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Applications of 5G Cellular Communication Systems in optimizing the use of the Internet of Things ("IoT") in Healthcare Systems

The Internet of Things is best defined as an "intelligent" system of physical devices and objects ("things") which are embedded with sensing and actuating capabilities in order to act as a node in a computing network which processes and handles data, as well as communicates with other nodes that process and handle data. The name comes from the process of a given node in this intelligent system interacting with other nodes in this system by communicating via Internet protocols or other communication protocols.

The implementation of the Internet of Things (hereby referred to as "IoT") in larger information systems has become ubiquitous in recent years, and has been poised across industries and media outlets as being an innovation with the potential to transform our lifestyles as we know it. One key industry that has been cited in this discourse is the Healthcare industry. Major U.S.-based companies such as AT&T[1], Microsoft[2] and IBM[3] have all weighed in on IoT's potential to advance the reliability and quality of healthcare at each stage, including but not limited to data

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[1] "Cybersecurity, Networking & IOT Healthcare Solutions at AT&T.," AT&T Business, accessed April 28, 2022, https://www.business.att.com/industries/healthcare.html.

[2] "IOT in Healthcare Solutions: Microsoft Azure," IoT in Healthcare Solutions | Microsoft Azure (Microsoft), accessed April 28, 2022, https://azure.microsoft.com/en-us/overview/iot/industry/healthcare/#overview.

[3] Amar Das et al., "Cognitive IOT for Heathcare," ed. Jeff Rogers and John Knickerbocker, IBM (IBM Research, July 25, 2016), https://researcher.watson.ibm.com/researcher/view_group.php?id=7866.

confidentiality between patients and caregivers, reality available and reliable data in the operating room and in research labs, virtual healthcare, data on healthcare coverage, and more.

Forbes' Technology Council Member Ben Forgan wrote an article in May of 2021 entitled "How IoT is Transforming Healthcare" that highlights various examples of how the ubiquity of IoT can really improve our healthcare providers' ability to monitor our condition over important periods of time in our lives. To this end, he brings up examples about how a reliable IoT implementation can be useful in monitoring maternity care for pregnant women, or monitoring care for people living with diabetes. Some of the impacts that he mentions include the following:

> "*smart technology could enable alerts for changes in maternal and fetal health in high-risk pregnancies and could also help monitor pregnant women in rural environments who have limited access to care. In addition, continuous monitoring via sensors and IoT could improve care delivery and quality of life for diabetic patients. This is crucial to avoid deterioration of patient health, which could impact the patient's eyes, internal organs, nerves and other parts of the body. Similarly, improved monitoring and patient support could help manage the health of patients with [COPD], potentially avoiding complications and hospitalizations.*"[4]

One of the key words that Forgan uses to describe the impact of a reliable IoT system on improving healthcare infrastructure is "continuous monitoring." In order to have an IoT system that is effectively sustains accurate and dependable data transfer at a constant rate, regardless of location, an important design parameter that must be taken into consideration is the protocol used to transmit this data as packets over a network connection.

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[4] Ben Forgan, "Council Post: How IOT Is Transforming Healthcare," Forbes (Forbes Magazine, March 31, 2021), https://www.forbes.com/sites/forbestechcouncil/2021/03/31/how-iot-is-transforming-healthcare/?sh=4579809467e5.

As newer global wireless standards become available and ubiquitous in use by common handheld and wearable devices, new questions arise about if they are feasible to adopt, and if so, how to incorporate these new communication protocols into existing IoT systems to yield the benefits of the new technology at a minimal cost. Specifically 5G, or the 5th Generation technology standard for broadband cellular networks, has become a widely-researched topic as it applies to IoT implementations. 5G has been poised as a generation of communication standards that promises the low latency, high speed data transfer needed to implement reliable, IoT based healthcare systems.

There is a potential for 5G to become the new main design protocol over protocols such as Low Power, Wide Area Networks (e.g. LoRaWAN), which is "designed to wirelessly connect battery operated 'things' to the internet in regional, national or global networks, and targets key Internet of Things (IoT) requirements such as bi-directional communication, end-to-end security, mobility and localization services."[5] By this definition, LoRaWAN seems to provide the reliability necessary to transfer healthcare data across wireless devices over long distances.

