which is still quite small. The organic food market was two decades in the making in the US (it is much more mainstream outside the US, especially in Europe), and while sales have grown double digits that whole time, it is still only about 4% of total food sales. This topic is too large to address here.

THE INTERNET OF THINGS (IOT)

IoT devices are simply devices that require an internet connection to work. They may obtain their inputs from a human or another device, but to respond with outputs or actions, they must communicate over the internet to get commands on how to deliver the output. Whenever we say "internet," we can also be referring to wi-fi or some combination of wi-fi and internet.

IoT devices are already with us in a big way. There were an estimated 7 billion IoT devices in use globally in 2018 with an expectation for 10 billion by 2020 and 22 billion in 2025. This includes all internet-connected devices, including smartphones and industrial devices, such as smart meters.[47] One pundit envisions a day when your refrigerator tells your car that the milk is low, so on the way home from work, your autonomous car takes you automatically to the grocery store. While you may never actually want this to happen, it illustrates the real-time device-to-device communication that will define the 5G generation. In this same vein are fully autonomous vehicles, driverless taxis, full body health monitoring, telemedicine/telesurgery, just-in-time inventory management, and life-like interactive robots.

The IoT process starts when a device receives an input either (a) automatically as in an image or sound from a sensor, (b) from a person as a voice, touch or typewritten command, or (c) from another device. The IoT device transmits the input to a central cloud-based controller where it is stored and processed. The processing of data involves artificial intelligence (AI) algorithms (see Appendix I) that determine an action for the device to take, and this action is transmitted back to the devices as a command. Upon receiving the command, the device carries it out. Alternatively, AI algorithms can be built into the device so that actions can be determined locally, and thus more quickly. Any data that need to be stored can be sent to cloud storage at a later time. This latter mode is called "edge" computing, since it happens at the edge of the cloud.

IoT components

IoT comprises six component types:

1. **Sensors** – the devices within the IoT device that automatically and continuously take in information to be acted upon. Many of the fundamental IoT sensors are identical to the ones in smartphones, discussed above. For voice recognition, the advanced microphone technology used for smartphones is being incorporated into IoT devices that need them. Likewise, smartphone camera technologies suffice for vision sensors in most IoT situations.

However, a great deal of research is going into the ability to capture high resolution images under all conditions, since this is one of the critical aspects in creating self-driving cars. Autonomous driving will rely heavily on 5G. While all the sensors on a single car will be connected to each other, they will also be connected to the auto manufacturer's cloud system via 5G. While the actual autonomous driving functionality will reside in an on-board computer, data from all the sensors will be constantly uploaded to cloud databases as raw data for the training of AI algorithms. It is also envisioned that cars will "talk" with each other as another level of safety on the road. And, the customer experience in the car will be elevated to include personalized entertainment; web search; e-commerce services, such as restaurant recommendations and reservations, movie ticket purchases, etc.

There are four types of sensors that are being used in the development of autonomous driving.[48,49] The devices themselves are all similar in how they operate, differing mainly in the type of electromagnetic or sonic radiation waves used. The sensor emits radiation waves, then measures the reflected waves as they bounce off objects. By analyzing the angle of the received waves, and the difference between the transmitted and received waves, the device can determine the position of an object and how fast it is moving.

The first, and most common, sensor is a regular camera which uses visible light as the electromagnetic wave. Cameras are inexpensive ($5-$20 per unit in quantity) and have very high-resolution images, but cannot capture sufficiently good images in low light, in bad weather or in dusty conditions.

The second most common sensor is radar (Radio Detection and Ranging), which uses pulses of radio waves. An antenna transmits and receives radio waves in all directions. Since radio waves can penetrate most objects, it will work in all types of weather, light and dirt conditions. But, because it does not penetrate metal, there is inherent noise in the reflected signal, meaning that the resolution is not good and decreases with distance. Radar has been in use by the military since World War II, so the technology is well developed and inexpensive ($10 per unit in quantity).

The third, and latest, technology is lidar (light radar), which is similar to radar, except it uses laser light. Unlike visible light, which carries a wide variety

of frequencies, a laser (Light Amplification by Stimulated Emission of Radiation) will emit light in a very narrow frequency band. Lidar requires special sensor chips and a complex rotating mirror system to obtain a 360o view but produces very high-resolution 3D images. The downside is that the units are quite large, and the cost is very high. Velodyne (private) invented the 3D lidar unit that sits atop most autonomous cars today and is the market leader. Its flagship 64-laser unit costs $75,000 for a single unit. Another consideration is that lidar is not effective at close ranges.

At the present time, because none of these light-based systems is adequate by itself, combinations are being used around the perimeter of a car. And, to reduce the cost, lidar is being replaced with ultrasonic sensors, which use ultrasonic sound waves rather than light waves. These are low cost ($5-$10 per unit in quantity) and are useful for the detection of objects up to about 10 meters.

Note that training AI algorithms to integrate multiple sensor inputs is significantly more complex than for a single (lidar) input.

At Tesla's Autonomy Investor Day on April 2, 2019, Elon Musk was highly critical of lidar, complaining primarily of its cost. Tesla is using only radar sen-sors around the perimeter of its cars, along with eight cameras, 12 ultrasonic sensors and an on-board computer. Tesla has revealed that it is de-veloping its own self-driving chip, claiming it is 21x faster than the Nvidia (NVDA-US) chip Tesla has been using; Samsung is fabricating Tesla's chip.

Research by startups and auto makers is ongoing to create both high resolution radar and lower cost lidar. Waymo, the self-driving technology company started by Google, is selling its internally developed lidar to other robotics companies for $7,500 per unit.[50] Other lidar developers on the same quest, using various competing technologies, are Velodyne (private; 16-laser unit for $4,000), Luminar Technologies (private), AEye (private), Ouster (private, 64-laser unit on a single chip for $24,000; upgrading to 128 lasers; shorter-range unit $3,500), Blackmore (private, Doppler system under $20,000), Baraja (private; targeting cost of low hundreds of dollars per unit in quantities of hundreds-of-thousands), Quanergy (private), Cepton technologies (private; focusing on Advanced Drive Assistance Systems (ADAS), rather than autonomous driving), and Innoviz Technologies (private; also focusing on ADAS, with some autonomous capabilities).[51]

The fourth sensor type, ultrahigh-resolution radar, is lidar's competition. In January 2019, Arbe Robotics (private) launched the first high resolution 4D (3-dimensions plus velocity) radar sensor chip for the automotive industry.

