5G ultra-low-power network for collective ephemeral hyper-local context

Furaha Damien[1]
McGill University,
School of Computer Science
Montreal, Quebec, Canada
Email: furaha.damien@mail.mcgill.ca

Jeffrey Dungeon[1,2]
reelyActive
Montreal, Quebec, Canada
Email: jeff@reelyactive.com

Abstract — It is common today to find in any given physical space a mix of devices that are radio-identifiable with the ability to communicate wirelessly with an IP protocol. In our previous paper[2] we demonstrated a machine-readable real-time representation of the real-world on a human scale, something called hyperlocal context, and how co-located infrastructure can share this information to mutual benefit over an IP network, typically WiFi if wireless. Today, with the next to come commercial deployment of 5G networks, it becomes envisageable for co-located infrastructure to communicate over 5G instead. In this paper we examine how the novel properties of 5G, especially low latency,facilitate the exchange of hyperlocal context among co-located wireless devices. Specifically, we compare how mobile devices like smartphones, mobile and RFID readers can establish ephemeral connections to exchange information as they pass through the space, when using 5G as compared to when using another wireless communication protocol like WiFi. We demonstrate that for sharing hyperlocal context, which requires a latency of no more than 1 second, WiFi is unsuitable. However, based on the findings that we present, we show that 5G is theoretically suitable. Moreover, the low latency and high speed properties of 5G allow for a ultra-lower-power exchange of information than WiFi for applications such as the presented scenario. We recommend other researchers perform tests of 5G in this context in a variety of typical real-world situations.

Keywords — IoT, 5G, wireless machine to machine communication, Bluetooth Low Energy, WI-FI, ZigBee, ephemeral networks, hyer-local context, 4G-LTE, Low-Power-Wider Area Network(LPWA), Radi-Frequency Identification(RFID), RAIN

1. Introduction

The Internet of Things has been a crucial component of the industry 4.0. Over the last few years, the growth of this industry has led to a massive growth in the number of connected devices produced. Indeed, Statista[3] reports that the number of installed connected devices will increase to 75 billion by 2025 representing a five-fold increase ten years. However, this increase in connected device will come with the need to keep meet their service requests. One area that needs massive evolution is how devices listen to packet traffic and forward location and payload to other devices. This includes how data from one device is interpreted by another device. In their paper,[2], in 2015, reelyActive, for example, proposed a software library that would help in this situation. Building on top of that, in 2017, reelyActive proposed[1] characteristics of contextual real-time location systems. They observed that the efficiency of how collocation systems discover one another and exchange data, is affected by the speed at which crowd-sensing between both passive and active RFID systems happens. This dependency on the speed at which data packets can be listened to and processed will increase with the surge in smart devices, a thing that will affect power consumption efficiency. In the quest to keep up with all wireless communications and remain connected, every single device will need to continuously connect and disconnect to several other devices. This will be very costly in terms of maintaining battery life. The current wireless communication protocols provide less efficiency in maintaining low-power usage in such situations. Every time a new strong WI-FI, Bluetooth Low Energy(BLE), LTE or ZigBee network is established, a device will try to disconnect from the previous one in a quest to establish a stronger connection[6]. In addition to that, in terms of WI-FI, the device continues scanning for even stronger networks.

Several studies have shown the cost of these ephemeral connections, with several others looking into how this problem can be solved. In this paper, we propose a new approach that will take advantage of the next to come 5G networks to reduce energy consumption in IoT devices while at the same time leveraging the high speed and low latency provided by 5G

This paper is organized as follows. Firstly(II), we look at the current IoT requirements for real-time location systems in terms of latency and power consumption. We then(III) give a broad overview of the current wireless communication protocols. Then(IV) we provide a clear look into the energy needs associated with these protocols. We later(V) present some of the current technologies developed to address the shortfalls especially in terms of power maintenance. Lastly(VI) We present 5G as a solution to the current power and low latency need of IoT devices by analyzing its latency and power consumption using a mathematical model[26]. Finally, we give a conclusion on how we think we can efficiently leverage the benefits of 5G.