In this research paper, I will be exploring the ways in which 5G implementation in IoT can help progress the advancement of healthcare information systems in comparison to the LoRaWAN protocol, as well as the tradeoffs of making such a design choice for this type of communication system.

[5] "What Is Lorawan® Specification," LoRa Alliance®, October 14, 2021, https://lora-alliance.org/about-lorawan/.

How does the implementation of 5G in IoT improve performance metrics such as bit error rate, number of retransmissions, latency and reliability compared to LoRaWAN?

In order to effectively answer this question, it would be best to review how these metrics are calculated in 5G, predict trends in this metrics as it pertains to 5G, and then compare this these metrics in LoRaWAN.

Before we can look for relationships between metrics, we need to define these metrics in the context of what they mean in 5G and in LoRaWAN. In the table below, I will summarize the meanings of the metrics to used and their context within each protocol, and then I will expand on those definitions as it pertains to their usages in 5G and in LoRaWAN.

Metrics / Definitions	Definition	Requirement in 5G	Requirement in LoRaWAN
Bit Error Rate ("BER")	The probability of a bit error occurring as a result of data transmission, as detected during the process of decoding at the receiver.	The BER of a data packet is less than 0.001% for a given transmission.	The BER is required to be minimized in LoRaWAN; this is achieved by prediction.
Latency	The amount of time or delay between the transmission and the receipt of a data packet.	The latency of a given transmission of a data packet does not exceed 1 ms.	Latency is minimized, with consideration of the limits of duty cycle and holding period.
(Average) Number of Required Retransmissions	In a given set of data transmissions, the number of retransmissions that will have to be requested in order to ensure that the data transmitted was accurate.	5G aims to limit the number of retransmissions that are required by using Hybrid-ARQ (Hybrid Automatic Repeat Request); The goal is minimization.	LoRaWAN limits retransmissions by scheduling a "back-off" period where retransmission attempts will only occur in that period of time.
Reliability	The percentage of data packets that are delivered "successfully"—this success criteria is defined by each individual communication protocol.	Due to Ultra Reliable Low Latency Communication (URLLC) requirements, a 5G system is deemed "unreliable" for data transmissions if: (1) the BER of a data packet exceeds 0.001%, (2) the packets do not arrive by their deadline (say 1 millisecond), or (3) a sufficiently large packets are lost forever.	LoRaWAN's official documentation with *The Things Network* directly specifies the limitations of the reliability of LoRaWan. These limitations are specified with examples of suitable vs. non-suitable use cases for transmitting data with LoRaWAN.

[6] THE DEFINITION AND 5G COLUMNS ON THE TABLE WAS FILLED IN USING THE COURSE TEXTBOOK FOR ECE 5960, SPRING ’22 AT CORNELL UNIVERSITY.
[7] THE LORAWAN COLUMN ON THE TABLE WAS FILLED IN, IN PART, USING THE IEEE RESEARCH PAPER “ON THE ERROR RATE OF THE LORA MODULATION WITH INTERFERENCE,”
[8] THE LORAWAN COLUMN ON THE TABLE WAS FILLED IN, IN PART, USING THE IEEE RESEARCH PAPER “ANALYSIS OF LATENCY AND MAC-LAYER PERFORMANCE FOR CLASS A LORAWAN”
[9] THE LORAWAN COLUMN ON THE TABLE WAS FILLED IN, IN PART, USING A PAGE FROM DOCUMENTATION OF THE LEADING LORA DEVELOPERS.
[10] THE LORAWAN COLUMN ON THE TABLE WAS FILLED IN, IN PART, USING A PAGE FROM DOCUMENTATION OF LORAWAN WITH THE THINGS NETWORK.

In 5G, many of the requirements specified are directly defined, but it is important for the purposes of this research to clarify the details of the Hybrid-ARQ process used in 5G to limit the number of retransmissions that are required to obtain an accurate data packet. Hybrid-ARQ proceeds as follows:

1. Error Correction is attempted on the newly received data packet.
2. Residual error detection is applied to the error correction result in order to see if there are any remaining errors or if new errors were created in the process of performing step 1. This is often done with a cyclic redundancy check (“CRC”).
3. If it is determined from step 2 that a retransmission request is necessary, one is requested.