The major manufacturers of radar sensors are: Robert Bosch GmbH (private), Lockheed Martin Corporation (LMT-US), Raytheon Company (RTN-US), Saab AB (SAAB.B-SE), Northrop Grumman Corporation (NOC-US), Aptiv (Formerly Delphi Automotive, APTV-US), Hitachi, Ltd. (6501-JP), Continental AG (CON-DE), ZF Friedrichshafen AG (private), Denso Corporation (6902-JP), Infineon Technologies AG (IFX-DE), NXP Semiconductors N.V. (NXPI-US), Omniradar BV (private), and Airbus Group (AIR-FR).[52]

Radar provides better reliability than lidar or cameras in inclement weather, so radar will undoubtedly be used in some combination with cameras, lidar and ultrasound to provide the safest autonomous driving system. Of course, the caveat is only if the total cost of the system is no more than about $10,000 total. Even at this price point, customers may opt out of the autonomous driving option. The cost would have to be under $1,000 to become ubiquitous. If history is any guide, once an optimal configuration is determined, it will be fabricated into mass produced chips and circuit boards and the price will drop precipitously. This will most likely happen within five years.

"Radar provides better reliability than lidar or cameras in inclement weather"

2. **The network** – the wireless network, i.e., 5G and wi-fi, plus the internet.

3. **Computation** – the process of analyzing the input data and calculating a course of action. This is a complex step as it involves (a) an AI algorithm, (b) a computer that may reside locally in the device as a specialized chip or in the cloud, and (c) data storage on the device and in the cloud. Many assume that an IoT device will constantly be connected to the internet. Ideally, this will be the case. But, any critically important device in the wild – a robot in a disaster site or a car on the highway – cannot assume that an internet connection will be available at all times. Here, edge computing will be a necessity, even if only as a backup, for certain high value IoT devices. For edge computing, specialized microprocessor chips will be necessary, as well as high capacity memory chips. Tesla is taking this approach, as mentioned above. For most simple IoT devices, just a sensor, basic microprocessor and memory chips, and wi-fi connection are required.

4. **The cloud platform** – All of the above requires a unified operational platform, so that all IoT devices can operate together. There are commercial platforms, such as Amazon Alexa and Google Home. Each major IoT device maker will connect to one of these commercial platforms, or will have one of their own platforms, or both. Note: to connect to a commercial platform, you need at least two devices for it to make sense; just one device will be controlled by a smartphone. Any industrial IoT device will have a proprietary platform.

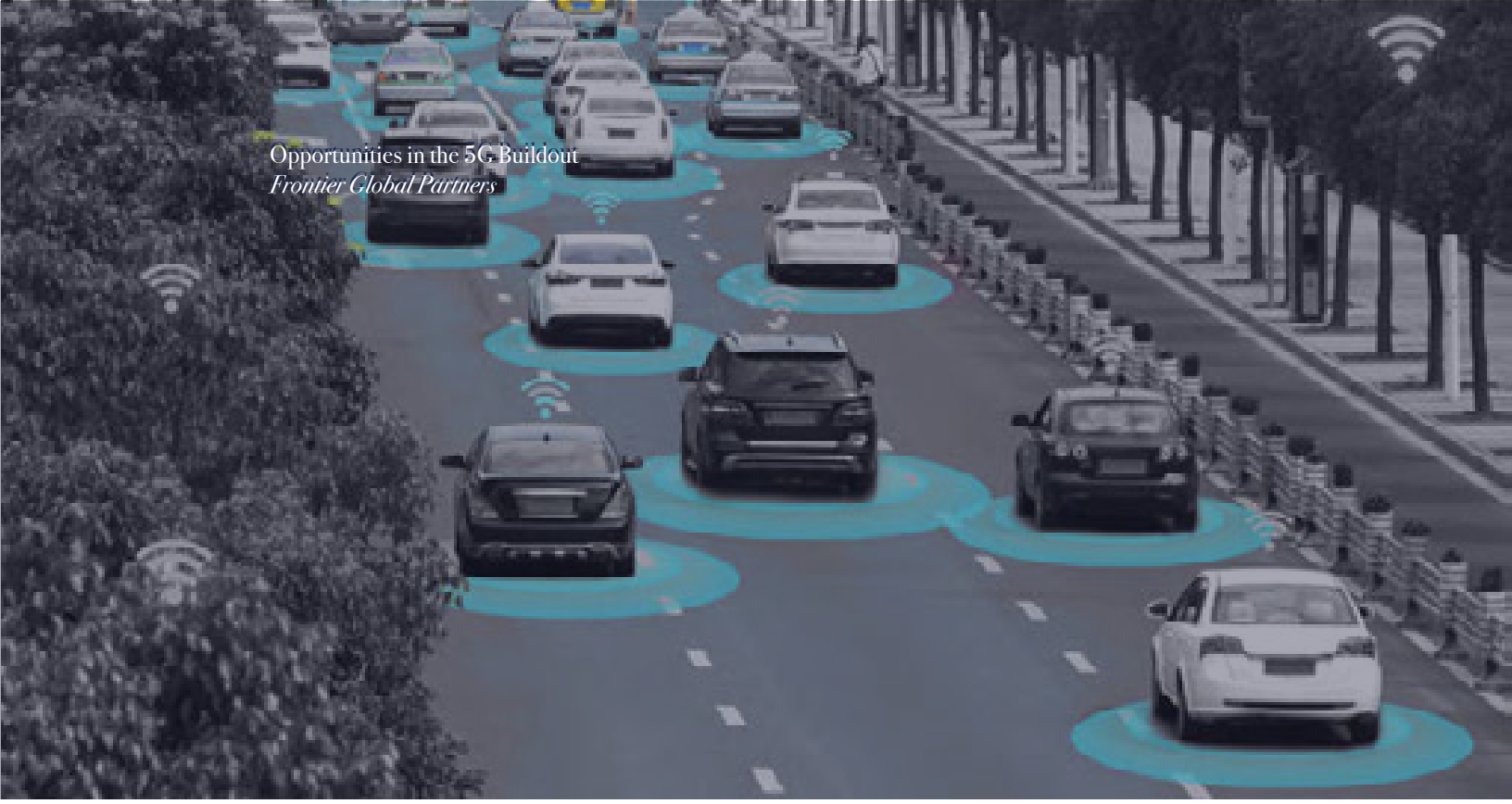
As we have seen with Sony's partnership with Microsoft in gaming, even a company with the resources of Sony will turn to the established leaders in cloud platforms, rather than create and manage one's own cloud platform. Microsoft, Amazon and Google will continue to grow. However, Amazon and Google are often competitors of those companies that seek cloud services, so expect Microsoft to win the bulk of this new business.

