UAV-enabled Ultra-Reliable Low-Latency Communications for 6G: A Comprehensive Survey

UAV-Enabled Ultra-Reliable Low-Latency Communications for 6G: A Comprehensive Survey

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ABSTRACT Ultra-reliable low-latency communications (URLLCs) and the adoption of unmanned aerial vehicles (UAVs) for network coverage improvement have emerged as key enabling communication paradigms for the successful deployment of mobile communication services envisioned in both the fifth-generation (5G) and the sixth-generation (6G) networks. This paper provides a comprehensive survey about the current state-of-the-art (SoA) on UAV-enabled URLLC networks. The core idea is to highlight the main characteristics of this new network concept as well as its critical aspects. We first perform an overview of URLLC by illustrating the main features and related implementation challenges. Subsequently, an in-depth discussion on UAV-enabled networks is provided, with a special emphasis on how URLLCs and UAV communication can be classified as complementary paradigms. Finally, a comprehensive analysis and classification of the current research advancements on UAV-enabled URLLC networks is carried out. This paper is concluded by pointing out some of the open challenges and our visions related to future directions which should be undertaken in order to pave the way towards the practical implementation of this promising network architecture.

INDEX TERMS Beyond fifth-generation (5G), ultra-reliable low-latency communications (URLLCs), unmanned aerial vehicles (UAVs).

I. INTRODUCTION

The concept of Internet of Things (IoT) represents one of the key communication scenarios in the vision for both 5G and 6G mobile communication networks. Under this perspective, as illustrated in Fig. 2, it is foreseen that wireless connectivity will be available for any type of device that may benefit from being connected [1], enabling then a wide range of emerging applications, such as industrial automation, intelligent transportation, telemedicine, tactile internet, and virtual/augmented reality (VR/AR) [2]–[5]. The realization of such vision for beyond 5G and 6G networks poses new implementation challenges. Indeed, the vast majority of future wireless connections will most likely be originated by autonomous machines and devices rather than by human-operated mobile terminals. To this point, in addition to providing a substantial improvement in data rate over the previous generation cellular technologies, 6G will also be designed to address the specific needs and challenges of ultra-reliable and low-latency communications (URLLCs). Indeed, according to standard requirements [6], URLLCs should guarantee a moderately low throughput level (e.g., 50 Mb/s), but with an end-to-end (E2E) latency not higher than 1 ms and a packet error probability of $10^{-5} - 10^{-7}$. Examples of URLLC use cases include critical connections for industrial automation reliable wireless coordination among autonomous vehicles, and reliable cloud and edge connectivity [7], [8]. As a result, compared with the existing cellular networks, the delay and reliability require significant improvements, i.e., at least two orders of magnitude.
are usually referred to as packet length or BT\(^k\) is typically encoded into b\(^i\), a measure of the spectral efficiency of a communication unit bandwidth, represents the net transmission rate and is i.e., the number of transmitted payload bits per second per T\(^i\) of to transmit a continuous signal with duration and bandwidth k\(^i\) state estimation. The total amount of symbols numbers representing entries from quadrature amplitude theory about channel capacity are valid [13]. Based on which the fundamental results from information design approach than the one used in current high data rate communications. This requires a fundamentally different traffic generated by sensors and exchanged in machine-type communications [12]. Indeed, short packets represent the typical form of milliseconds, which are suitable for short-packet communications. This requires a fundamentally different design approach than the one used in current high data rate systems [9]–[11]. Such approaches are introduced and discussed within the next subsections.

### A. PHYSICAL LAYER ASPECTS

To reduce over-the-air latency, 5G new radio (NR) has introduced short time slots spanning over only a fraction of a millisecond, which are suitable for short-packet communications [12]. Indeed, short packets represent the typical form of traffic generated by sensors and exchanged in machine-type communications. This requires a fundamentally different design approach than the one used in current high data rate systems, such as 4G long-term evolution (LTE) and WiFi. Indeed, most of the current wireless systems have been designed under the assumptions of long packet transmissions, based on which the fundamental results from information theory about channel capacity are valid [13].

Basically, as illustrated in Fig. 3, a packet consists of b = b\(_i\) + b\(_o\) payload bits. The payload, which contains b\(_i\) information and b\(_o\) media-access-control (MAC) bits, is typically encoded into k\(_e\) data symbols, e.g., complex numbers representing entries from quadrature amplitude modulation (QAM) modulation, which enables forward error correction to increase the reliability in packet transmission. Furthermore, k\(_o\) symbols are usually added with the aim of enabling packet error detection, synchronization or channel state estimation. The total amount of symbols k = k\(_e\) + k\(_o\) ∼ BT are usually referred to as packet length or channel uses to transmit a continuous signal with duration and bandwidth of T seconds and B Hz, respectively. The ratio R = b\(_i\)/k, i.e., the number of transmitted payload bits per second per unit bandwidth, represents the net transmission rate and is a measure of the spectral efficiency of a communication system. Since in most current wireless systems we have b\(_i\) ≫ b\(_o\) and k\(_e\) ≫ k\(_o\) and both of them assume large value, it follows that R ≈ b\(_i\)/k\(_e\) and information-theoretic metrics, such as capacity [13] and outage capacity [14], are asymptotically accurate. In other words, let R\(^i\)(k, ε) the maximum coding rate at finite packet length k and finite packet error probability ε, the channel capacity C can be expressed as:

\[
C = \lim_{\epsilon \to 0} \lim_{k \to \infty} R^i(k, \epsilon) \approx \sqrt{\frac{V}{k}} \cdot Q^{-1}(\epsilon) + 0 \left(\frac{\log k}{k}\right)
\]

where Q\(^-1\) denotes the inverse of the Gaussian Q function and V = 1 − (1 + γ\(^-\)\(^2\)) denotes the so-called channel dispersion, with γ representing the signal-to-noise ratio (SNR). As a result, as illustrated in Fig. 1, an increase of reliability requirements, i.e., lower values of ε, corresponds to a decrease of the effective channel capacity

To summarize, in short-packet communications, the main remarks are:

- Classic information-theoretical results are not applicable; The size of the metadata, i.e., b\(_o\), is comparable to the size of the payload and inefficient encoding of metadata significantly affects the overall efficiency of the transmission.