[6] Dahlman, Erik; Parkvall, Stefan; Skold, Johan. 5G NR . Elsevier Science. Kindle Edition.

[7] Orion Afisiadis et al., “On the Error Rate of the Lora Modulation with Interference,” IEEE Xplore (IEEE, December 2019), https://arxiv.org/pdf/1905.11252.pdf.

[8] R. B. Sørensen, D. M. Kim, J. J. Nielsen, and P. Popovski, “Analysis of latency and MAC-layer performance for class A LoRaWAN,” IEEE Wireless Communications Letters, vol. 6, no. 5, pp. 566–569, Oct. 2017.

[9] “Joining and Rejoining,” LoRa Developer Portal, accessed April 30, 2022, https://lora-developers.semtech.com/documentation/tech-papers-and-guides/the-book/joining-and-rejoining.

[10] “Limitations,” The Things Network, accessed April 30, 2022, https://www.thethingsnetwork.org/docs/lorawan/limitations/.

Hybrid-ARQ is an approach in that it attempts to balance minimizing the BER with some-what counteractive attempts to increase throughput by reducing retransmission requests, which is an act that occurs at the expense of marginally increasing the BER. Sometimes though, Hybrid-ARQ doesn't work; we may see a decoder error from performing step 2 which requires us to perform step 3 and request a retransmission. To boost the performance of this approach and thus minimize the impact of such a tradeoff, Hybrid-ARQ employs a method called soft-combining. In soft-combining, the receiver keeps the received data that triggered a retransmission, and then combines this kept data with subsequent versions of the same packet content. This is done by having "soft values," which are multi-bit estimates of the received values, so that they can be combined methodically later on.

In LoRaWAN, many of the requirements specified are also very directly defined. I believe though, that it is important to direct attention to the reliability parameter of LoRaWAN. Taking these use cases into consideration, there is already a case in favor of using 5G as a communication protocol over LoRaWAN in the context of healthcare because one of the use cases where LoRaWAN is not deemed "suitable" is Realtime data because "you can only send small packets every couple of minutes"[11] which may be an issue if you are trying to monitor/transmit a patient's data for a chronic health condition with many indicators, such as diabetes. On the other hand, LoRaWAN has the advantage over 5G of security (the protocol is "128bit end-to-end encrypted") and accessibility, as gateways for LoRaWAN connections can be installed at a relatively low cost compared to installing a new 5G tower.

We can graph the trends in these metrics for comparison, assuming 16-QAM modulation (see appendix for equations):

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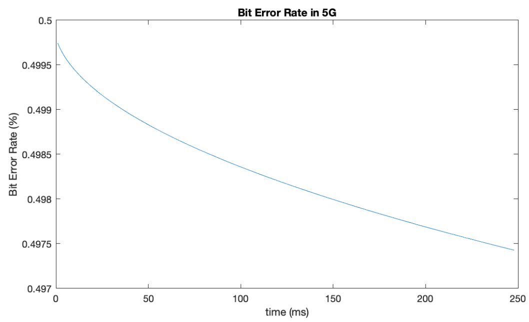
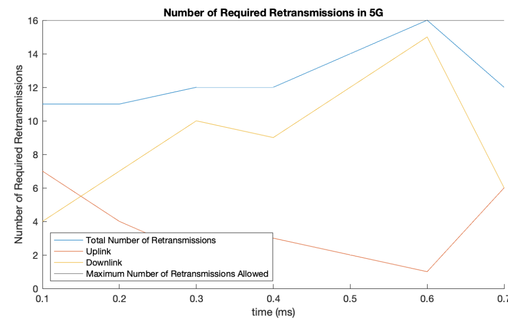
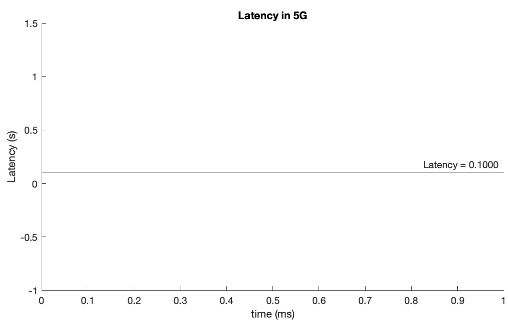
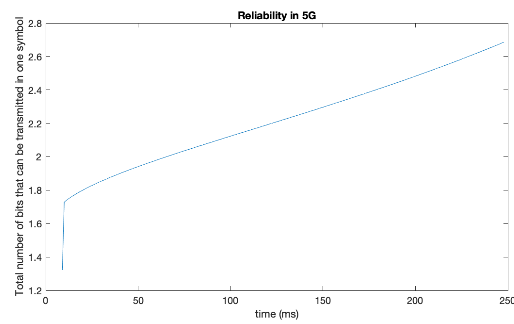
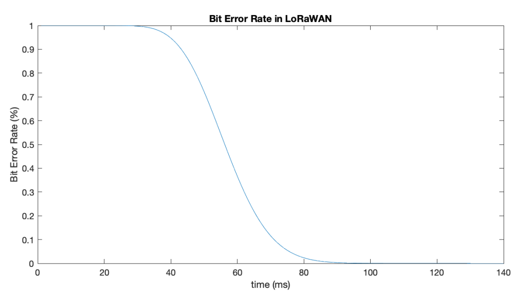
[11] "Limitations," The Things Network, accessed April 30, 2022, https://www.thethingsnetwork.org/docs/lorawan/limitations/.