5. **The IoT devices themselves**, i.e., the fundamental mechanical devices that hold the sensors, memory chips, microprocessor chips and connections to the network. We will break these up into two categories:

a. **Home appliances** – The smart home is already with us. The concept involves connecting and controlling a home's appliances, window shades, thermostats, door locks, security systems, garage doors, EV charging units, and utilities via wi-fi and smartphone over the internet. Many new homes built by Lennar (LEN-US) in Orange County, California are being constructed with a built-in Alexa-specific wi-fi network, so that it is separate from the regular wi-fi network. Of the many thousands of appliance manufacturers, those recognized as being in the top five in the smart home industry are Haier (a portfolio company, 1169-HK), Electrolux (ELUX.B-SE), LG Electronics (66570-KR), Whirlpool (WHR-US), and Samsung Electronics (5930-KR).[53]

b. **Autonomous cars** – The sensor makers for the autonomous car industry were discussed in detail above. All major auto makers and auto parts makers are involved in this sector as well. Techworld recently reviewed this sector and identified the top 25 players as: Volvo (VOLV.B-SE), Waymo (sub of Alphabet GOOGL-US), Mercedes-Benz (sub of Daimler DAI-DE), BMW (BMW-DE), Nvidia (NVDA-US), Continental (CON-DE), Oxbotica (private), Addison Lee (private), Huawei (private), Toyota (7203-JP), Baidu (BIDU-US), General Motors (GM-US), Ford (F-US), Stagecoach (SGC-LN), Samsung (5930-KR), Volkswagen (VOW3-DE), Uber (UBER-US), Fiat Chrysler (FCAU-US), Apple (AAPL-US), Intel (INTC-US), Audi (sub of Volkswagen VOW3-DE), nuTonomy (sub of Aptiv APTV-US), Bosch (private), Tesla (TSLA-US), and FiveAI (private).[54]

Autonomous driving will become standard in the shipping sector. Roughly 71% of all goods moved in the US are transported via truck.[55] For safety reasons, truck drivers are limited by regulation to driving 11 hours maximum per day and a maximum of 70 hours in any eight-day period.[56] Autonomous trucks would not have any such limitations, and driving on highways is far simpler than driving in cities and residential streets, as there is much less stopping and starting. In February 2018, Starsky Robotics (private) completed a seven-mile driverless trip in Florida with a driver in the cab. Further driverless tests, also with drivers in the cabs, were undertaken on a Florida toll road in May 2019.[57] Also that month, the US Postal Service announced that TuSimple (private) would run a two-week pilot test of autonomous mail hauling between Phoenix and Dallas.[58] Driverless trucks could also help the industry, as the driver turnover rate was 89% in 2018 and it is hard to recruit younger drivers.[59] In April 2019, the California Department of Motor Vehicles proposed regulations to allow the testing



of autonomous smaller delivery vehicles. At present, 62 companies, including all the usual suspects, have permits to test autonomous vehicles on California roads with a driver present. Only Waymo (GOOGL-US) has a permit for driverless testing.[60]

Autonomous short haul delivery, including robo-taxis, is also under testing. Waymo launched a robo-taxi service in Chandler, Arizona, to a limited audience. These riders can hail a taxi using an app and ride within a 100 square mile area. Robo-taxis are being planned for 2020 by Uber (UBER-US), Lyft (TSLA-US), Tesla (TSLA-US), and others. In 2015, Domino's launched the world's first autonomous pizza delivery vehicle in New Zealand – a small robot that could travel on sidewalks. It is currently not in use. In 2018, Pizza Hut and Toyota announced a partnership to develop a driverless vehicle that would cook and deliver pizzas, with test models targeted for 2020.

So, regardless of the demand for autonomous driving in the consumer sector, there is great demand and clear opportunities in the commercial sector. However, as with advances in auto technology that are developed and perfected on the auto racing circuit, it's highly possible that even if autonomous driving does not turn out to be as pervasive as originally thought, the sensor and AI technologies that are developed and perfected in the process will be applicable to many aspects of auto safety and to other industries, especially robotics.

6. **Robots** – Autonomous vehicles are robots. But, while this is occupying much of the world's attention, it is just a small slice of the whole world of autonomous robots. While the current state of the art in robotics is impressive, there is still much to be done beyond the 5G era. Regardless of the robot involved, the technological challenges are similar: using sensors and AI to accomplish useful physical

tasks. The role of 5G is to enable these processes to be performed in real-time and better than if a human did it.

Stationary robots – Robots are invaluable in manufacturing due to their ability to do repetitive tasks accurately and indefatigably. Here, the robots can be large, stationary, with vision capabilities and multiple arms that can move in three dimensions. These are not autonomous in the way we have been using that term in that there are no decisions to be made – the robots perform specific tasks repeatedly, such as welding the frame of a car on the assembly line.

