What does it take for mobile networks to support ultra-reliable low-latency communication?

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Abstract—The support of ultra-reliable low-latency communication (URLLC) is a key distinction between today’s and tomorrow’s mobile networks. The challenge lies in meeting the stringent reliability and latency requirements in stochastic wireless networks. In this paper, we study what is needed from the mobile network to support URLLC at the network scale. The type and magnitude of resources demanded to support URLLC significantly vary according to the URLLC requirement of interest and can even exceed today’s norm in mobile communication. Higher frequency bands, despite greater path loss, exhibit features that can facilitate URLLC. In addition, we also consider how network sharing can ease the provision of additional resources to meet URLLC goals.

I. INTRODUCTION

Ultra-reliable low-latency communication (URLLC) is part of 3GPP’s grand vision for the next generations of mobile networks. URLLC will enable critical-communication services such as remote-controlled vessels, factory automation, mobile virtual-reality, and yet-to-come applications. Achieving URLLC is challenging because of the stringent delay and reliability requirements and the stochastic nature of wireless networks. A general URLLC requirement specified by the 3GPP is the transmission of 32 bytes within a 1 ms deadline with a 99.999% success probability [1]. Therefore, URLLC is sensitive to even highly improbable events that may occur only 0.001% of the time.

A natural way to compensate for uncertainty in wireless communication, increase reliability and reduce latency is to provision additional resources. This has been shown effective at the link level by a range of techniques, including (a) additional antennas (e.g., multi-antenna communication in [2], space diversity in [3]); (b) additional frequency channels (e.g., channel hopping in [3]); (c) additional time slots (e.g., timely retransmissions in [4]); or (d) additional links (e.g., multi-connectivity in [5]). Similarly, several works focus on the prioritization of URLLC traffic, which is also a form of provisioning additional resources, as resources are available to URLLC traffic at the expense of less resources being available to lower priority traffic (e.g., bandwidth provisioning in [6]).

The works cited in the previous paragraph show that achieving URLLC is possible as long as sufficient resources are made available. Then, the question is what level of resources is needed to achieve URLLC at the network scale. The magnitude and type of resources are of direct relevance to future network expansion campaigns by carriers (e.g., in the form of acquisition of spectrum and/or deployment of base stations) and ongoing standardization and spectrum planning efforts, and can even determine the fate of URLLC in the next generations of mobile networks.

In this paper, we consider bandwidth and network density as key resources and study the fundamental limits on the magnitude of those resources that are required to support URLLC at the network level. Fig. 1 illustrates how additional bandwidth and network density can enhance link connectivity and expand the reach of URLLC (white zones, with reliability \(\alpha \geq 99.999\%\)). Blue markers depict base stations.

![Fig. 1: An example of network expansion campaign. The provision of additional bandwidth and/or network density expands the reach of URLLC (white zones, with reliability \(\alpha \geq 99.999\%\)). Blue markers depict base stations.](image-url)

Our contribution is twofold: we firstly map the URLLC requirements onto two network assets, bandwidth and network density, and then we quantify the magnitude of resources needed to meet URLLC goals in a 3GPP network model. As our results indicate, the type and magnitude of resources required differ significantly according to the degree of reliability needed (e.g., 90%, 99.9%, or 99.999%). The magnitude of those resources can exceed what is typically available in today’s mobile networks. We examine how the move towards...
higher frequency bands will be crucial to obtain the bandwidth that is needed to achieve extremely high reliability. We also identify network sharing as a potential approach to facilitate the provision of additional resources and quantify the expected gains from sharing between operators.

II. PRELIMINARIES

A. Expressing reliability

We adopt the 3GPP definition of reliability for URLLC [1]: the success probability $\alpha$ of transmitting $\delta$ bytes of data within a user plane latency deadline $\tau$, i.e., $\Pr(T \leq \tau) \geq \alpha$. We consider a typical mobile-to-base station link, without intermediate relays. The user plane latency $T$ is a sum of physical and data link layers' delays, which generally includes (a) a processing delay, incurred by signal processing; (b) a medium access delay, incurred by scheduling or contention for the medium; and (c) a transmission delay. The processing delay is fairly constant and hardware/implementation related; the medium access delay can be deterministic (scheduling-based approaches) or random (contention-based approaches). In URLLC, scheduling-based medium access (or some sort of prioritization) is likely to be adopted [3], resulting in a quasi-deterministic medium access delay.