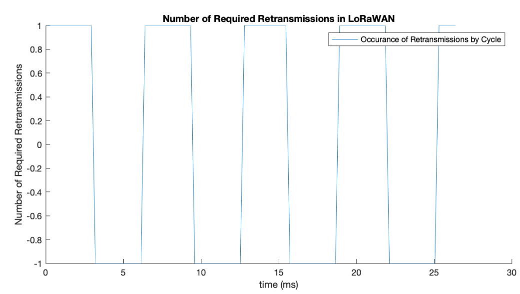


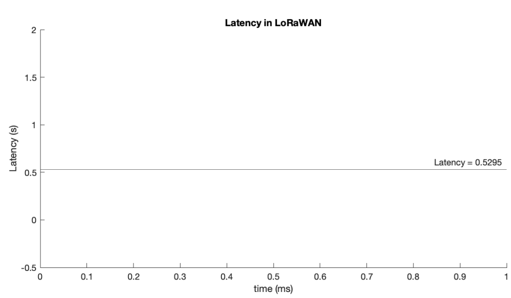


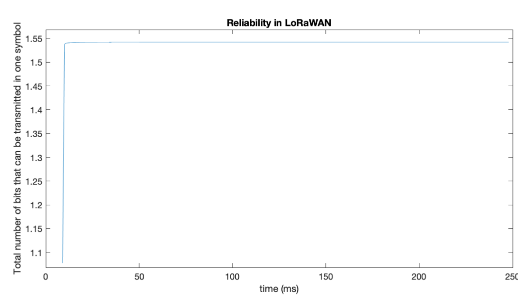












Looking at the trend in these metrics as more data is transmitted over time, I can see that latency is less in 5G than it is in LoRaWAN, and the average reliability of 5G is much greater than that of LoRaWAN over time. In contrast, the BER of LoRaWAN seems to decrease faster and more drastically in time than that of 5G, and retransmissions occur with less frequency in LoRaWAN than in 5G.

What are the metric tradeoffs that we obtain due to these improvements? Are we actually better off with 5G based on this? In terms of these performance metrics, is there a threshold or point where these metrics are at their most ideal given the potential tradeoffs?

In 5G, it seems as though a shorter transmission is more likely to lead to a constant, optimal BER and optimal number of required retransmissions on average, while latency remains constant and reliability increases in time. This makes sense, because a system that can be deemed reliable is one that can sustain accurate and timely data transmission over time.

In LoRaWAN, it appears that latency remains constant in time and average reliability reaches a plateau, while BER decreases instantaneously at a given point in time, and the number of required retransmissions on average is constant within specified intervals of time. Given the use cases provided in LoRaWAN documentation about optimal applications of LoRaWAN, these trends also make sense.

While LoRaWAN seems to have a point at which the performance metrics can be optimized without much of a tradeoff between one another in the short run, the metrics in 5G can be optimized in more applicable ways to the healthcare industry, and thus present a greater level of stability as a data-based solution for the healthcare industry.

What impact may these benefits and tradeoffs of 5G have on the real-world impact on IoT solutions in healthcare?