Then, in order to enable URLLCs services, it is mandatory to adopt new analytical models, as well as to design more optimal and efficient physical layer technologies.

### B. INTEGRATION OF INNOVATIVE UPPER-LAYER TECHNOLOGIES

In addition to physical layer related aspects, the stochastic delays in upper networking layers, such as queuing delay, processing delay, and access delay, represent other key bottlenecks of the next-generation radio access network (RAN) for achieving URLLCs. This has also created unprecedented research challenges to wireless network design, and several potential methods have been proposed in literature, ranging from cross-layer design optimization to the integration of deep learning approaches [17]. In particular, these approaches aim to optimize as much as possible the procedures involved.
in the interaction between different layers of 5G/6G network protocol stack, which include channel quality measurements, mobility management procedures, traffic prioritization, beamforming management, handover requests, and so forth. Indeed, for the case of dense networks, all these cross-layer procedures could turn out into high overhead operations, not enabling therefore the possibility to guarantee URLLCs service requirements. Recently, integrating unmanned aerial vehicles (UAVs) into cellular networks has also been recommended by the Third Generation Partnership Project (3GPP) as a promising solution to fulfill some challenging demands of 5G wireless networks [18]. Compared to terrestrial communication systems or those based on high altitude platforms, on-demand communication systems with low-altitude and highly mobile UAVs are generally more cost-effective and more flexible. Moreover, UAVs are more likely to establish short-distance line-of-sight (LoS) communication links, thus providing better link qualities [19]. Then, the UAV communication has received significant research attention along the last years [20]–[27]. However, the majority works on UAV communications mainly focused on the data links while issues on the delay and reliability in the links between UAVs and the ground control station have recently started to gain attention and interest from both academia and industrial sectors.

C. MOTIVATION AND CONTRIBUTION
Based on the previous discussions, it turns out that URLLC will result essential in order to enable future 5G/6G network services. At the same time, UAV communications provide several improvements in terms of channel quality conditions which, compared to the conventional terrestrial communications, can be easily translated into lower error probability and higher channel reliability. As a result, the possibility to exploit UAV communications as potential key enabling technology for future URLLC is becoming a very attractive research topic. To the best of our knowledge, there are neither tutorials nor review papers which provide a clear understanding of this innovative communication paradigm, as well as a view about current challenges and future directions. Under these perspectives, this paper provides a comprehensive discussion of the most relevant and current research activities in the field of UAV-enabled URLLC. More specifically, the main contributions of this article can be summarized as follow:

- We provide a brief overview of the challenges, and the enabling techniques for URLLC.
We highlight the most important features which make UAV-aided communications a promising solution to improve future network performances.

Subsequently a review of the most promising UAV-aided network architectures and frameworks for URLLCs is provided and summarized.

Finally, we conclude this article by providing the remaining challenges and future directions in this research area.

The rest of the paper is organized as follow. An overview about URLLCs requirements and possible ways to achieve some related challenges is provided in Section II. The potential of UAV in enabling future 5G/6G networks and the current challenges of this technology are briefly exposed in Section III. All the most important available works on UAV-enabled URLLCs are classified and reviewed in Section IV. Section V provides our vision on future research directions on UAV-enabled URLLCs. Finally, Section VI concludes this paper.

II. OVERVIEW ON URLLC

As illustrated in Fig. 4, compared with other types of services envisaged for 5G/6G networks, such as enhanced mobile broad-band (eMBB) service, Low-Latency Communication (LLC), Ultra Reliable Communications (URC) and massive Machine-Type Communication (mMTC) [28], the requirements on the E2E delay and reliability are much more stringent for URLLCs. For example, in eMBB communication systems it is more feasible to trade reliability with delay by retransmissions. As result, guaranteeing the quality-of-service (QoS) requirements of URLLCs is more challenging than eMBB services. Furthermore, in addition to the E2E, there are some other relevant Key Performance Indicators (KPIs) which play an important role in the implementation of URLLC services, such as factory automation, VR/AR applications, Tele-surgery, vehicle safety and remote robotic control. Such KPIs are summarized in Fig. 5 and discussed below with some specific use cases and related challenges.

A. SPECTRAL AND ENERGY EFFICIENCY

As the density of devices increases, improving the spectral efficiency (SE), i.e., the number of services that can be supported with a given total bandwidth, becomes an urgent task. This represents the services like factory automation, tele-robotic control, autonomous driving/safety and VR/AR. In addition, since in these types of scenarios a huge amount of energy-constrained sensors are involved, energy efficiency (EE) represents another important KPI [29]–[31] in order to enable higher transmission rates with low power consumption. At date, most of the research activities aimed to maximize those KPI by proposing optimization algorithms have been conducted under the assumption of small and medium-scale scenarios. Then, when the density of devices increases, those algorithms might not be efficient in optimizing SE and EE while guaranteeing URLLCs constraints. Moreover, packet arrival processes from a large number of users will lead to strong interference in the air interface as well as increase of network congestion. In other words, scalability of optimization algorithms and network...
congestion represent main open problems for maximizing SE and EE into URLLC networks.