The challenging part is the stochastic nature of the transmission delay, prone to time-varying channel conditions because of phenomena such as fading and interference. We adopt a general formulation where the transmission delay relates to the Shannon-Hartley capacity, which is agnostic to the radio access technology (e.g., 3G, 4G, or 5G) and allows us to study the minimum amount of resources needed to support URLLC in mobile networks. The transmission delay is expressed as:

$$T_{tx} = \frac{\delta_{\text{bits}}}{w \times \log_2(1 + \Gamma)},$$

where $w$ and $\Gamma$ are the bandwidth and signal-to-interference-plus-noise ratio (SINR). We assume the SINR to be static during time $\tau$, which is a reasonable assumption for small values of $\tau$, such as in URLLC (often a few milliseconds).

B. The network model

We are interested in the magnitude of network assets to support URLLC in a mobile network. To that end, we adopt the 3GPP urban-macro network model in TR 38.901 [7]. The model defines (a) antenna array configurations for base stations (Sec. 7.3 of [7]); (b) path loss; (c) fading; and (d) line-of-sight (LOS) probabilities (Sec. 7.4 of [7]) for different frequency bands ranging from 0.5 to 100 GHz. We consider three frequency bands centered at 700 MHz, 4 GHz, and 30 GHz to study low, mid, and high bands (as recommended by the 3GPP in TR 38.913 [1]) and base station antenna arrays of size 2x2, 4x4, and 8x8, respectively. Further parameters, in compliance with the aforementioned reports, are as follows: (a) base stations: i. 25 m high and ii. 49 dBm transmit power; (b) mobile user: i. 1.5 m high, ii. 0 dBi omnidirectional antenna, and iii. 9 dB noise figure; (c) -90 dBm noise floor.

III. WHAT ARE THE MINIMUM REQUIREMENTS FOR THE MOBILE NETWORK TO MEET URLLC GOALS?

In this section, we start our analysis of the magnitude of resources needed to meet URLLC goals in mobile networks. Let us consider the general URLLC case of $\delta = 32$ bytes and $\tau = 1$ ms [1]. We assume processing and medium access delays to be negligible. In practice, processing and medium access delays consume a fraction of the delay budget $\tau$; however, these delays can be considered deterministic in URLLC, as discussed in § II-A. We focus on the transmission delay (i.e., $T = T_{tx}$), for it involves the primary sources of uncertainty in wireless networks, including path loss, fading, and interference. This allows us to quantify the minimum resources needed to support URLLC. We focus on three reliability regimes, which, from now on, we denote as: (a) reliable ($\alpha = 90\%$); (b) highly-reliable ($\alpha = 99.9\%$); and (c) ultra-reliable ($\alpha = 99.999\%$).

We consider two network scenarios in our study. The first scenario corresponds to mobile networks subject to stochastic path loss and fading, and negligible interference, which we refer to as a noise-limited network, reflecting networks with a high frequency reuse, tight coordination between transmitters, or low load. The second scenario, an interference-limited network, includes interference, representing mobile networks subject to full frequency reuse, little or no interference coordination between transmitters, and high load. Practical networks may operate somewhere in between noise- and interference-limited models, for they may have some forms of interference mitigation. Nevertheless, we consider noise- and interference-limited networks as the lower- and upper-bound estimates of the minimum amount of resources necessary to support URLLC at the mobile network scale.

Our results stem from system-level Monte Carlo experiments. In each experiment, we consider the performance of a typical mobile user placed at the origin and base stations deployed according to a Poisson point process (PPP) [8] of density $\lambda$ base stations (BSs) per km$^2$. The mobile associates with the base station of the highest average received power. We assume perfect beam alignment between mobile and serving base station. We generate $3 \times 10^7$ experiments for each network density to capture even low-probability channel conditions in the order of $0.001\%$ when $\alpha = 99.999\%$.