When evaluating the benefits and tradeoffs of using 5G over other communication protocols such as LoRaWAN, it is helpful to connect the impact of 5G methodology on challenges that are faced in 5G in IoT and then apply that to challenges faced when it comes to taking an IoT approach in handling health-related data.

As mentioned in Forgan's article "How IoT is Transforming Healthcare" in Forbes, two major factors that have played a role in accelerating the development of IoT approaches to healthcare are (1) the on-set of the COVID-19 global pandemic creating a greater need for on-demand tele-healthcare from any location, and (2) "a greater dependence on big data—combining both internal and external data from numerous sources—to enhance decision-making."[12] Expanding on the content discussed in the previous sections, we can see that 5G NR is well equipped to address these challenges. This is especially true when you consider the introduction of Industrial IoT considerations into the newest releases of 5G NR.

Industrial IoT (hereby referred to as "IIoT") with URLLC (ultra reliable low latency communications) enhancements were major focuses of 5G NR release 16, which became available in December of 2020. The highlight of this new release has been further reductions in latency and increasing reliability in transmitting data. The following table summaries the enhancements made for release 16 compared to those that were already available in prior releases.

Features from releases <= 15	**Enhancements for releases 16+**
Mini-slot transmission (we don't have to start on slot transmission nor on slot boundaries)	Preemption has been extended to uplinks across devices
Front-loaded designs (fast processing / pre-processing)	Improved prioritization from individual UEs
Downlink interdevice preemption	Enhanced/configured grants
Robust MCS and CQI with greater reliability at the expense of channel efficiency	Enhanced PUSCH and PDCCH
Data duplication and multisite connectivity (more diversity in the nodes that are part of a communication/IoT network implies greater reliability of transmissions)	Multi-connectivity and PDCP duplication
	Time-sensitive networking

[12] Ben Forgan, "Council Post: How IoT Is Transforming Healthcare," Forbes (Forbes Magazine, March 31, 2021), https://www.forbes.com/sites/forbestechcouncil/2021/03/31/how-iot-is-transforming-healthcare/?sh=4579809467e5.

TABLE: FEATURE ENHANCEMENTS MADE IN RELEASE 16 WITH AN IIOT FOCUS IN MIND, VERSUS THOSE THAT WERE ALREADY AVAILABLE IN RELEASES 15 AND PRIOR.[13]

As mentioned at the beginning of this paper, a major goal of IoT-based health information systems is to ensure the reliable and secure transmission of health data on demand. As such, many of the feature enhancements in releases 15, and later 16, help with working towards this goal.

For instance, having preemption extended to uplinks across devices has lent itself to improved prioritization from individual UEs (User Equipment). Let there be an IoT network using 5G as a communication protocol, with N handheld devices being defined as the nodes of this network; devices D_1 to D_N. Any given device D_i ($i \in [1, N]$) might be handling several different services of varying priorities and latency requirements. In most cases, the bandwidth available is sufficient for avoiding data collisions since data that is not latency-critical can be scheduled to use resources block slots that are not already in use by latency-critical data.

Though, let's assume for the time being that we are not looking at an ideal case, so the system load on D_i is sufficiently large such that the scheduler is not able to avoid scheduling latency-critical data (such as the transmission of a diabetic patient's vital signs and blood sugar, and patient ID number) on the same resource block(s) as non latency-critical, low priority data (such as the exact location of the patient at the time of the reading). Handling this at the downlink level is more straight-forward than at the uplink in releases 15 and prior, as the gNodeB (gNB) will prioritize the transmission of the higher-priority data over the data which is not latency-critical. Though the less latency-critical data is more prone to collisions and transmission errors due to this, because it is less latency-critical the system can afford use Hybrid-ARQ to facilitate this

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[13] Dahlman, Erik; Parkvall, Stefan; Skold, Johan. 5G NR . Elsevier Science. Kindle Edition.

downlink preemption of the low-priority data by resending retransmission requests to correct errors in that data.

Meanwhile, prior to added support for uplink preemption in release 16, avoiding scheduling latency-critical data on the same resource block(s) as non latency-critical, low priority data was a challenge because devices would face the issue of handling uplink resource conflicts if both types data originated from the same device D_i. If the data was coming from different devices, say D_i and D_{i+1}, then scheduling a high priority data transmission over a lower priority data transmission created a greater risk of transmission inference, which would increase the risk of bit errors and create a need to request a retransmission on both sets of data; this is particularly an issue for making the deadline for delivering latency-critical data in real time.