2. Real-time location systems requirements

To maintain the efficiency of Machine to Machine communication the Internet of Things has to meet certain requirements[4], 1. However, there are different[5] IoT applications and it is difficult to have one standard that caters for all applications. One requirement that has to be met by all applications however, is Low latency. Again, this is also very diverse ranging from delay-tolerant applications to applications that require low latency[4]. In this paper, we focus on real-time locations systems that have an acceptable latency of less than a second[4].
Another requirement that IoT devices have to meet is long battery life[4]. Most IoT devices are expected to operate for a long time without human intervention. Research[6] has shown that most energy used in IoT is due to communication. This will become an even bigger problem for small devices like RFID beacons since of the 75 billion devices expected as of 2025, 19 billion will be BLE and RAIN devices. This is the reason why a low-power wireless communication protocol is needed for IoT.

3. Current wireless communication protocols

Several wireless communication technologies have been developed for the Internet of Things. These technologies cater for both short-range and long-range connectivities.

3.1. WI-FI

This is probably the most popular of all wireless communication protocols. It has had tremendous growth over the last few years and has developed to an almost defacto protocol for data transfer in the Wireless Local Area Networking (WLAN). This radio communication technology has evolved through different version specified by various IEEE 802.11 protocol standards. However, most of these have had one common shortfall: fairly large power consumption. To counter this shortfall, in 2006 the WI-FI Alliance started developing a technology to reduce energy consumption. They introduced the DUTY CYCLING[5] technology that allows chips to stay in sleep mode. Nonetheless, even with this WI-FI still has higher power consumption compared to some other standards designed to support wireless personal area network (PAN) applications.

3.2. IEEE 802.15.4

IEEE 802.15.4[7] is a technical standard which defines the operation of low-rate wireless personal area networks (LR-WPANs). This technology aims to offer low-cost and low-speed ubiquitous machine to machine communication. It is the technology onto which ZigBee8 protocol and 6LoWPAN protocol is based. This technology uses way less power compared to other technologies like WI-FI due to its little underlying infrastructure. For example, 6LoWPAN protocol brings Internet Protocol into small and low-cost smart devices.

3.3. Bluetooth Low Energy(BLE)

[1,2] BLE is another wireless personal area network technology that provides low power communication between small smart devices over short distances. Working at 2.4 GHz radio frequencies unlicensed band, BLE is based on classic Bluetooth. It leverages the current surge in smart devices to open up novel application scenarios such as using smartphone connectivity to monitor BLE wearables[9].

3.4. Cellular technologies

Cellular communication uses a two way radio system between a mobile unit and a wireless network to establish a mobile communication. It has evolved over the years from 1G in 1980s that allowed voice-only communication via ”brick phones” to the current 3GPP technologies like GSM and LTE that support more demanding services like gaming, HD mobile TV, video conferencing, and 3D TV[10]. Cellular technologies also allow machine to machine to machine communication over very long distances. There is a bigger revolution in these technologies with the coming of new radio access technologies like narrow-Band IoT(NB-IoT) that are specifically tailored to form a Low Power Wide Area (LPWA) IoT[11].

Most of the devices that make up the internet of things are small smart devices in smart homes and industries that use short range communication protocols like zigBee and BLE. However, these have less bandwidth and low latency making them not suitable for the next generation IoT. There is thus a need toto more ubiquitous transmission technologies like WI-FI. On the other hand, WI-FI provides a greater bandwidth and much faster speed. However, this technology fails if the devices are not connected to the same network and even worse, its power consumption trumps any of the short range communication protocols. Real time location system require a communication protocol that combines greater bandwidth and low latency as shown in Figure 1.