B. THROUGHPUT, NETWORK AVAILABILITY AND SECURITY

Some URLLC services, which require high levels of throughput with high network availability, i.e., 99% of coverage probability, have been a common trend in beyond 5G networks. Tele-surgery, autonomous vehicles, and remote robotic control are classical examples of URLLC services which require particular attention on these aspects [4], [32]–[34]. Indeed, in the context of tele-surgery and remote robotic control, maintaining high levels of network availability at higher throughput will permit to maintain high quality of control and then good stability of the teleoperated activities. On the other hand, high levels of these KPIs will permit to increase the safety of vehicular networks. In fact, it would be possible to continuously share informations which enhance road safety by sharing street maps and safety messages among vehicles. At date, current cellular networks can achieve 95% of network availability and existing tools for analyzing it are only applicable in small-scale networks [35]. Then, the main challenge is represented by the need to improve the network availability by several orders of magnitude and how to analyze and improve network availability in large-scale networks. Last but not least, security aspects should be considered for such type of URLLC related services. This will prevent catastrophic situations in which devices are controlled by unauthorized agents via spoofed control signals or that malicious messages are intentionally forwarded within the considered networks.

III. UAV COMMUNICATIONS: BENEFITS AND CHALLENGES

UAVs have gained great interest by the academic and industrial communities due to their diverse military and civilian applications. They are envisaged to be part of future airspace traffic, by providing application functions which rely on information exchange among UAVs as well as between UAVs and ground stations (GSs). Then, in just a few years, drones will be assisting humans in every domain.

Among the various applications enabled by UAVs, thanks to its mobility, flexibility and good channel condition, the use of UAVs for achieving high-speed wireless communications is expected to play an important role in beyond 5G systems [36], [37]. Indeed, in contrast to the conventional static base station (BS) communication, a distinct feature of the UAV communication is the existence of line-of-sight (LoS), which offers reduced small-scale fading between UAVs and ground users, providing the possibility to increase network performance. Moreover, the UAV position can be dynamically optimized, permitting to improve channel gains statistics of users and then network metric performances [38]. Despite such benefits, most of the UAV applications need to deal with some important key challenges.

A. ENERGY EFFICIENCY

The UAV’s battery capacity is a key factor for enabling persistent activities. As the battery capacity increases, its weight also increases, which causes the UAV to consume more energy for a given operation. Although power storage technologies have advanced dramatically over the past few decades, limited energy availability still severely hampers UAV durability. Then, effective energy-aware deployment mechanisms, as well as energy-efficient operation with minimum energy consumption are needed. To this end, one effective approach is the inter-cooperation of multiple UAVs in order to enable sequential energy replenishment. For example, this can be performed through the adoption of wireless power transfer techniques (WPTs) for charging drone battery [39]. On the other hand, energy-efficient operations aim to reduce unnecessary energy consumption by the UAVs. One way of guaranteeing that would consists in performing energy-efficient mobility, which means that the movement of the UAVs should be carefully controlled by taking into account the energy consumption associated with every maneuver. Another possible solution consists in performing energy-efficient communications, aiming to satisfy the communication requirement while employing the minimum energy expenditure on communication-related functions, such as communication circuits and signal transmission. In this case, one common approach consists of optimizing the communication strategies to maximize the EE in bits per Joule.

B. UAV DEPLOYMENT AND PATH PLANNING

The deployment of UAVs within the area of interest represents another challenging design aspect for UAV-assisted communication networks. Indeed, optimal deployments will allow to improve channel gains statistics of users and then the network performance metrics. Currently, the vast majority of research contributions has been conducted by considering a single UAV deployed within the area of interest, while only few research contributions have considered multiple-UAV network scenarios. Compared to single-UAV scenario, the deployment of multiple UAVs within the area of interest yields higher performance in terms of improved channel quality and network coverage. Furthermore, it is noteworthy that the cooperative deployment of multiple UAVs has been envisaged as a promising strategy for providing reliable service for users. However, although UAVs are capable of adjusting their three-dimensional (3D) positions dynamically and swiftly to maintain a high performance, the current state-of-the-art (SoA) mainly focuses on the two-dimensional (2D) placement despite of the 3D modeling covers a more realistic scenario. Last, but not least, such existing works only consider static users, while in real scenarios ground users are roaming continuously.

Beside the aspects related to UAV deployment strategies, another important design aspect of UAV systems is represented by path planning. For UAV-aided communications, appropriate path planning may significantly shorten the
communication distance which is crucial for obtaining high-capacity performance. Unfortunately, finding the optimal flying path for UAV is a challenging task in general. On one hand, UAV path optimization problems essentially involve an infinite number of variables due to the continuous UAV trajectory to be determined. On the other hand, the optimization problems are also usually subject to a variety of practical constraints, many of which are time-varying in nature and are difficult to model accurately, i.e., connectivity, fuel limitation, collision, and terrain avoidance. Then, the optimal UAV flight path critically depends on the application scenarios. However, in all of them the following non-trivial trade-off remains: increasing UAV altitude leads to higher free space path loss, while it increases the possibility of having LoS links with the ground terminals. One useful method for UAV path planning is to approximate the UAV dynamics by a discrete-time state space, with the state vector typically consisting of the position and velocity in a 3D coordinate system. The UAV trajectory is then given by the sequence of states, which are subject to finite transition constraints to reflect the practical UAV mobility limitations. Many of the resulting problems with such an approximation belong to the class of mixed integer linear programming (MILP), which often turns out difficult to solve [40].