Release 16 addresses this issue by adding the following two mechanisms in order to better support uplink preemption: (1) the cancellation or suppression of low priority transmissions and (2) the introduction of power-boosting, where higher priority data transmissions would be done at a higher power level compared to transmissions without uplink preemption.[14]

These new mechanisms are useful in increasing reliability and reducing latency overall because suppressing low priority transmissions can help with avoiding data collisions by reducing uplink resource conflicts in attempting to transmit the data, and transmitting higher-priority data at a greater power level can facilitate the successful transfer of the desired data by using existing open-loop power control to boost the transmission so that the signs remains strong over the distance that it will have to travel to reach the receiver. Other kinds of new features, such as multi-connectivity and PDCP duplication, create more robustness by providing multiple pathways to

[14] Dahlman, Erik; Parkvall, Stefan; Skold, Johan. 5G NR . Elsevier Science. Kindle Edition.

transmitting the same packet of data, thereby reducing the likelihood of encountering high bit-error rates and needing to make a retransmission request.

Overall, by introducing a new release which focuses on improving 5G integration with IoT systems, the 5G communication protocol has positioned itself as a more viable cellular-based choice for transmitting data in an IoT system. Looking at these effects, one can see that 5G Release 16 as a choice of communication protocol for IoT-based health information systems can have a net positive impact on the advancement of local, regional, and even global healthcare.

However, it is important to also consider who the beneficiaries of this "net positive impact" are. As Rohit Mehta points out in the article "Pros and cons of 5G technology" from *The Times of India*, access to and coverage of 5G technology is very limited to major cities in it's current stage, since there is an expense for adding the towers needed that acts as a greater barrier to access for rural areas. As a result of this financial barrier, it may be years before rural communities enjoy these benefits, by which point, communication technology will likely have moved on to the newest protocol, leaving these communities lacking access behind.[15]

This a cyclic problem; one that parallels systemic socio-economic barriers to affordable, reliable and accessible healthcare in rural communities. This argument is not meant to takeaway from the impact of 5G developments in IoT as it relates to healthcare information systems, but rather to contextualize who gets to enjoy these benefits, which is interconnected with how social identities such as socio-economic status afford individuals with the privilege of access to new technologies as they are released.

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[15] Rohit Mehta, "Pros and Cons of 5G Technology," Times of India Blog (India Times, November 12, 2021), https://timesofindia.indiatimes.com/blogs/digital-mehta/pros-and-cons-of-5g-technology/.

As mentioned in the beginning, my goal throughout this research paper was to analyze the tradeoffs of implementing the 5G protocol in an IoT healthcare system versus using the LoRaWAN protocol. In the process of performing this analysis, I explored the following questions:

(1) *How does the implementation of 5G in IoT improve performance metrics such as bit error rate, number of retransmissions, latency and reliability compared to LoRaWAN?* I found that the answer to this question, in the context of handling healthcare data, is that both 5G and LoRaWAN offer different, valuable approaches to facilitating the retransmission of healthcare data in IoT-based system. However, in an industry where effectively monitoring patient data continuously and in real time with minimal latency matters greatly, using 5G as the communication protocol in an IoT-based health information system seems to be a more ideal design choice.

(2) *What are the metric tradeoffs that we obtain due to these improvements? Are we actually better off with 5G based on this?* I*s there a threshold or point where these metrics are at their most ideal given the potential tradeoffs?* I discovered that LoRaWAN offers more room to optimize all of these performance metrics with less tradeoffs than with 5G. However, the metrics in 5G can be optimized in more applicable ways to the healthcare industry, and thus present a greater level of stability as a data-based solution for the healthcare industry.

(3) *What impact may these benefits and tradeoffs of 5G have on the real-world impact on IOT solutions in healthcare?* I concluded that 5G approaches to IoT and healthcare can serve to increase the overall dependability of the system, which is extremely important for healthcare as it can mean life or death for some patients. However, these impacts may be limited to a population which is already predisposed to accessible and affordable healthcare for there relative socio-economic status, rather than making healthcare more accessible to a larger population due to the relationship between socio-economic status and access to 5G technology.