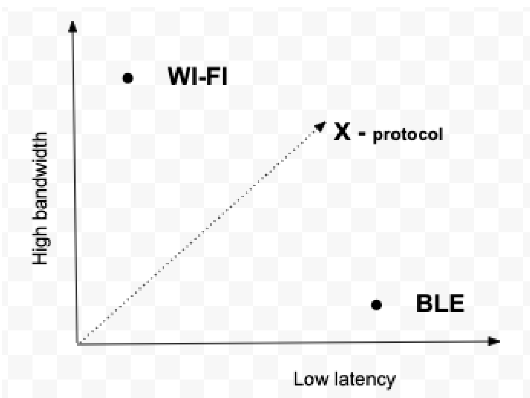

Figure 1 : real time location systems require protocol X that maximizes data transfer and low latency

Current cellular technologies also consume an enormous amount of energy. With the Information Communication

Technology sector contributing 10% [13] to the world's power consumption. 0.5 % of the energy consumption in the ICT sector is contributed by the mobile communication networks. This trend is expect to grow even large with the increase in devices that require cellular communication.

4. Attempts to obtain a low-power machine to machine communication

Wireless communication protocols need to evolve to allow for efficient machine to machine communication. For this to happen, most wireless communication protocols have undergone enormous version revisions over the years. Like earlier mentioned, the key flaws in almost all the current communication technologies are communication speed and energy consumption. In an attempt to reduce power consumption, in 2006, WI-FI alliance started[5] using duty cycling. A duty cycle is the fraction of one period in which a signal or system is active[14]. This technology reduces the energy consumption caused by idle listening in Wireless Sensor Networks (WSNs)[15]. The WI-FI alliance has also introduced Tunneled Direct Link Setup(TDLS)[16]. This is a standard for creating direct links between devices and uses an optimization trick that allows two devices to decide if they will connect to each other via WI-FI Direct or not based on the signal strength between them. Another technology that has undergone revision to reduce energy consumption and latency is Bluetooth Low Energy. To increase the battery lifespan of BLE beacons, some manufacturers have moved from the traditional coin-cell batteries to larger size alkaline batteries like AA or AAA[17]. These AA or AAA batteries however, undermine the whole essence of BLE beacons as they increase the size and weight[17]. BLE beacons are supposed to be highly scalable due to their minimal protocol and easy deployment. To solve this problem, some manufacturers have developed beacons with energy harvesting capabilities. Several researchers[18] are currently working on energy harvesting wireless sensor nodes.

5. 5G and its solutions to power consumption and latency

5.1. 5G Overview

5G is the fifth generation cellular network technology that follows previous other generations namely 2G, 3G, 4G and their associated technologies like Global Systems for Mobile Communications(GSM), Long-Term Evolution(LTE) and others. The technology governed by 3GPP is based on the new 5G New Radio(5G NR) radio access technology[19]. 5G technologies use radio waves for devices to communicate with a local antenna. The antennas are connected to the internet and telephone network using the high bandwidth optical fiber cables or wireless backhaul connection. When a user moves from one antenna to another, their device gets handed off to the new antennae. Unlike previous technologies, 5G comes with a new technology called beamforming[29]. This technology will allow service stations to do all the heavy lifting by looking for nearby antennas and handing the device to the nearest antenna instead of the device having to establish its own antenna connection.

Unlike the previous generation of cellular communication, 5G will be based on millimeter waves[20]. Millimeter-wave antennas are smaller than the large antennas used in previous cellular networks. Millimeter waves, however, unlike other radio waves can not move through walls. As a result, 5G antennas are super small and can be embedded even under your living room carpet or on the walls, unlike the previous antennas that had to be placed on top of the roofs. In addition to that, the technology will come with Multiple-Input Multiple-Output(MIM0)[21] technique. This technique increases data rates by allowing multiple antennas to communicate with a device, while the device does likewise. These two are some of the techniques that are being used to achieve an air latency of up to 14 milliseconds. Though still early in the deployment process, Verizon reports[22] that it has been able to achieve an impressive 30 milliseconds air latency in its deployments. Another key feature of the 5G technology is that it aims to reduce energy use by up to 10% of the current 4G networks consumption. This will mostly be due to reduced power requirements for base antennas and devices as the enhanced data rates will reduce packet latency. This low packet latency will allow short data transmission periods. As a result there will be longer duty cycling[5] periods. In so doing the battery lifetime will be extended.