**IV. RECENT WORKS ON UAV-ENABLED URLLCs**

As discussed in previous sections, URLLC and UAV communications are complementary to each other. Indeed, UAV communications are able to improve the propagation environment of wireless communication by providing good channel condition at both transmitter and receiver sides. As a result, this fosters the possibility of having a reliable and low-latency communication channel, i.e., consistent reduction of packet error probability and then delay reduction due to possible retransmission. However, in order to successfully realize UAV-enabled URLLC, it is still necessary to address some challenges which, depending on the considered application scenario, ranges from jointly optimizing different KPIs to perform cross-layer optimization. In light of that, this section provides a systematic review of the most recent works on UAV-enabled URLLCs networks, which are summarized in Tables 1-2. Furthermore, in order to provide a clear view, a classification of the current state-of-the-art on this research field is provided. For the sake of better visualization, the proposed classification is summarized in Fig. 6, which contains references for each class.

**A. ANALYTICAL APPROACHES**

Authors in [42] studied the average achievable data rate (AADR) of a UAV communication system under the assumption of short packet transmission with ultra-high reliability and low latency requirements. In particular, supposing an uplink communication scenario in which a ground control station (GCS) needs to send remote control signals to a UAV able to fly freely in any direction in the space within an inverted cone volume centered at the GCS, an approximated closed-form expression for the AADR and a correspondent lower bound expression have been
TABLE 1. Summary of current state of the art on UAV-enabled URLLCs studies: Part-1.

<table>
<thead>
<tr>
<th>Work reference</th>
<th>Investigated Scenario/Objective</th>
<th>Results and Insights</th>
</tr>
</thead>
<tbody>
<tr>
<td>[41]</td>
<td>Impact of UAV’s height to minimize the bandwidth for URLLC requirements.</td>
<td>The LoS probability and the network availability are strictly concave with the communication distance.</td>
</tr>
<tr>
<td>[42]</td>
<td>A ground control station (GCS) needs to send remote control signals to a UAV in uplink.</td>
<td>Approximated closed-form expression for the average achievable rate (AADR).</td>
</tr>
<tr>
<td>[43]–[45]</td>
<td>A downlink URLLC system where a central controller Unit (CU) needs to send command information to a distant robot by using a UAV as relay.</td>
<td>A novel perturbation-based iterative algorithm aimed to jointly optimize the location of the UAV and blocklength allocation by minimizing the decoding error probability. Insights and performance comparison under different assumptions on relay protocols and channel models has been provided.</td>
</tr>
<tr>
<td>[46]</td>
<td>A ground Control Station sends control signals to a UAV, which has stringent QoS requirements in terms of ultra-high reliability and ultra-low latency.</td>
<td>Closed-form expression for the average packet error probability (APEP) and the effective throughput (ET). Furthermore, engineering insights on the packet size design and more understanding of the packet error rate incurred in transmission have been provided.</td>
</tr>
<tr>
<td>[47]</td>
<td>A comprehensive framework to characterize and optimize the performance of a UAV-assisted D2D network underlaying cellular transmissions.</td>
<td>Closed-form expressions for a variety of performance URLLC relevant metrics, such as outage probability, ergodic capacity and frame decoding error probability. Subsequently, an optimization problem has been studied to minimize the total transmit power of all users and maximize the aggregate throughput of D2D users.</td>
</tr>
<tr>
<td>[48]</td>
<td>Investigating the possibility to implement URLLCs in downlink by jointly using UAV and reflective intelligent surfaces (RIS).</td>
<td>It has been illustrated how to an increase of the number of antenna elements in RIS as well as of the allocated blocklength, leads to a decrease of the decoding error probability. Moreover, UAV’s position resulted to be crucial for achieving ultrahigh reliability for short packets.</td>
</tr>
<tr>
<td>[49]</td>
<td>Study case where URLLC packets between ground IoT devices are delivered through multi-hop UAV relay links.</td>
<td>Low-complexity optimization algorithm aimed to minimize the total decoding error probability, by jointly optimizing the message blocklength and the relative distance between UAVs.</td>
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</table>

derived. More specifically, the AADR approximation has been obtained using the Gauss-Chebyshev quadrature (GCQ) method. Simulation results, obtained by varying the message blocklength and the decoding error probability, verified the correctness and tightness of the derived expressions. Furthermore, this study highlighted how the usage of the conventional Shannon’s capacity formula can incur into an over estimation of the AADR. This means that for dimensioning highly reliable communications, the capacity under short channel blocklength proposed in [16] should be adopted.

A study on the average packet error probability (APEP) and the effective throughput (ET) in a control link communication between a GCS and a UAV that requires URLLC has been presented in [46]. As in [42], it has been assumed that a GCS sends control signals to a UAV, which is able to fly freely in any direction within the space defined by an inverted cone centered at the GCS, and which has stringent QoS requirements in terms of ultra-high reliability and ultra-low latency. In this case, the Gauss-Chebyshev quadrature method has been adopted to derive the closed-form expression of APEP and ET under short packet transmission. These expressions, in conjunction with a respective lower bound, resulted able to provide engineering insights on the packet size design and more understanding of the packet error rate incurred in transmission. Furthermore, an optimization problem, which aims to maximize the ET by finding the optimal value of packet length, has been analyzed.