A. Noise-limited networks

Fig. 2 shows the demand for bandwidth to reach certain levels of reliability in different network densities for the three frequency bands of interest, 700 MHz, 4 GHz, and 30 GHz. Let us consider a typical dense urban mobile network of 35 BS/km$^2$ [1]. This network can be tailored to support reliable (i.e., $\alpha = 90\%$) to ultra-reliable communication (i.e., $\alpha = 99.999\%$) by the provision of an order of magnitude additional bandwidth (see vertical red arrows in Fig. 2). Alternatively, increased density can ease the demand for bandwidth, such as illustrated by the horizontal red arrow in Fig. 2, where ultra-reliable communication demands as much as bandwidth as highly-reliable communication at the cost of an approximately twice denser deployment.
The relationship between bandwidth and network density changes for different reliability degrees \( \alpha \). An increase in network density can be traded for up to an order of magnitude of bandwidth in ultra-reliable communication, whereas it has marginal impact on less reliable scenarios, such as \( \alpha = 90\% \). This is a consequence of how network density impacts coverage. As illustrated in Fig. 1, the farther the mobile is from the base station, the harder it is to meet the reliability requirements because of weak coverage, increasing the demand for additional bandwidth. Increased network density improves coverage by reducing the distance between transmitter and receiver, as well as the probability of non-line-of-sight (NLOS) communication. As ultra-reliable communication is more sensitive to long distance communication than less reliable regimes, ultra-reliable communication benefits the most from increased network density.

### B. Interference-limited networks

Interference-limited networks demand additional network resources to compensate for interference. Fig. 2 is Fig. 1’s counterpart and shows that achieving highly- (i.e., \( \alpha = 99.9\% \)) and ultra-reliable communication (i.e., \( \alpha = 99.999\% \)) can demand orders of magnitude more bandwidth than in noise-limited networks, whereas the requirements are somewhat similar for reliable communication (i.e., \( \alpha = 90\% \)) in both cases.

The substantial amount of bandwidth needed to support ultra-reliable communication favors the use of high frequency bands, where wider bandwidth is typically available. For instance, all the frequency bands in Fig. 3 demand hundreds of megahertz of bandwidth to meet ultra-reliability in dense urban mobile networks (i.e., density of 35 BS/km\(^2\) \( \square \)), which is impractical at the 700 MHz band, barely achievable at the 4 GHz band, and feasible at the 30 GHz band, considering the respective recommended bandwidths of 20 MHz, 200 MHz, and 1 GHz by the 3GPP in \( \square \). Higher frequency bands also benefit from denser antenna arrays, which, in turn, provide higher directionality and compensate for greater path loss than that experienced in lower bands.

Increased network density can ease the bandwidth requirements to some extent. Network density increases coverage until interference prevails, that is, dominant interfering links transit from NLOS to LOS, and network density becomes negligible (or even harmful) to coverage \( \square \). Interestingly, interference prevails at different network densities for different reliability levels. For instance, Fig. 3 suggests that increased network density leads to marginal returns in reliable communication, where interference prevails beyond 30 BS/km\(^2\). On the other hand, densification substantially eases the demand for bandwidth in highly- and ultra-reliable communication, where interference only prevails beyond 60 BS/km\(^2\) and 100 BS/km\(^2\), respectively.

Another way to look at the mapping from URLLC requirements onto network density is to consider the transmission delay at a fixed bandwidth. Fig. 4 illustrates this mapping from \( \alpha \) and \( \tau \) to network density when bandwidth is fixed at 200 MHz in the 4 GHz band. Lower reliability regimes (e.g., \( \alpha \leq 99\% \)) are only marginally impacted by network density; in fact, tighter deadlines in that region tend to demand a decrease in network density as shown in the upper left side of Fig. 4. On the other hand, as we increase the reliability requirements (e.g., \( \alpha \geq 99.999\% \)), there is a substantial demand for increased network density. For instance, a general URLLC requirement of \( \alpha = 99.999\% \) and \( \tau = 1 \) ms demands a network density of 75 BS/km\(^2\) or greater in Fig. 4.

The distinct trends in network density for different reliability regimes are due to how network density impacts overall and edge coverage. Unlike in noise-limited networks, where network density directly maps onto signal strength, the relationship between network density and coverage is subtle in interference-limited networks, for increased network density increases both signal strength and interference. As shown in
C. Discussion

Our study maps the URLLC requirements onto network assets. As we have shown in a 3GPP network model, mobile networks can support URLLC if the appropriate amount of bandwidth and network density is made available. In both noise- and interference-limited networks, an increase in reliability requirements significantly increases the demand for network resources.