5.2. Leveraging the impact of low-power and low latency 5G networks in IOT

5G will come with enormous benefits to the sector of the Internet of Things. 5G is expected to enhance network bandwidth to accommodate speeds of up to 10-100 times faster than the current cellular connections can provide[23]. This will significantly reduce the lag time between initial data transfer and network response. The other benefit of 5G referred to earlier on is its ability to reduce the power consumption of connected smart devices by up to 10%. This will be hugely significant in small smart device devices as they will have the ability to maintain the coil-cell battery for up to 10 years or more. These benefits of 5G will be particularly important in collective ephemeral hyperlocal context. With research showing that most of the power consumption by IoT devices is spent on communication[6], finding an efficient way for devices that constantly connect and disconnect to a network will be important in reducing power consumption in Machine to Machine communication. The key step toward countering this problem of ephemeral hyperlocal context is making 5G network the defacto communication protocol for all devices that have built-in sim cards, rather than having other communication protocols. This will significantly reduce the power consumption by machine to machine communication. As seen below, the power consumption of devices running on 5G is significantly lower than those running on WI-FI.

For devices with no inbuilt SIM card slot, we need to take a different approach to get the same benefit. Devices like BLE beacons and other passive and active RFID systems communicate with each other via electric fields. This is an efficient way for these tags and sensors to communicate.5G will helper when all the data that is obtained by passive readers form active tags is to be processed. We can not run packet processing software[2] on the active tags themselves. This will compromise the minimalistic nature and easy deployment of RFID devices. To solve this problem, we propose two solutions. First, devices will have to have a common pool, like a server where where they can send all their data using their underlying BLE protocol. Another group of devices can send their data to a different server. This is where the benefits of 5G can be leveraged. The low latency will allow the instantaneous transfer of data from the readers to the data pool, which may be a server in the cloud. The servers can now communicate amongst each other over 5G. Here the data can be processed and the right format sent back in near real-time. Figure 1 gives a good picture of the proposed infrastructure in IoT devices with non SIM cards

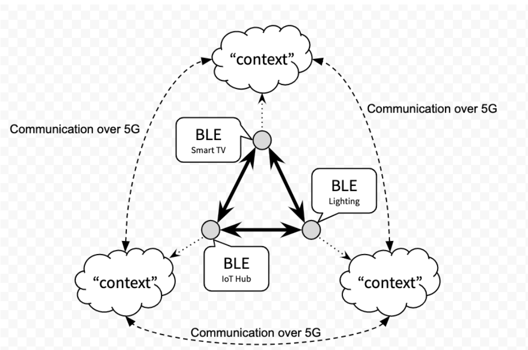

Figure 1 : devices with no sim card send the data to respective servers. the servers then communicate using 5G

Another approach that we propose for devices with no sim card is that of a "greedy sensor". Using the techniques of duty cycling, only one BLE sensor could be awake at a time. The sensor could obtain data packets from nearby beacons. Occasionally, the other BLE sensors on the network will wake up and connect to the greedy sensor which will then share its view to the other sensors. Likewise, we could use 5G to allow the "non-greedy" sensors to send data to their respective servers for processing. Figure 2 shows how this approach would work.

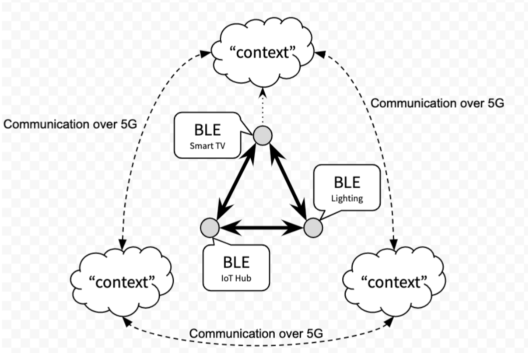

Figure 2 : Only one awake sensor listens to devices and shares its context with other sensors when they wake up.

In the two cases, we are reducing the energy consumption that would have been used by the devices to establish a new connection every time they moved to a different connection. With 5G being a wide area network, the deceives can communicate with each other purely via this cellular technology and through beamforming[24],25, the base stations that the devices are connected to can do all the heavy lifting of organizing antennas for the device. This will save the device a lot of energy.