This was a topic that I found to be important to explore because healthcare is a topic that impacts everyone, but that impact is directly proportional to access to healthcare. Coverage of healthcare, like coverage in communication protocols across certain areas in the United States and other parts of the world, is directly related to the average socio-economic statuses of the residents affected, as well as other social identities they hold such as race, gender status and identity, sexual orientation and more. If we can implement more reliable IoT based healthcare systems using IoT, and then make that technology readily available to communities that are historically underrepresented when it comes to addressing healthcare needs adequately and in a timely matter, significant progress can be made in closing the gap when it comes to disparities in healthcare access due to the social identities that one may hold.

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Appendix

Equations for Performance metrics in 5G vs LoRaWAN

To describe these metrics mathematically in 5G communication, I have complied the following list of equations with respect to time:

Metrics in 5G	Equation with respect to time
Bit Error Rate	Finally, we can get the probability that an error has occurred (let event := E). $Pr(E) = Pr(E\|b=0)Pr(b=0) + Pr(E\|b=1)Pr(b=1)$ $= Pr(\hat{b}=1\|b=0)(1/2) + Pr(\hat{b}=0\|b=1)(1/2)$ $= \frac{1}{2}(P_F + P_M)$ $Pr(E) = Q(\sqrt{P} \div N)$
(Average) Number of Required Retransmissions	The maximum number of HARQ processes that can occur in 5G NR for a given transmission, by definition, is 16. Each HARQ process takes approximately 8 ms to complete if a retransmission is required, and 3-4ms to complete if not.
Latency	According chapter 4 of the course textbook *5G NR*, we can take the end-to-end latency of a data-based application to be less than or equal to 100ms. For the scope of this research paper, I will assume that the latency in 5G remains constant in time at 100ms.
Reliability	$M = \sum_{n=n_1}^{n_2} \log_2 \left\| 1 + \frac{3}{[Q^{-1}(\mathcal{P}/4)]^2} \frac{\gamma_n P \|H_n\|^2}{U_n} \right\| \quad (4)$ where $\sum_{n=n_1}^{n_2} \gamma_n = 1$

[16] RELIABILITY EQUATION (“TOTAL NUMBER OF BITS THAT CAN BE TRANSMITTED IN ONE

[16] J. A. C. Bingham, "Multicarrier modulation for data transmission: an idea whose time has come," in IEEE Communications Magazine, vol. 28, no. 5, pp. 5-14, May 1990, doi: 10.1109/35.54342.

SYMBOL WITH ERROR PROBABILITY *P* USING N_C SUB-BANDS") IS FROM BINGHAM'S RESEARCH PAPER.
[17] THE BER EQUATION COMES FROM ECE 4670, SPRING 2022, HOMEWORK 2 SOLUTION, PROBLEM 4C, MY PERSONAL WRITEUP (NETID: MDD94).
[18] THE NUMBER OF REQUIRED RETRANSMISSIONS DATA IS FROM DEVOPEDIA.

I have also complied the following list of equations with respect to time for LoRaWAN communication:

Metrics in LoRaWAN	Equation with respect to time
Bit Error Rate	$P(\hat{b} = b) = 24 * Q(\sqrt{2SNR} - \sqrt{2(log(2)SF) + \gamma_{EM}})$
(Average) Number of Required Retransmissions	Retransmission requests must be scheduled within the following time intervals immediately following the error detection: *8.7s per 24 hours.*
Latency	$T_{latency} = t_{transmission} + \frac{p_{serversbusy,all}}{((\sum_{n=1}^{c} \frac{\delta_i}{t_{transmission}}) + \lambda) * 2}$
Reliability	Reliability is dependent on LoRaWAN being used in the defined use cases: • Examples of suitable use-cases for LoRaWAN: **Long range**, **Low power**, **Low cost**, **Low bandwidth, Coverage everywhere**, **Secure data** • Examples of non-suitable use-cases for LoRaWAN: **Realtime data**