Moving robots – The next level of evolution in industrial robots occurred when robots became mobile, physically untethered to a controller. This is when mobile communication became important. The robots needed not only to communicate with a controller, but also needed to be aware of other robots working around them in order to avoid collisions and general chaos. The automated warehouses run by Amazon Robotics (AMZN-US) provide a good example. Here simple robots perform complex tasks, i.e., fulfilling a customer's order by moving autonomously through a warehouse, picking products and bringing them to the shipping area. Robots can also perform tasks just like a human. A video by Boston Dynamics showcases robots' abilities to walk, run, jump, do backflips, and move heavy objects.[61] Knowing that animals have evolved to perfectly adapt to their environments, some of the most interesting robots are those that mimic animals, with the goal of exploring natural environments as no human could do. There are four-legged dog and cheetah robots, fish and manta ray robots, octopus and snake robots, and flying robots, including drones.[62]

Drones, or unmanned aerial vehicles (UAVs), first captured the public's imagination when video from Predator drones making military missile attacks were shown. The much smaller, low-cost multi-propeller drones made for recreational use became popular in 2015. There was high interest in drone delivery by pizza companies and by Amazon and other package delivery companies. But in June 2016, the FAA issued rules governing drone flights. Those require drones to be operated by a licensed drone pilot and the drone to be within line-of-sight of the pilot at all times, thus killing drone delivery. Despite these restrictions, drones are standard tools for surveillance and monitoring.

Agricultural robots are another important sector. Autonomous tractors can till soil, fertilize, and plant seeds. Picker robots can harvest strawberries, apples, asparagus, and almonds with minimal human guidance. "Precision farming" includes the ability of robotic weed-killing robots to travel through a field and identify a wide variety of weed plants in the soil next to crops; the robot then sprays herbicide on that weed only, or zaps the weed with laser light if at an organic farm. Drones can monitor the condition of crops and can deliver water, fertilizer or pesticides precisely as needed. The productivity improvement, and cost reduction, potential of using robots in agriculture is enormous and worthy of further detailed analysis.

Medical robots are an area of interest mainly in surgery. AI is clearly of great interest in almost all aspects of medicine, but our focus here is on robots.

"Telesurgery would allow surgical expertise to be available anywhere in the world"

Automated robotic surgery is already here: An autonomous robot performed dental surgery in China, where a robot arm implanted two 3D-printed teeth with no human intervention.[63] The technology was developed to address the shortage of dentists in China. The robot was developed by the Stomatological Hospital and Beihang University, both in China. The FDA has approved the Yomi robot developed by Neocis (private) for dental implant surgery. Yomi does not work autonomously, but instead helps guide the surgeon's hand to ensure proper placement of the implant. Non-autonomous robots also exist for "minimally invasive" or "laparoscopic" surgery, i.e., surgery that is performed with miniature surgical instruments through a series of small small incisions. The da Vinci system[64] is the most advanced: three arms control the instruments and a fourth arm holds a high-definition 3D camera, while all four arms are controlled by the surgeon in the operating room. This system first gained FDA approval in 2000 and is made by Intuitive Surgical (ISRG-US). It's possible that the public will never accept autonomous surgery, but the possibility of telesurgery is more realistic.

Telesurgery is when the surgeon is controlling a robotic surgery system from far outside the operating room. Telesurgery would allow surgical expertise to be available anywhere in the world, especially remote locales, including battlefields.

This is where 5G would be critical, since precise surgical movements can have no time lag to avoid mistakes. The first telesurgery was performed in 2001 using a landline internet connection; dubbed the "Lindbergh operation", it was performed by French surgeons located in New York on a patient located in France.[65] In January 2019, the first 5G-enabled telesurgery, a procedure performed on a dog, was reported to have occurred in China.[66]

Collaborative robots – The next level is when robots work together. This involves not only recognizing the presence of other robots but communicating and coordinating actions. A video from Boston Dynamics shows two four-legged robots working together to go through a door.[67] Swarm robotics seeks to have a group of small, inexpensive robots form a collective level of intelligence that each individual robot does not have, e.g., working together to move a large object or build a structure.[68]

Human-like robots – The final evolution of robots are human-like robots. The robots do not necessarily have to look like humans but must act and talk like humans. One of the most ambitious, and whimsical, projects is the Henn-Na Hotel in Nagasaki, Japan, which opened in 2015. At the Henn-Na, robots perform all service tasks: check-in/out via a robot that looks like a velociraptor, taking luggage to the room, and controlling room functions with a voice-operated bot. In a rather ironic life-like situation, half of the 243 robots on staff were "fired" early in 2019. Complaints from customers and employees created more work, rather than saving labor costs.[69]

Of course, people will be more accepting of robots if they look human. Hanson Robotics (private, hansonrobotics.com) specializes in making robots that look life-like, can simulate personalities and facial expressions, and can socialize with humans. These robots are designed to learn how to be more human through interactions with humans. However, Hanson's robots are focused on the head and face, and usually do not have a body. On the other hand, PAL Robotics (private, pal-robotics.com) is working on perfecting the fine motor control of a robot's joints, arms, legs and hands to create a stand-alone robot that mimics the human skeleton. Of course, these robots are purely mechanical and do not have faces or personalities like Hanson's robots. Merging these two disciplines to create a humanoid is constrained by the limited AI processing ability. The next evolutionary step may be to put Hanson's head on PAL's body and put the "brain" in the cloud via a 5G connection.

SUMMARY

We expect 5G to live up to the hype. There are too many applications that have been waiting for a real-time communication network with these capabilities. Unlike previous generations of mobile service, commercial customers are waiting to use this service, rather than having to be sold on it. On the retail side, as was discussed, some selling will be required.

The network upgrade to 5G will be expensive and will take time. But, since the 4G infrastructure can be used, the timeframe will be a couple of years, not many years. Also, 5G is not a political hot button, so there will be little governmental resistance to the infrastructure construction that needs to occur. And the 5G buildout will proceed despite the China-US trade war and any economic slowdowns that might occur.

There are two important common threads throughout all of this 5G discussion: the cloud and edge computing. Managing and processing data from 5G applications makes the most sense in the cloud. But, mission critical applications, such as autonomous driving, will require edge computing.

In the short term, aside from cloud and edge computing, the highest level of activity will be with the network equipment makers. The Huawei ban will create opportunities for other equipment makers to catch up to the market leader. Of course, as the buildout matures, demand for replacement equipment and maintenance will be steady, but not growing. When the developed world becomes saturated with 5G in the 2023-2024 time frame, it will also become more evident if the low-earth orbit (LEO) satellite megaconstellation strategy is going to work.