5.3. 5G low latency and low-power evaluation

To evaluate how the proposed solution could reduce power consumption and time lag in data transfer, we used the model discussed in section 4.1. As shown in figure X, Our infrastructure allows short range smart devices to communicate using their native communication protocols. For example in BLE beacons, they would communicate over BLE. They would then send their data to their local servers which would in return communicate and exchange data using 5G. The total delay time for this process would then be that between the BLE beacons and the 5G delay incurred in the communication between servers. In the theoretical calculations below, we use 3 packets as proposed by iOS and android[source****], we let the advertising interval to be 100ms as recommended by Apple for iBeacons[28]. We use 30ms as the connection interval, the default for iOS devices. Form the model in section 4.1 [26], the latency for BLE is as follows:

$T_{discover(I_{adv},N_{adv})} =$
$(0.5.I_{adv} + T_{proc,disc}).exp^{\frac{2N_{adv}}{3(0.5.I_{adv}+T_{proc,disc})}}$
$= (0.5*100ms + 9.7ms).exp^{\frac{2(3)}{3(0.5*100ms+9.7ms}}$
$= 61.73ms$

$T_{connect(I_{adv},I_{conn},N_{adv})} = T_{discover(I_{adv},N_{adv})} + 3.I_{conn}$
$= 61.73 ms + 3*30ms$
$= 151.73ms$

$T_{transfer(I_{conn},N_{pkt})} = \frac{3}{2}.I_{conn}.N_{pkt}$

$$= \frac{3}{2} * 7.5ms * 3$$
$$= 135ms$$

The optimal latency for 5G networks is purported to be 1-4ms. This means that the total latency in our proposal adds up to 352.46ms with both the communication between the devices over BLE and that between servers over 5G put into consideration.

For devices with SIM cards, the commutation latency becomes less complicated. The devices do not have to go through the process of advertising, connection and data transfer. Since they can always be on the same 5G network, their total communication latency drops to 1-4ms for 5G compared to 85.144ms(VERIZON LTE)[27] if they were using 4G-LTE for instance.

Another communication protocol whose latency and power consumption we should consider is WIFI. This communication protocol has the highest latency of all the protocols that we have looked at. This is because, the total latency of WIFI accounts the time from when a device starts to scan networks, successfully connect to a specific Access Point, to when it obtains an IP address. A study[30] of 5 million mobile users and 7 million APs, showed that 80 percent of the devices take an average of 5 seconds to set up a successful connection. About 3 percent of the devices take a connection time cost larger than 15 seconds. Those that can not obtain an IP address within 30 seconds are timed out. This connection time cost does not include the round-trip delay time (RTD)[31] which is the time it takes for a packet of data to be exchanged between devices. The RTD is averages at 0.19 seconds[31] for 3 hops. All this put together, we can see that the time that it takes for a device to successfully connect to an IP address and send signals averages at just over 5seconds for 80 percent of the devices. Of this connection time cost, 47 percent[30] of it is spent on the scanning phase. This makes it even worse because longer scanning time lead to higher power consumption. This process repeats every time the device detects a new AP in it vicinity. As for scanning, the device will update the list of available AP's SSIDs every 100 ms[32].

This latency and energy consumption becomes very intense in terms of ephemeral connections. Devices would have to go through the process of advertising, connection and data transfer every time they join a network. On the other hand, if we let 5G be the defacto communication protocol the we will be able to leverage all the benefits talked of.

6. Conclusion

The increase in smart devices means that device will favour an efficient communication protocol that provides low energy consumption and low latency in machine type communication. In section 6.3, we showed that for the same number of packets of data, BLE would take 352ms to transmit data with Verizon 4G-LTE showing an 85.144ms latency[27] . 5G would do the same operation in a meagre 4ms. We showed that WIFI averages total latency of at least 5 seconds for discovery to eventual transfer of data packets in 80 percent of the mobile devices studied with 3 percent showing a latency of over 15 seconds. This time lag is longer compared to 4s ms observed for similar devices in 5G.With network latency having a major impact on battery life in IoT devices, we observe that networks with low latency will lead to longer battery lives. For moving devices that need to disconnect from a network and re-establish a connection frequently, this becomes an even bigger problem since the device has to go through the process of establishing a connection every time. This is even worse for WIFI since the device needs to stay in the vicinity of the network for up to 3.4 seconds in 80 percent of devices for a connection to be established. This is unacceptable in real-time location systems where IoT devices have to move from one spot to another. To solve this, we intruded the idea of "greedy" and "non-greedy" devices. The non-greedy approach provides high accuracy for real-time location systems while the greedy approach provides efficient battery consumption through it duty cycling technique.