This is the MatLab code that I used to create the graphs:

```
%% Michelle Davies (mdd94), Cornell University, Spring 2022, ECE 5960 Research Paper:
% "Applications of 5G Cellular Communication Systems in optimizing the use of the In-
ternet of Things ("IoT") in Healthcare Systems"

%% Defining the Equation Parameters needed:

% let p_5g be the probability that an error will occur in 5G assuming PAM
% modulation
p_5g = 0.01:0.004:1;
Nb = 24000; % number of bits

% 5G BER
ber_5g = qfunc(sqrt(p_5g./Nb));

% 5G (Average) Number of Required Retransmissions
max_reqQ = 16;
reqQ_UL = [7, 4, 2, 3, 2, 1, 6];
reqQ_DL = [4, 7, 10, 9, 12, 15, 6];
reqQ = reqQ_UL + reqQ_DL;
```

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[17] ECE 4670, Spring 2022, Homework 2 Solution, Problem 4c, mdd94 writeup.

[18] Arvindpdmn. "5G NR Hybrid Arq." Devopedia. Devopedia Foundation, December 19, 2021.

```
t = 100e-3:100e-3:700e-3;

% 5G Latency - assuming that latency in 5G NR remains constant in time
lat_5g = 100e-3;

% 5G Reliability
Un = [0, 0, 0, 0, 0, 0, 0, 0, 1:100:Nb];
num_dep = [0, 0, 0, 0, 0, 0, 0, 0, 0.2*1:100:Nb];
M = log2(1 + (3./abs(qfuncinv(p_5g./4))) + (num_dep./Un));

% let p_lora be the probability that an error will occur in LoRaWAN assuming PAM
% modulation
p_lora = 2e-3;

% LoRaWAN BER
SNR = 1:140;
SF = [7, 7:0.036:12];
gamma_EM = 0.1e3;
ber_LoRaWAN = qfunc(sqrt(2.*SNR)-sqrt(2.*log(2).*SF + gamma_EM));

% LoRaWAN (Average) Number of Required Retransmissions
t_rq = linspace(0,8.4*pi)';
LoRaWAN_reqQ = square(t_rq);

% LoRaWAN Latency
prob_busy = 0.10;
t_transmission = 30e-3;
lambda = 0.1e-3;
delta_over_t_transmission = 100e-3:700e-3;
lat_LoRaWAN = t_transmission + (prob_busy./((delta_over_t_transmission+lambda)*2));

% LoRaWAN Reliability
M_LoRaWAN = log2(1 + (3./abs(qfuncinv(p_lora./4))) + (num_dep./Un));

%% Graphing these results:

% 5G Graphs
subplot(2,2,1)
plot(ber_5g)
title('Bit Error Rate in 5G')
xlabel('time (ms)')
ylabel('Bit Error Rate (%)')

subplot(2,2,2)
hold on
plot(t, reqQ)
plot(t, reqQ_UL)
plot(t, reqQ_DL)
yline(max_reqQ)
hold off
title('Number of Required Retransmissions in 5G')
xlabel('time (ms)')
ylabel('Number of Required Retransmissions')
legend({'Total Number of Retransmissions', 'Uplink', 'Downlink', 'Maximum Number of
Retransmissions Allowed'},'Location','southwest')

subplot(2,2,3)
yline(lat_5g, '-','Latency = 0.1000')
title('Latency in 5G')
xlabel('time (ms)')
ylabel('Latency (s)')

subplot(2,2,4)
plot(M)
```

```
title('Reliability in 5G')
xlabel('time (ms)')
ylabel('Total number of bits that can be transmitted in one symbol')

figure;

% LoRaWAN Graphs

subplot(2,2,1)
plot(ber_LoRaWAN)
title('Bit Error Rate in LoRaWAN')
xlabel('time (ms)')
ylabel('Bit Error Rate (%)')

subplot(2,2,2)
hold on
plot(t_rq, LoRaWAN_reqQ)
hold off
title('Number of Required Retransmissions in LoRaWAN')
xlabel('time (ms)')
ylabel('Number of Required Retransmissions')
legend('Occurance of Retransmissions by Cycle')

subplot(2,2,3)
yline(lat_LoRaWAN, '-','Latency = 0.5295')
title('Latency in LoRaWAN')
xlabel('time (ms)')
ylabel('Latency (s)')

subplot(2,2,4)
plot(M_LoRaWAN)
title('Reliability in LoRaWAN')
xlabel('time (ms)')
ylabel('Total number of bits that can be transmitted in one symbol')
```