A comprehensive framework to characterize and optimize the performance of a UAV-assisted device-to-device (D2D) network, where D2D transmissions underlay cellular transmissions, has been developed in [47]. More specifically, authors supposed that each D2D pair either selects direct or UAV-assisted relay communications to perform finite blocklength transmissions, and that all D2D transmission channels are shared with cellular users. Then, according to the specific transmission criterion, it has been assumed that both the aerial and terrestrial transmissions experience LoS Rician fading or NLoS Nakagami-m fading, respectively. Under this context, a closed-form expressions for a variety of performance metrics relevant in the context of URLLC transmissions, such as outage probability, ergodic capacity and frame decoding error probability, have been derived. These expressions have been employed to MINLP optimization problems which aim to minimize the total transmit power of all users and maximize the aggregate throughput of D2D users, while maintaining the URLLC requirements.
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### TABLE 2. Summary of current state of the art works on UAV-enabled URLLCs studies: Part-2.

<table>
<thead>
<tr>
<th>Work reference</th>
<th>Investigated Scenario/Objective</th>
<th>Results and Insights</th>
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<tr>
<td>[50]</td>
<td>UAV-enabled mobile edge MEC system, where UAV base stations (UBSs) are deployed to cache, process, and deliver virtual reality (VR) content from a cloud server to VR users.</td>
<td>An iterative optimization algorithm aimed to optimize various resource allocation parameters, such as, association of VRUs with UBSs, caching policy, computing-capacity allocation, and location of UBSs, with the objective of minimizing the maximum latency.</td>
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<tr>
<td>[51]</td>
<td>A novel framework to deliver different critical URLLC services deploying UAVs in an out-of-coverage area with sporadic URLLC traffic related features.</td>
<td>A low complexity near-optimal successive minimization algorithm aimed to jointly optimize UAV deployment strategy while maximizing the average sum-rate and minimizing UAV’s transmit power.</td>
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<td>[52], [53]</td>
<td>The problem of minimizing the sum uplink power, in order to enable low-power URLLCs assisted by a mobile UAV in a multiuser IoT communication scenario.</td>
<td>It has been illustrated how the required uplink power increases/decreases as either the minimal rate demand increases/decreases or the overall required error probability decreases/increases. Furthermore, the average transmit power can be also greatly reduced by increasing the number of UAVs.</td>
</tr>
<tr>
<td>[54]</td>
<td>Uplink/Dowlink power control for a URLLC-enabled UAV system incorporated with Deep Neural Network-based channel estimation.</td>
<td>The performances of the proposed approach in terms of power consumptions at both UAV and BS and the impacts of DNN channel error estimation, have been analyzed considering both a circular and vertically ascending trajectories for the UAV.</td>
</tr>
<tr>
<td>[55]</td>
<td>A full duplex multi-UAV relay communication scenario in which a set of UAV are employed to assist a remote ground BS (GRS) in providing enhanced mobile broadband (eMBB) services to a set of remote users.</td>
<td>A two steps optimization algorithm for multiplexing eMBB payload communication and URLLC control information communication has been proposed.</td>
</tr>
<tr>
<td>[56]</td>
<td>An industrial and safety alarm scenario, in which multiple UAVs over a certain area are deployed in order to meet the latency and reliability requirements of energy limited IoT devices, by minimizing their transmit power.</td>
<td>The power of devices in URLLC can be decreased by placing more UAVs. Furthermore, the higher the latency can be tolerated, the significantly lower will be the power required by IoT devices.</td>
</tr>
<tr>
<td>[57]</td>
<td>Analysis, aimed to analyze practical limits in realizing Beyond Visible LoS (BVLoS) operation of UAVs.</td>
<td>It has been observed how message size impact on both delay and error probability. Furthermore, minimum distance between UAVs to avoid any crash for different altitudes when speed of UAVs is 15 m/s, has been studied.</td>
</tr>
<tr>
<td>[58]</td>
<td>A challenging communication scenario, in which a UAV is employed to deliver massive machine-type communication (mMTC) and URLLC related services, by using NOMA transmissions.</td>
<td>A complete analysis on how energy efficiency and latency are affected by the main scenario-relevant parameters like, UAV position and incorrect detection probability due to SIC in NOMA transmissions, has been also provided.</td>
</tr>
</tbody>
</table>

An interesting analysis, which aimed to evaluate practical limits in realizing Beyond Visible LoS (BVLoS) operation of UAVs, has been conducted in [57]. This represents an innovative scenario to investigate. Indeed, in most countries, it is currently required to have a visual line-of-sight (VLoS) between the operator and the UAV [59]. However, there are some applications such as cargo delivery and remote surveillance, for which BVLoS operations represent a step towards fully or partly autonomous operation of UAVs, i.e., system architecture enabling either remote or autonomous piloting tasks on servers or clouds. In this view, the reliability and latency performance with respect to different communication parameters for URLLC has been studied. In particular, through simulation analysis, it has been observed that for message sizes in the range of 30 and 50 bits, and coded packet size in the range of 200 and 300 bits, delay becomes between 2 ms and 8 ms while error probability is between $5 \times 10^{-4}$ and $5 \times 10^{-2}$, which is very promising for BVLoS operation. Furthermore, minimum distance between UAVs to avoid any crash for different altitudes when speed of UAVs is 15 m/s, has been studied.