Having studied and used mathematical models to understand the latency associated with WIFI, BLE and 4G-LTE, we observed that 5G provides by far greater efficiency in machine type communication through its fast speed, low latency and eventual ultra-low power consumption. Since real time location systems require an air latency of not more than 1 second, 5G proves to be the most suitable communication protocol for IoT devices and should indeed be the defacto communication protocol for these ephemeral hyper-local context due to its wide area coverage, its low latency and ultra-low energy consumption.

References

[1] J. Dungen and J. P. Neto, "Towards collective hyperlocal contextual awareness among heterogeneous RFID systems," 2017 IEEE SmartWorld, Ubiquitous Intelligence Computing, Advanced Trusted Computed, Scalable Computing Communications, Cloud Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), San Francisco, CA, 2017, pp. 1-6.

[2] M. I. Jameel and J. Dungen, "Low-power wireless advertising software library for distributed M2M and contextual IoT," 2015 IEEE 2nd World Forum on Internet of Things (WF-IoT), Milan, 2015, pp. 597-602. doi: 10.1109/WF-IoT.2015.7389121

[3] Rahimi, H., Zibaeenejad, A., Safavi, A.A. (2018). A Novel IoT Architecture based on 5G-IoT and Next Generation Technologies. 2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), 81-88.

[4] G. A. Akpakwu, B. J. Silva, G. P. Hancke and A. M. Abu-Mahfouz, "A Survey on 5G Networks for the Internet of Things: Communication Technologies and Challenges," in IEEE Access, vol. 6, pp. 3619-3647, 2018. doi: 10.1109/ACCESS.2017.2779844

[5] Mahmoud, Mahmoud Mohamad, Auday. (2016). A Study of Efficient Power Consumption Wireless Communication Techniques/ Modules for Internet of Things (IoT) Applications. Advances in Internet of Things. 06. 19-29. 10.4236/ait.2016.62002.

[6] Holger Karl and Andreas Willig. 2007. Protocols and Architectures for Wireless Sensor Networks. Wiley-Interscience, New York, NY, USA.

[7] IEEE 802.15 WPAN Task Group 4, http://www.ieee802.org/15/pub/TG4.html

[8] Gascłn, David (February 5, 2009). "Security in 802.15.4 and ZigBee networks". Retrieved 9 December 2010.

[9] J. Nieminen et al., "Networking solutions for connecting bluetooth low energy enabled machines to the internet of things," in IEEE Network, vol. 28, no. 6, pp. 83-90, Nov.-Dec. 2014. doi: 10.1109/MNET.2014.6963809

[10] Fendelman, Adam (2017-12-18). "1G, 2G, 3G, 4G, 5G Explained". Lifewire. Retrieved 2018-02-27

[11] Ericsson White Paper. Cellular Networks for Massive IoT

[12] Thomas, D., Wilkie, E., Irvine, J. (2016). Comparison of Power Consumption of WiFi Inbuilt Internet of Things Device with Bluetooth Low Energy.

[13] Gerhard Fettweis and Ernesto Zimmermann., (2008) ICT ENERGY CONSUMPTION TRENDS AND CHALLENGES , The 11th International Symposium on Wireless Personal Multimedia Communications

[14] Barrett, Steven Frank; Pack, Daniel J. (2006). "Timing subsystem". Microcontrollers Fundamentals for Engineers and Scientists. Morgan and Claypool Publishers. pp. 5164. ISBN 1-598-29058-4.