The mapping from requirements to network resources is key to support URLLC for several reasons. Firstly, the type of resources is strongly dependent on the target level of reliability. For instance, both bandwidth and network density are valuable assets towards ultra-reliable communication: network density can be traded for bandwidth, and vice-versa (see Figs. 2-3 for $\alpha = 99.999\%$). On the other hand, network density is less valuable for less reliable regimes, such as $\alpha = 90\%$, where the impact of network density is marginal (e.g., Fig. 2, or even slightly harmful (e.g., Fig. 3). These can directly steer future network expansion campaigns to what type of network resources to acquire according to the URLLC requirements to be supported by the network.

Secondly, the amount of resources can be beyond what is typically available in today’s mobile networks. Fig. 3 implies that supporting ultra-reliable communication can demand up to gigahertz of bandwidth in the presence of interference. However, gigahertz of bandwidth exceeds today’s norm. For instance, a gigahertz of bandwidth (a) was only recently auctioned in the US, and yet it requires the acquisition of several frequency blocks in upper 37 GHz bands ($\geq 10$ blocks for 1 GHz of bandwidth) [11]; (b) is beyond the maximum transmission bandwidth supported by the long term evolution (LTE) interface, up to 640 MHz [12]; and (c) requires the aggregation of several carriers in the new radio (NR) interface (channel bandwidths are up to 400 MHz wide) [12]. The bandwidth magnitude is of direct relevance to future expansion campaigns, so mobile network operators can bid for the appropriate bands and bandwidth, and to ongoing spectrum and radio interface standardization, so appropriate amounts of bandwidth are made available by regulators and supported by mobile radio technologies.

Thirdly, our results indicate that higher frequency bands may be more suitable for URLLC than lower frequency bands. As we pointed out, higher frequency bands are often coupled with wider bandwidth, which, in some cases, is key to achieve URLLC goals. In addition, higher frequency bands also benefit from denser antenna arrays, providing higher antenna directionality, which, in turn, compensates for greater path loss and mitigates interference by comparison with lower bands. This is particularly important in interference-limited networks, as shown in Fig. 3, where higher frequency bands demand less resources than lower bands.

IV. AN ALTERNATIVE APPROACH TO EXPAND THE NETWORK

As we have discussed, URLLC can demand resources that are beyond what is typically available in today’s mobile networks. In this section, we consider network sharing as an alternative approach to facilitate the provision of additional resources, particularly focusing on the ultra-reliable communication regime.

We consider a multi-mobile network operator (M-MNO) sharing arrangement: the M-MNO network consists of base
stations from underlying single-mobile network operators (S-MNOs) (analogously to infrastructure sharing in [13]). M-MNO sharing is akin to traditional roaming or mobile virtual network operators such as Google Fi, in the US. However, unlike aforementioned approaches, where users are often subject to the same performance as subscribers of the underlying mobile operators, we assume bandwidth can be reserved and isolated for URLLC users at each underlying S-MNO (e.g., through network slicing).

M-MNO sharing differs from denser S-MNO deployments in the way the network is built. In S-MNO, the operator expands the network to improve coverage so that high demand or weakly covered regions are better served. In M-MNO, the network is composed from multiple S-MNOs with similar interests, such as alike network planning to cover dense central business districts. As a result, the M-MNO network exhibits spatial characteristics, such as clustering [14], and also accounts for greater spectrum diversity because underlying S-MNOs operate in their private licensed spectrum.

Let the M-MNO network comprise two clustered S-MNOs of equal density \( \lambda_{S-MNO} \). We model clustering as a Gaussian-Poisson point process [15] of density \( \lambda_{M-MNO} = 2\lambda_{S-MNO} \), where clusters are deployed according to a PPP. Each cluster consists of two points (i.e., a base station of each underlying S-MNO), the first is at the center of the cluster, and the second is randomly placed at a distance \( \nu \) from the other. Each S-MNO operates in its private licensed band with full frequency reuse, which naturally mitigates interference in M-MNO.

The relief in M-MNO (blue arrow) is close to the relief in a counterpart S-MNO of 70 BS/km\(^2\) (red arrow). As such, network sharing can be an alternative approach to support URLLC based on existing network infrastructure without the outright deployment of additional base stations.