Since the integration of UAVs into spectrum sensing cognitive communication networks can offer many benefits for massive connectivity services in 5G communications and beyond, authors in [58] analysed the performance of non-orthogonal multiple access (NOMA) based cognitive UAV-assisted URLLCs and massive machine-type communication (mMTC) services. In particular, since mMTC service requires better EE and connection probability, while a URLLC service requires latency minimization, analytical expressions of throughput, EE, and latency for a mMTC/URLLC-UAV network have been derived. These expressions have been subsequently used to analyse how EE and latency are affected by the main scenario-relevant parameters like, UAV position and incorrect detection probability due to successive interference cancellation (SIC) in
NOMA. Furthermore, these expressions have been also used to evaluate the performance of an optimization algorithm proposed to maximise EE while satisfying the needs of URLLC latency and mMTC throughput.

**B. SYSTEM OPTIMIZATION FRAMEWORKS**

This subsection contains the current contribution to UAV-enabled URLLCs in terms of system optimisation. In particular, as also illustrated in the classification diagram (see Fig. 6), this subsection has been further divided into two subsubsection.

1) **JOINT OPTIMIZATION WITH UAV POSITION**

The potential of using UAVs in supporting URLLCs has been investigated in [41]. Through this analysis, which represents one of the first scientific studies in this area, authors showed that by establishing LoS communications employing UAV in the area of interest, URLLC requirements can be achieved. In particular, it has been firstly pointed out that the probability of LoS path and the network availability, defined as the probability that the QoS of users can be satisfied, are strictly concave in the communication distance between a ground user and a UAV. Subsequently, given the density of UAVs in the area of interest, an optimization problem, aimed to find the optimal UAV’s height to minimize the bandwidth required to maintain the URLLC requirements has been formulated. By solving this problem, authors showed that the requirements of URLLC can be satisfied with a single ground-to-air wireless link in sub-urban areas, while multiple ground-to-air or ground-to-ground wireless links are needed in urban areas. Furthermore, increasing the density of UAVs can remarkably save the required bandwidth.

A downlink communication system where a central controller Unit (CU) needs to send command information to a distant robot that performs certain reconnaissance missions has been analyzed in [44]. In particular, considering the adoption of amplify-and-Forward (AF) relay, it has been proposed an iterative algorithm aimed to minimize the decoding error probability by optimizing UAV position and the transmitting power at both GCS and UAV. Simulation analysis, conducted adopting either a free-space channel model or a 3D channel model, showed the performance advantages of the proposed algorithms respect to a fixed power allocation policy and a fixed location policy. Furthermore, it has also been illustrated how it is more beneficial to adopt the AF relay than a decode-and-forward (DF) relay when the latency requirement is stringent, which is usually the case in URLLC applications.

A novel framework to deliver different critical URLLC services deploying UAVs in an out-of-coverage area has been proposed in [51]. Notably, that study also considers the sporadic URLLC traffic problem, which represent one of the most relevant challenges of integrating 5G features on energy-constrained UAV systems, particularly serving out-of-coverage users. To cope with this traffic-related problem, an efficient online URLLC traffic prediction model based on Gaussian Process Regression (GPR) has been proposed. Then, a joint optimization problem that incorporates optimal deployment strategy of UAV for maximizing the average sum-rate while minimizing its transmit power with the constraints to satisfy stringent URLLC requirements and
considering the traffic sporadicity, has been formulated. Subsequently, a low complexity near-optimal successive minimization algorithm has been proposed to solve such mixed-integer non-linear problem (MINLP).

2) JOINT OPTIMIZATION WITH BLOCKLENGTH ALLOCATION

As in [44], a downlink communication system where a central CU needs to send command information to a distant robot that performs certain reconnaissance missions has been analyzed in [43]. In this case, it has been assumed that the channel gain between the controller and the robot is weak and negligible, and requires a UAV to assist the transmission between the controller and the robot through a DF d paradigm. Under these assumptions, a novel perturbation-based iterative algorithm, aimed to jointly optimize the location of the UAV and blocklength allocation, by minimizing the decoding error probability subject to the latency and location constraints, has been proposed. Through this study, it has been possible to highlight that the joint optimization of message blocklength and UAV position permits to obtain lower values of decoding error probability than only optimizing them separately. On the other hand, a similar scenario but with multiple number of remote devices has been considered in [45]. In this case, under the premise of ensuring the fairness among remote devices, by maximizing the transmitted effective amount of information received by the central controller, subject to the latency and reliability constraints, authors formulated a joint blocklength and transmit power optimization problem, for which an efficient iterative algorithm was proposed to solve it.

A recent study in [48] investigates the possibility to implement URLLC by jointly using UAV and reflective intelligent surfaces (RIS). Similar to [43], [44], in this work authors considered a downlink communication scenario where both GCS and the respective remote IoT device are separated by several obstacles which weaken the control signal. However, in this case the problem of ultra-high reliability in URLLC assisted by a mobile UAV equipped with RIS, and under a short packet transmissions communication scenario, has been formulated. In order to solve such non-convex and non-linear optimization problem, which aims to minimize the total decoding error probability by jointly optimizing the passive beamforming at the RIS, the blocklength and UAV position, a polytope-based method from the class of direct search methods (DSM) named Nelder-Mead Simplex (NMS) has been proposed. Through simulation results, it has been firstly shown that the proposed approach reaches favorable convergence performance compared to traditional gradient descent optimization algorithms, i.e., convergence is reached more quickly. Secondly, it has been illustrated how to increase the number of antenna elements in RIS as well as of the allocated blocklength, leads to a decrease of the decoding error probability. Last but not least, they highlighted how UAV position is crucial for achieving ultra-high reliability for short packets.