Investment opportunities in 5G rely on timing as much as on the companies themselves. Our recommended strategy is as follows:

• I**mmediate focus:** Now while the 5G infrastructure is actually being built

The Cloud – Microsoft is the primary cloud play. AWS is less than 4% of Amazon's total revenue, so it's hard to financially engineer a way to isolate the AWS component. To make the cloud work, data storage and security will be key products that are purchased by these platforms. NetApp is still the purest storage play within our investment parameters. Cisco is the best security provider. In the previous quarter, Cisco provided a positive outlook, while NetApp lowered its short-term outlook due to a rare execution misstep, unexpectedly low renewals of maintenance contracts. In the latest quarter, the roles were reversed as Cisco had to lower its outlook for 2020Q1, despite beating analyst expectations, as the China-US trade war finally had an effect on revenue. On the other hand, NetApp handily beat analyst earnings estimates and raised its outlook for 2020Q2 based on new cloud partnerships with Microsoft Azure and Google Cloud.

"Opportunities in 5G rely on timing as much as on the companies themselves."

The continued strong growth of cloud services indicates that corporations are moving their business processes to the major data-center platforms. This can only mean that cloud services, such as security and storage, will also grow. While the trade war is expected to delay the recovery of the semiconductor

market, the corporate market's focus on 5G and the cloud may help balance that loss of demand.

Edge computing – This will rely on specialized chips and memory. Nvidia is the most immediate play on custom AI chips and memory chip makers. Regarding the latter, it is not immediately clear how much memory storage needs to be located on the edge since 5G allows data transfer to the cloud on a regular, or real-time, basis. However, the large num-ber of edge computing devices is a driver at this stage. The actual computers themselves are com-modities – the focus should be on the processor and memory.

AI – The cloud and edge computing are important because of AI. For obvious reasons, proprietary AI software development is being undertaken by the device companies themselves. General research is being done in academia and the military. So, there are no good direct investments in AI software. The exception might be if Palantir goes public.

Network equipment – Ericsson, Nokia and, to some extent, Samsung, will benefit from the Huawei ban in the US. Huawei is not a reliable vendor, due to the political uncertainty of the trade war and any ongoing fallout that may result. Outside the US, Huawei will remain strong primarily due to its 25% lower cost.

IoT and sensors, including autos – The "smart home" is an area of interest, especially in light of the aging population in the US and abroad. Companies that combine 5G and AI with fundamentally strong device/appliance businesses are the most attractive. Investing in the underlying vision nd voice sensor makers might make sense. However, given the vast universe of sensor makers, more research would need to be done to distinguish them. The exception to this would be the auto sector. The intense competition among auto makers and auto parts makers to become the first in autonomous driving is causing the development of cutting-edge vision sensors, AI, computers and peripherals to come together in a hurry. Because many of the key auto players are private, the public companies that make good, strategic acquisitions will be a good investment guide. Due to high private valuations, much of that M&A has not yet accelerated. But, given the disappointing IPO market this year, more startups may be happy with being acquired at lower valuations.

• **Intermediate focus:** later in 2019H2 as 5G becomes more available

Smartphone and apps – Consumer adoption of 5G smartphones and smartphone apps will become evident in this timeframe. If the development of compelling 5G-enabled apps lags, then this focus should slip to 2020. Games and entertainment will be a key driver in consumer acceptance of 5G; expect industry consolidation and restructuring as a result.

• **Long term focus:** 2020 and beyond The potential is significant for 5G-driven advances in medical and agricultural technology and in mass market uses of human-like or human-acting robots. These remain in early stages of development and the viability of the technology is still in question. While these sectors are worth monitoring, they will be appropriate for focus well beyond 2020. Getting internet access, let alone 5G, to rural and under-developed parts of the world, including the US, is a major, world-wide social issue. As the technology gap grows wider, the digital divide grows deeper and the potential for civil unrest grows. Public-private partnerships, NGOs, and the effort of many non-profits might be the only way to attack this problem, as it

is a capital-intensive problem with no clear solution and no clear path to profits. LEO satellites appear to be the most viable solution at this time. As discussed above, it's possible that solar-powered 5G/wifi microcells in conjunction with satellites will be viable.

Closing thoughts: unintended consequences

Employment – Clearly 5G will spur greater use of automation, which contributes to fears of job loss. Low level, manual labor jobs in the factory will continue to decline as a new generation of 5G enabled robots accelerates the decades-long trend begun by stationary robots. Even higher paying jobs in transportation, such as truck driving, will be lost. However, the 5G network is far more advanced and the equipment it enables will be in greater need of programming, calibration and maintenance. These equipment installation and maintenance jobs will require skilled labor, including at least rudimentary understanding of wireless communication, the internet, and mechanical engineering. These will be even higher paying jobs and, given the sheer numbers of small cell sites needed for needed for 5G, it will be necessary to have many of these workers. These jobs will not require a college degree, but rather advanced technical training. Community colleges and technical schools would benefit from this while lower-tier four-year colleges would likely suffer. Of course, we still need a steady flow of scientists and engineers, so mid- and upper-tier colleges will still have customers as long as scientists and engineers continue to be paid above-average wages.

Waste – If the vast number of IoT devices being envisioned comes to pass (and there is every indication that it will), then there will soon be a significant amount of electronic waste. Society already is woefully unable to handle its waste problems. Recycling must become more engrained into the supply cycle. This is especial-ly important for those commodities that are in danger of being in short supply. But recycling alone cannot solve the e-waste problem.[70] Rather than replace de-vices when broken or during an upgrade cycle, devices should be fixed. This is especially true of smartphones. Alternatively, the 5G network might be the solution here. If computing and other functionality can be eas-ily accessed via the network, the smartphone does not need to be smart; it only needs to be a simple way to ac-cess external resources. Simple cell phones with a nice screen can last a very long time.