V. CONCLUSION

We studied the magnitude and types of network resources needed to support URLLC in future mobile networks. We mapped URLLC requirements onto two network assets, bandwidth and network density, adopting an urban-macro network model from the 3GPP. Our study indicates that mobile networks can support URLLC if sufficient resources are made available. The key takeaways of this paper are: (a) the demand for bandwidth can vary orders of magnitude with the URLLC requirement of interest (e.g., 90%, 99.9% or 99.999% reliability) and even exceed today’s norm in mobile communication; (b) the relevance of network assets can depend on the URLLC requirement (e.g., the relevance of network density increases with the reliability requirement); (c) higher frequency bands, often coupled with wider bandwidth and denser antenna arrays, can facilitate achieving URLLC in mobile networks; and (d) network sharing is a potential alternative to facilitate ultra-reliable communication without the outright deployment of more base stations.

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REFERENCES

[1] 3GPP, “Study on scenarios and requirements for next generation access technologies,” 3rd Generation Partnership Project (3GPP), Tech. Rep. 38.913, 07 2020, version 16.0.0.
[2] O. N. Yilmaz, Y.-P. E. Wang, N. A. Johansson, N. Brahmi, S. A. Ashraf, and J. Sachs, “Analysis of ultra-reliable and low-latency 5G communication for a factory automation use case,” in 2015 IEEE international conference on communication workshop (ICCW). IEEE, 2015, pp. 1190–1195.
[3] G. J. Sutton, J. Zeng, R. P. Liu, W. Ni, D. N. Nguyen, B. A. Jayawickrama, X. Huang, M. Abolhasan, Z. Zhang, E. Dutkiewicz, and T. Lv, “Enabling technologies for ultra-reliable and low latency communications: From PHY and MAC layer perspectives,” IEEE Communications Surveys Tutorials, vol. 21, no. 3, pp. 2488–2524, 2019.
[4] M. Haenggi and R. Smarandache, “Diversity polynomials for the analysis of temporal correlations in wireless networks,” IEEE Transactions on Wireless Communications, vol. 12, no. 11, pp. 5940–5951, 2013.
[5] A. Gomes, J. Kibilda, A. Farhang, R. Farrell, and L. A. Da Silva, “Multi-operator connectivity sharing for reliable networks: A data-driven risk analysis,” IEEE Transactions on Network and Service Management, pp. 1–1, 2021.
[6] A. Anand, G. De Veciana, and S. Shakkottai, “Joint scheduling of URLLC and eMBB traffic in 5G wireless networks,” IEEE/ACM Transactions on Networking, vol. 28, no. 2, pp. 477–490, 2020.
[7] 3GPP, “Technical specification group radio access network; study on channel model for frequencies from 0.5 to 100 GHz,” 3rd Generation Partnership Project (3GPP), Tech. Rep. 38.901, 12 2019, version 16.1.0.
[8] J. G. Andrews, F. Baccelli, and R. K. Ganti, “A tractable approach to coverage and rate in cellular networks,” IEEE Transactions on Communications, vol. 59, no. 11, pp. 3122–3134, 2011.
[9] M. Ding, P. Wang, D. López-Pérez, G. Mao, and Z. Lin, “Performance impact of LOS and NLOS transmissions in dense cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 15, no. 3, pp. 2365–2380, 2016.

[10] M. Rebato, M. Mezzavilla, S. Rangan, F. Boccardi, and M. Zorzi, “Understanding noise and interference regimes in 5G millimeter-wave cellular networks,” in *European Wireless 2016; 22th European Wireless Conference*, 2016, pp. 1–5.

[11] “Auction 103: Spectrum frontiers – upper 37 GHz, 39 GHz, and 47 GHz,” [Federal Communications Commission](https://www.fcc.gov/auction/103), accessed: October 2021.

[12] ITU-R, “Detailed specifications of the terrestrial radio interfaces of International Mobile Telecommunications-2020 (IMT-2020),” International Telecommunication Union (ITU), Tech. Rep. ITU-R M.2150-0, 02 2021.

[13] J. Kibiłda, N. J. Kaminski, and L. A. DaSilva, “Radio access network and spectrum sharing in mobile networks: A stochastic geometry perspective,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 4, pp. 2562–2575, 2017.

[14] J. Kibiłda, B. Galkin, and L. A. DaSilva, “Modelling multi-operator base station deployment patterns in cellular networks,” *IEEE Transactions on Mobile Computing*, vol. 15, no. 12, pp. 3087–3099, 2016.

[15] A. Guo, Y. Zhong, W. Zhang, and M. Haenggi, “The Gauss–Poisson process for wireless networks and the benefits of cooperation,” *IEEE Transactions on Communications*, vol. 64, no. 5, pp. 1916–1929, 2016.

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