All the previously mentioned works, studied cases where URLLC are performed using a single UAV which serves as relay node between transmitter and receiver. Under this perspective, authors in [49] investigated a case where URLLC instruction packets between ground IoT devices are delivered through multi-hop UAV relay links. The considered scenario consists of a multi-hop downlink communication scenario between two IoT devices, where two UAVs serves as DF relays between. Under these assumptions, an optimization problem aimed to minimize the total decoding error probability, by jointly optimizing the message blocklength and the relative distance between UAVs, has been formulated. A semi-empirical based non-iterative algorithm has been proposed to solve the quasi-optimization problem. Simulation results illustrated how the proposed algorithm yields the same performance as exhaustive search algorithms but with reduced computational complexity, permitting then to guarantee the ultra-reliable regime requirements.

C. CROSS-LAYER AND OTHERS OPTIMIZATION FRAMEWORKS

Recently, to provide high Quality-of-Experience (QoE) to final users, UAV-enabled mobile edge computing (MEC) has received a lot of attraction [60]–[62]. Under this view, the possibility of an UAV-enabled MEC system, where UAV base stations (UBSs) are deployed to cache, process, and deliver virtual reality (VR) content from a cloud server to VR users (VRUs) has been investigated in [50]. Specifically, under the assumption of Rician fading channel model, authors proposed an iterative optimization algorithm aimed to optimize various resource allocation parameters, such as, association of VRUs with UBSs, caching policy, computing-capacity allocation, and location of UBSs, with the objective of minimizing the maximum latency, subject to computing caching, and power constraints at the UBSs.

A reduction of power consumption, while fulfilling the strict demands for ultra-reliability for short packets, is of paramount importance in order to realize future 5G communication networks and their services [63]. Under this perspective, the problem of minimizing the sum uplink power, in order to enable green URLLC assisted by a mobile UAV in a multiuser IoT communication scenario, has been studied in [52]. In order to solve the resultant optimization problem, a perturbation-based iterative algorithm, which has a lower sum consumption than benchmark algorithms and achieves a performance similar to the exhaustive search while maintaining a lower time complexity, has been proposed. Furthermore, it has been also illustrated how the required uplink power increases/decreases as either the minimal rate demand increases/decreases or the overall required error probability decreases/increases. Last but not least, it has been showed that Shannon’s formula is not an optimum choice to model sum power consumption for short packets as it can significantly underestimate the sum power. A more extensive study which aims to minimize the uplink transmitting power of IoT devices subject to URLLC constraints, but considering
multiple UAVs in the area of interest, has been proposed in [53]. In this case authors formulated an optimization problem to minimize the average transmit power of the system by jointly optimizing IoT devices scheduling and association, power control and bandwidth allocation as well as the deployment of UAVs under the constraints of latency and reliability. Simulation results illustrated how he minimal average transmit power decreases and as the available bandwidth of each UAV increases. Furthermore, it has been also highlighted that when the bandwidth resources are limited, the minimal average transmit power increases drastically as the threshold of decoding error decreases from $10^{-3}$ to $10^{-9}$. The average transmit power can be also greatly reduced by increasing the number of UAV. But in this case, it has been also illustrated that after a certain number of deployed UAV, no more improvements are achieved in terms of power requirements in uplink.

The power control for a URLLC-enabled UAV system incorporated with deep neural network (DNN) based channel estimation has been investigated in [54]. In this case, it was considered an uplink and downlink UAV communication scenario in which a BS, equipped with a vertically placed K-element uniform linear array, is utilized to transmit ultra-reliable and low-latency control message to a UAV, which is at the same time responsible for sending high-speed payload back to the BS. In this context, the communication problem of jointly optimizing the BS and UAV transmit power to guarantee high-speed downlink payload transmission, while satisfying the URLLC requirement of uplink control and non-payload signal delivery, has been formulated. In order to solve this problem, analytically tractable channel models based on DNN-estimation results, for both uplink and downlink directions, have been firstly proposed. Subsequently, using the proposed channel models and adopting a semi-definite relaxation (SDR) approach, the non-convex power control problem is effectively solved. The performances of the proposed approach in terms of power consumptions at both UAV and BS and the impacts of DNN channel error estimation, have been analyzed considering two different predefined trajectories for the UAV, i.e. a circular trajectory and a vertical ascent trajectory.

An exhaustive and complete analysis, which considers both uplink and downlink transmissions, has been proposed in [55]. More specifically, in this case authors considered a multi-UAV relay communication scenario in which a set of UAV are employed to assist a remote ground BS (GBS) in providing eMBB services to a set of remote users. While uplink transmissions, i.e., UE-to-GBS via UAV relay, are used to guarantee eMMB services, supposing UAV operating in a full-duplex mode, downlink communications will be employed to transmit control messages for UAVs constrained by the URLLC requirements. Under these circumstances, an optimization problem for multiplexing eMBB payload communication and URLLC control information communication has been formulated. To mitigate this challenging problem, which aims to jointly optimize the association between ground users and UAV, as well as bandwidth and transmit power, the problem has been equivalently decomposed it into a URLLC problem and an eMBB problem. Subsequently, a closed-form solution of the URLLC problem has been provided, while an iterative solution framework for the eMBB problem has been developed. Simulation results demonstrated the convergence of the proposed framework and how respect to other benchmark algorithm it outperforms in terms of average uplink throughput, user coverage, required bandwidth and power consumption. Due to the obstruction of buildings on the ground, the channel quality between the IoT devices and a ground base station (GBS) may not be good enough, and the requirements of latency and reliability cannot be guaranteed in URLLC. This issue would be addressed by increasing the transmit power of IoT devices. However, in most cases IoT devices are power constrained by their battery lifetime. In this perspective, an industrial and safety alarm scenario, in which the deployment of multiple UAVs over a certain area would result beneficial in order to meet the latency and reliability requirements of energy limited IoT devices, by minimizing their transmit power, has been studied in [56]. In this case, the problem to jointly optimize the device association, i.e., IoT-to-GBS or IoT-to-UAV, and UAV placement, to minimize the total power of the IoT devices by maintaining the URLLC constraints, has been formulated. This permitted to demonstrate that the power of devices in URLLC can be decreased by placing more UAVs to assist the wireless communications. Furthermore, the higher the latency can be tolerated, the significantly lower will be the power required by IoT devices.