[15] Y. Zhang, C. Feng, I. Demirkol and W. B. Heinzelman, "Energy-Efficient Duty Cycle Assignment for Receiver-Based Convergecast in Wireless Sensor Networks," 2010 IEEE Global Telecommunications Conference GLOBECOM 2010, Miami, FL, 2010, pp. 1-5. doi: 10.1109/GLOCOM.2010.5683478

[16] KitKat Feature Spotlight: Wi-Fi TDLS Support Allows For Faster Direct Data Transfer On A Wi-Fi Network Without Slowing Other Devices, androidpolice.com

[17] K. E. Jeon, J. She, P. Soonsawad and P. C. Ng, "BLE Beacons for Internet of Things Applications: Survey, Challenges, and Opportunities," in IEEE Internet of Things Journal, vol. 5, no. 2, pp. 811-828, April 2018. doi: 10.1109/JIOT.2017.2788449

[18] Yongpan Liu, Hehe Li, Xueqing Li, Jason Chun Xue, Yuan Xie and Huazhong Yang, "Self-powered wearable sensor node: Challenges and opportunities," 2015 International Conference on Compilers, Architecture and Synthesis for Embedded Systems (CASES), Amsterdam, 2015, pp. 189-189. doi: 10.1109/CASES.2015.7324561

[19] "Making 5G New Radio (NR) a Reality The Global 5G Standard - IEEE Communications Society". comsoc.org.

[20] Rappaport, T.S.; Sun, Shu; Mayzus, R.; Zhao, Hang; Azar, Y.; Wang, K.; Wong, G.N.; Schulz, J.K.; Samimi, M. (2013-01-01). "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!". IEEE Access. 1: 335349. doi:10.1109/ACCESS.2013.2260813. ISSN 2169-3536.

[21] Nordrum, Amy; Clark, Kristen (27 January 2017). "Everything you need to know about 5G". IEEE Spectrum magazine. Institute of Electrical and Electronic Engineers. Retrieved 23 January 2019.

[22] Customers in Chicago and Minneapolis are first in the world to get 5G-enabled smartphones connected to a 5G network". verizon.com. 2019-04-03. Retrieved 2019-05-08.

[23] Michael Hoffmann, (Jan 18, 2019How can) 5G Accelerate the Internet of Things (IoT)?, globalxetfs.com/how-can-5g-accelerate-iot

[24] Golbon-Haghighi, M. H. (2016). Beamforming in Wireless Networks (PDF). InTech Open. pp. 163199. doi:10.5772/66.399. ISBN 9781466557529.

[25] Van Veen, B. D.; Buckley, K. M. (1988). "Beamforming: A versatile approach to spatial filtering" (PDF). IEEE ASSP Magazine. 5 (2): 4. doi:10.1109/53.665. Archived from the original (PDF) on 2008-11-22

[26] J. J. Treurniet, C. Sarkar, R. V. Prasad and W. d. Boer, "Energy Consumption and Latency in BLE Devices under Mutual Interference: An Experimental Study," 2015 3rd International Conference on Future Internet of Things and Cloud, Rome, 2015, pp. 333-340. doi: 10.1109/FiCloud.2015.10

[27] Mike Dano, (February 2014)3G/4G wireless network latecny: comparing Verizon, ATT, Sprint and T-Mobile in February 2014

[28] "Best iBeacon hardware crowned following extensive stress tests". 9to5 mac. 2014-11-03. Retrieved 2014-11-03.

[29] Golbon-Haghighi, M. H. (2016). Beamforming in Wireless Networks (PDF). InTech Open. pp. 163199. doi:10.5772/66.399. ISBN 9781466557529.

[30] Pei et al.(20172017arXiv170102528P Pei, C., and 8 colleagues 2017. Why It Takes So Long to Connect to a WiFi Access Point. arXiv e-prints arXiv:1701.02528

[31] Ar Reyouchi, El Miloud Ghoumid, Kamal Ameziane, Koutaiba El Mrabet, Otman Mekaoui, S.. (2013). Performance of Round Trip Delay Time in Practical Wireless Network for Telemanagement El Miloud Ar Reyouchi, Kamal Ghoumid, Koutaiba Ameziane, Otman El Mrabet, Slimane Mekaoui. International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering. 7.

[32] IEEE 802.11 Working Group et al. Ieee standard 802.11. IEEE Std, 802:11p, 2010.