- Miral Kim-E

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DISCLOSURE

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Appendix A: A Quick Overview of Artificial Intelligence

The ultimate goal of AI research is to develop a machine that is indistinguishable from a human. Despite tremendous strides in understanding how the human brain and human body work, this goal has proved elusive. However, when the focus has shifted away from machines that think, to machines that do a specific task, AI has proven very successful. These "expert systems" gave rise to speech recognition and Deep Blue, the first chess-playing computer to beat a reigning world chess champion. To solve their assigned "problems," both relied on using tremendous amounts of data (vastly different speech samples and chess games, respectively) in order to "train" the algorithms to recognize spoken words or to make the best chess moves.

Deep Blue illustrates the two aspects of an AI algorithm. First is the recognition of something, e.g., an opponent's chess move. The second is the response to that something, i.e. making a chess move.

The current state-of-the-art in AI recognition algorithms involves what is known as "neural networks" and "deep learning." Neural networks are large systems of equations with large numbers of unknown variables. This is similar to how we envision the human brain: a huge set of neurons waiting to be turned on with pieces of information. Neural networks are designed to recognize patterns through deep learning, i.e., exposing the algorithm to a vast number of examples (thousands, millions, as many as possible) in order to give values to those variables. For example, to recognize a tree, the neural network will be exposed to pictures of trees of all varieties, shapes, sizes, light conditions, with and without other objects, in different locations, etc., until it correctly identifies a random picture of a tree as a tree.

At this stage, a more efficient way of training neural networks has not been discovered. So, deep learning requires all the training data to be stored and re-used each time a new neural network is created. Of course, this requires massive amounts of data storage to hold all the writing, sound, image and video samples. Efforts are being directed primarily to voice and visual recognition. As is the case with many cutting-edge technologies, most of the early research and success was developed for national defense purposes. Post-9/11, AI research focused on identifying threats by monitoring telephone calls, internet traffic, and camera images.

In the private sector, the greatest successes to date in the area of AI responses are in voice AI. It started with automated telephone operators/attendants, where commands and responses were limited. It has expanded to voice attendants on smartphone and "smart home" systems, which are rudimentary Internet-of-Things systems that a person can control via voice on cloud platforms such Amazon Alexa, Apple Siri or Google Home. The systems can include music speakers, security cameras, thermostats, light switches, door locks, window shades, EV charging units, and more. Here, AI is used to recognize and interpret a variety of voice commands to control connected IoT devices.

Visual recognition is messier but advances are being made. In controlled environments, such as using a facial image to unlock a phone, AI works well enough as long as a consistent view is used. It is becoming more possible to recognize a face in a moving crowd and when part of the face is out of view. Disney is able to do this in its theme parks.[71] In the DARPA Robotics Challenge,[72] robots are able to semi-autonomously complete a series of difficult tasks that mimic a human response to a disaster. And, autonomous vehicles are able to recognize nearby cars and objects well enough to drive without human intervention on highways.

Despite these advances, there is still much left to be done. Nothing is working perfectly, as is evident from the deaths that have occurred while drivers were using the autonomous driving feature on Tesla automobiles. There is plenty of fast computing power, fast memory and, with 5G, fast communication. But the instructions coming out of AI algorithms are not always correct. This is because AI algorithms cannot yet think, i.e., they cannot reasonably extrapolate from their known set of "experiences" to determine the correct course of action when presented with a new experience. Tesla is attacking this problem by storing video from all of its autos' cameras and other sensors in order to create a vast library of data with which to train its autonomous driving algorithms. This works for humans too; wisdom often results from a tremendous amount of experience.

At the present time, it is not clear if there is any technological limitation to creating a thinking machine. The human brain has roughly 100 billion neurons. The largest neural network to date can hold about 16 million neurons, the size of a frog's brain.[73] Do frogs think? While fascinating, the technical and ethical issues surrounding the creation of a thinking machine is beyond the scope of this report.

Endnotes

1. https://en.wikipedia.org/wiki/History_of_mobile_phones
https://en.wikipedia.org/wiki/Personal_computer

2. "Mobile data traffic surpasses voice", Ericsson press release, March 23, 2010
https://www.ericsson.com/en/press-releases/2010/3/mobile-data-traffic-surpasses-voice

3. "Ericsson Mobility Report Q4 2018 update", Ericsson, 2018 Q4
https://www.ericsson.com/en/mobility-report/reports/q4-update-2018
For regular updates: https://www.ericsson.com/en/mobility-report

4. The need to access the broader telephony/internet network precludes direct device-to-device communication, such as walkie-talkies, Citizen Band ("CB") radio, and shortwave radio.

5. "How laptops overtook the world", Charles Arthur, The Guardian, October 28, 2009
https://www.theguardian.com/technology/2009/oct/28/laptops-sales-desktop-computers

6. "Everything you need to know about 5G", IEEE Spectrum, January 27, 2017
https://spectrum.ieee.org/video/telecom/wireless/everything-you-need-to-know-about-5g

7. "What is 5G?", Sascha Segan, PC World, January 28, 2019
https://www.pcmag.com/article/345387/what-is-5g

8. "Cell Phone and Cancer Risk", National Cancer Institute, January 9, 2019
https://www.cancer.gov/about-cancer/causes-prevention/risk/radiation/cell-phones-fact-sheet

9. "The Top 10 Competitiveness Enterprises in the Optical Communications Industries of China & Global market - 2018", Network Telecom Information Institute http://list.nti.news/index.html

10. "Top 100 Tower Companies in the U.S.", Wireless Estimator.com, December 2, 2018
http://wirelessestimator.com/top-100-us-tower-companies-list/

11. "Analyst Angle: The rise and outlook of antennas in 5G", Jake Saunders, RCR Wireless News, June 24, 2018
https://www.rcrwireless.com/20180624/wireless/analyst-angle-the-rise-and-outlook-of-antennas-in-5g

12. Information taken from the OneWeb website as of 5/22/19 www.oneweb.world

13. "Amazon planning 3,236-satellite constellation for internet connectivity", Caleb Henry, Space News, April 4, 2019
https://spacenews.com/amazon-planning-3236-satellite-constellation-for-internet-connectivity/

14. "Satellite data business is Amazon's next disruption target", Sandra Erwin, Space News, November 28, 2018
https://spacenews.com/satellite-data-business-is-amazons-next-disruption-target/

15. "Huawei Now World's Largest Telecom Equipment-Maker", Jason Tan, Caixin, March 19, 2018
https://www.caixinglobal.com/2018-03-19/huawei-now-worlds-largest-telecom-equipment-maker-101223256.html

16. While Microsoft does not explicitly break out Azure revenue, it can be calculated from the revenue and growth statistics reported for the various products/services that include Azure.

17. "Mirai (malware)", Wikipedia, last updated May 6, 2019
https://en.wikipedia.org/wiki/Mirai_(malware)

18. "Denial-of-service attack; Distributed DoS", Wikipedia, last updated May 13, 2019 https://en.wikipedia.org/wiki/Denial_of_Service_attack#Distributed_attack

19. "World's 10 biggest smartphone companies", Gadgets Now Bureau, Times of India, February 15, 2019
https://timesofindia.indiatimes.com/gadgets-news/worlds-10-biggest-smartphone-companies/photostory/68011218.cms

20. "Top 7 Smartphone Display Manufacturers", All Spares, November 29, 2018,
https://all-spares.com/en/articles-and-video/top-7-smartphone-display-manufacturers.html

21. "How to choose the best camera phone: sensor size vs megapixels", Karen Haslam, Macworld, April 25, 2018
https://www.macworld.co.uk/how-to/iphone/best-camera-phone-megapixels-3502115/

22. "Camera Chipset Manufacturer", CNOEM, 2017
http://cnoemphone.net/industry/industry-chain/camera-chipset-manufacturer

23. "All the Sensors in Your Smartphone, and How They Work", David Nield, Gizmodo, July 23, 2017
https://gizmodo.com/all-the-sensors-in-your-smartphone-and-how-they-work-1797121002

24. "IoT Sensors Market", Markets and Markets, 2017
https://www.marketsandmarkets.com/Market-Reports/sensors-iot-market-26520972.html

25. "Apple iPhone X: MEMS Microphones from Goertek, Knowles, and AAC Technologies", System Plus Consulting, July 3, 2018,
https://www.systemplus.fr/reverse-costing-reports/apple-iphone-x-mems-microphones-from-goertek-knowles-and-aac-technologies/

26. "Top 10 Lithium-ion Battery Manufacturers in the World", ELE Times, August 16, 2018
https://www.eletimes.com/top-10-lithium-ion-battery-manufacturers-in-the-world

27. "The search for new geologic sources of lithium could power a clean future", Carolyn Gramling, Science News, May 7, 2019
https://www.sciencenews.org/article/search-new-geologic-sources-lithium-could-power-clean-future

28. "Cobalt — Production remains steady but supply security fears remain high", S&P Global on mining.com, July 16, 2018
http://www.mining.com/web/cobalt-production-remains-steady-supply-security-fears-remain-high/

29. "Lithium-ion Batteries", Physics Central,
http://www.physicscentral.com/explore/action/lithium.cfm

30. "Top Lithium-mining Companies", Priscilla Barrera, Investing News, May 7, 2019
https://investingnews.com/daily/resource-investing/battery-metals-investing/lithium-investing/top-lithium-producers/

31. "5 Top Cobalt-mining Companies", Amanda Kay, Investing News, July 18, 2018
https://investingnews.com/daily/resource-investing/battery-metals-investing/cobalt-investing/top-cobalt-producing-companies/

32. "Number of apps available in leading app stores as of 1st quarter 2019", Statistica, 2019
https://www.statista.com/statistics/276623/number-of-apps-available-in-leading-app-stores/

33. "Global App Revenue Grew 23% in 2018 to More Than $71 Billion on iOS and Google Play", Randy Nelson, Sensor Tower, January 16, 2019
https://sensortower.com/blog/app-revenue-and-downloads-2018

34. Itunes Charts are updated weekly
Free Apps: https://www.apple.com/itunes/charts/free-apps/
Paid Apps: https://www.apple.com/itunes/charts/paid-apps/

35. "The Mobile Gaming Industry: Statistics, Revenue, Demographics, More", Mediakix, February 6, 2019
http://mediakix.com/mobile-gaming-industry-statistics-market-revenue/#gs.bu3nsk

36. "Blizzard is interested in bringing all of its franchises to mobile", Kellen Beck, Mashable, November 8, 2018,
https://mashable.com/article/blizzard-mobile-games/

37. "Mobile Hit New Milestones in Q1 2019", Lexi Sydow, App Annie, April 9, 2019,
https://www.appannie.com/en/insights/market-data/mobile-hit-new-milestones-in-q1-2019/

38. Ibid.

39. "25 Best Augmented Reality Games for Android and iOS", Think Mobiles, as of May 2019,
https://thinkmobiles.com/blog/best-augmented-reality-games/

40. "The 51 Best VR Games of 2018", CNet, as of May 2019,
https://www.cnet.com/pictures/best-vr-games/

41. "The Best VR Headsets for 2019", Will Greenwald, PC Magazine, April 30, 2019,
https://www.pcmag.com/article/342537/the-best-virtual-reality-vr-headsets

42. "Mobile eCommerce Stats in 2018 and the Future Online Shopping Trends of mCommerce", Justin Smith, OuterBox, April 22, 2019
https://www.outerboxdesign.com/web-design-articles/mobile-ecommerce-statistics

43. Ibid.

44. "U.S. Smartwatch Sales See Strong Gains", NPD Report, February 12, 2019,
https://www.npd.com/wps/portal/npd/us/news/press-releases/2019/us-smartwatch-sales-see-strong-gains-according-to-new-npd-report/

45. Cyrcadia Health website, http://cyrcadiahealth.com

46. "Wearable Health Devices—Vital Sign Monitoring, Systems and Technologies", Duarte Dias, Joao Paulo Silva Cunha, Sensors, published by MDPI, July 25, 2018
https://www.mdpi.com/1424-8220/18/8/2414

47. "State of the IoT 2018: Number of IoT devices now at 7B – Market accelerating", IoT Analytics, August 8, 2018
https://iot-analytics.com/state-of-the-iot-update-q1-q2-2018-number-of-iot-devices-now-7b/

48. "Three Sensor Types Drive Autonomous Vehicles", Gert Rudolph & Uwe Voelzke, Sensors Online, November 10, 2017,
https://www.sensorsmag.com/components/three-sensor-types-drive-autonomous-vehicles

49. "LiDAR vs. RADAR", Ann Neal, Sensors Online, April 24, 2018,
https://www.sensorsmag.com/components/lidar-vs-radar

50. "Waymo LiDAR sensor now available for robotics companies", Steve Crowe, The Robot Report, March 6, 2019
https://www.therobotreport.com/waymo-lidar-sensor-now-available/

51. "How 10 leading companies are trying to make powerful, low-cost lidar", Timothy B. Lee, Ars Technica, February 1, 2019
https://arstechnica.com/cars/2019/02/the-ars-technica-guide-to-the-lidar-industry/

52. "Radar Sensors Market Research Report - Global Forecast 2023", Market Research Future, May 2019
https://www.marketresearchfuture.com/reports/radar-sensors-market-4159

53. "Top 5 Companies in the Smart Home Appliances Industry", Technavio, April 13, 2018
https://blog.technavio.com/blog/top-5-companies-smart-home-appliances

54. "Which companies are making driverless cars?", Christina Mercer, Tom Macauley, Techworld, March 12, 2019 https://www.techworld.com/picture-gallery/data/-companies-working-on-driverless-cars-3641537/

55. "Reports, Trends & Statistics", American Trucking Associations, taken from website on 5/21/19,
https://www.trucking.org/News_and_Information_Reports.aspx

56. "Summary of Hours of Service Regulations", Federal Motor Carrier Safety Administration, March 9, 2017
https://www.fmcsa.dot.gov/regulations/hours-service/summary-hours-service-regulations

57. "Starsky Robotics tests self-driving truck on Florida highway", Clarissa Hawes, Freight Waves, May 20, 2019
https://www.freightwaves.com/news/starsky-robotics-tests-self-driving-truck-on-florida-highway

58. "Self-driving truck startup TuSimple will haul mail for USPS in two-week pilot", Kirsten Korosec, TechCrunch, May 21, 2019
https://techcrunch.com/2019/05/21/self-driving-truck-startup-tusimple-will-haul-mail-for-usps-in-two-week-pilot/

59. "Fourth Quarter Truck Driver Turnover Rate Shows Muddled Picture", press release, American Trucking Associations, March 13, 2019
https://www.trucking.org/article/Fourth-Quarter-Truck-Driver-Turnover-Rate-Shows-Muddled-Picture

60. DMV Takes Next Step To Allow Light-Duty Autonomous Delivery Vehicles", California DMV, April 12, 2019
https://www.dmv.ca.gov/portal/dmv/detail/pubs/newsrel/2019/2019_12

61. "Meet Boston Dynamics' family of robots", CNET, YouTube, April 17, 2018
https://www.youtube.com/watch?v=7Q3YW-3KCzU

62. "Spirit animals: 9 revolutionary robots inspired by real-world creatures", Luke Dormehl, Digital Trends, August 29, 2018
https://www.digitaltrends.com/cool-tech/biomimicry-robots/

"Backflipping MIT Mini Cheetah", MIT, YouTube, February 28, 2019
https://www.youtube.com/watch?v=xNeZWP5Mx9s

"This Wiggly Fish Is the Most Advanced Robot of Its Kind", Michael Greshko, National Geographic, March 21, 2018
https://news.nationalgeographic.com/2018/03/sofi-robotic-fish-mit-reefs-oceans-environment-science/

"Festo's Fantastical Flying Robots", IEEE Spectrum, YouTube, December 22, 2016
https://www.youtube.com/watch?v=g_qhMVNw7O4

63. "Chinese robot dentist is first to fit implants in patient's mouth without any human involvement", Alice Yan, South China Morning Post, September 21, 2017
https://www.scmp.com/news/china/article/2112197/chinese-robot-dentist-first-fit-implants-patients-mouth-without-any-human

64. Intuitive website: https://www.intuitive.com/en-us/products-and-services/da-vinci

65. "Lindbergh operation", Wikipedia, last updated September 15, 2018.
https://en.wikipedia.org/wiki/Lindbergh_operation

66. "China completes world's first 5G remote surgery in test on animal", South China Morning Post, YouTube, January 11, 2019,
https://www.youtube.com/watch?v=yFR61jjL1vo

67. "These robots work together to achieve a common goal", Bryan Clark, The Next Web, February 12, 2018
https://thenextweb.com/artificial-intelligence/2018/02/12/these-robots-work-together-to-achieve-a-common-goal/

68. "Swarm Robotics", Wikipedia, last updated March 28, 2019
https://en.wikipedia.org/wiki/Swarm_robotics

"Meet the dazzling flying machines of the future", Raffaello D'Andrea, TED, YouTube, March 22, 2016
https://www.youtube.com/watch?v=RCXGpEmFbOw

69. "Japan's Henn Na Hotel fires half its robot workforce, Esther Hertzfeld, Hotel Management, January 31, 2019
https://www.hotelmanagement.net/tech/japan-s-henn-na-hotel-fires-half-its-robot-workforce

70. "Recycling Is Not The Answer To The E-Waste Crisis", Vianney Vaute, Forbes, October 29, 2018
https://www.forbes.com/sites/vianneyvaute/2018/10/29/recycling-is-not-the-answer-to-the-e-waste-crisis/#581068e07381

71. "Deep Spatial Pyramid for Person Re-identification", Slawomir Bak and Peter Carr, Disney Research, 2017 14th IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS), August 29 – September 1, 2017
https://s3-us-west-1.amazonaws.com/disneyresearch/wp-content/uploads/20170814145721/Deep-Spatial-Pyramid-for-Person-Re-identification-Paper.pdf

72. DARPA Robotics Challenge Finals 2015, archived website, https://archive.darpa.mil/roboticschallenge/

73. "New AI method increases the power of artificial neural networks", Eindhovern University of Technology, Phys.org, June 20, 2018
https://phys.org/news/2018-06-ai-method-power-artificial-neural.html