V. CHALLENGES AND FUTURE DIRECTIONS

At the time of writing, most of the works on UAV-enabled URLLCs networks published in the literature focus their attention on proposing optimization frameworks aimed to mainly optimize UAV position and blocklength allocation in order to minimize and maximize the decoding error probability and sum data rate, respectively. Although some other contributions have been provided in terms of mathematical tools for performance analysis and cross-layer optimization, this research is still in its infancy stage. Under this perspective, in this section we provide some possible research directions which we believe will further contribute in providing implementation insights aimed to facilitate the deployment of UAV-enabled URLLCs services.

A. LARGE-SCALE DEPLOYMENT

The number of autonomous vehicles and mission-critical IoT devices is expected to increase rapidly within the deployment of future 5G and 6G networks [64]. In order to support massive such URLLCs, the adoption of novel communication and techniques will result necessary. This because the required bandwidth increases linearly with the number of devices. Then, in order to achieve better tradeoffs among delay, reliability, and scalability, other
multiple access technologies should be used, such as nonorthogonal multiple access and contention-based multiple access technologies [65]. Furthermore, since the usage of the above 6-GHz spectrum, including mmWave and the Terahertz band [66], [67], represents the main direction to mitigate the problem of spectrum shortage on future networks, the channel assumptions on current works may no longer be valid. Then, it is necessary to investigate impact of new channel characteristics on both reliability and latency. Furthermore, the possibility to obtain a closed-form expression of URLLCs related KPIs would be helpful to predict the performance of a proposed solution. Indeed, the main disadvantage of currently available theoretical analytical tools is that they are based on some assumptions and simplified models that may not be accurate enough for URLLC applications. Indeed, to analyze the E2E performance in URLLCs, the models may be very complicated, and closed-form results may not be available. Furthermore, the model mismatch may lead to severe QoS violations in real-world networks.

**B. REAL-TIME IMPLEMENTATION**

Basically, wireless communication networks are highly dynamic due to channel fading fluctuation. However, due of both UAV mobility and possibility of using above 6 GHz frequencies, the entity of these fluctuations can results higher in UAV-enabled URLLCs. As a result, the system needs to adjust resource allocation frequently according to these time-varying factors, which sometimes cannot permit to meet the low latency requirements. Furthermore, most of the current optimization algorithms only work well for small- and medium-scale problems. Then, although cross-layer optimization has the potential to achieve better E2E performances than dividing communication systems into separated layers, its implementation in practical systems still needs to address following issues:

- **High computation overheads** driven by the needs to adjust resource allocation frequently according to network time-varying factors like channel fading and traffic load fluctuations.
- **Problem intractability.** Indeed, due to complicated models from different layers, usually cross-layer optimization problems are usually nonconvex or nondeterministic polynomial-time (NP)-hard. Then, usually it takes a long time to solve such NP-hard problems, i.e. the resulting optimization algorithms are not suitable be implemented in real time.

In contrast to the development of optimization algorithms, another possible implementative approach for URLLCs is represented by the adoption of deep learning (DL) techniques, which results to be either model-based or model-free and can be more easily implemented in real-world communication systems [68]–[74]. Indeed, the adoption of such DL approach permits to find the optimal policy when this is not reachable or require long computation time by using an optimization approach. The basic idea is to approximate the optimal policy with a DNN and optimize the parameters of the DNN toward a loss function reflecting the design goal. However, even if this represent the most promising way to deal with real-world 5G/6G networks more research effort should be put on this innovative area. For example, how to design structures and hyperparameters of DNNs and adjust them in a very dynamic scenario is still unclear [17]. However, low-complexity numerical algorithms that can be executed in practical systems for URLLCs are still missing.

**C. URLLC SECURITY**

Future URLLC systems, as well as UAV-enabled networks may suffer from different kinds of security breaching attacks. For example, UAVs can be either hacked in flight by an attacker aiming at taking over their control, as well as by an eavesdropper attempting to collect sensible data or causing denial of services. In both cases, all these types of attack will result in inefficient communications. Although it is possible to adopt the widely used cryptography algorithms, this may results into high-complexity signal processing and then not suitable for URLLCs, especially for IoT devices with low computing capacities. Recently, the adoption of physical-layer security (PLS) has been recognised a valid solution against eavesdropping attacks in URLLCs [75], [76]. Furthermore, the LoS-dominated UAV channel plays an important for physical layer keys generation aimed (PLKG) to generate the secret keys to protect the confidential information exchanged between transceivers [77]. Then, based on the this technical results, technologies for improving physical-layer security need to be further investigated.

**VI. CONCLUSION**

In this paper, we have systematically reviewed the current SoA in the field of UAV-enabled URLLCs. For the sake of clarity and fluency, we have firstly provided a brief overview of the most relevant KPI and challenges for the implementation of both URLLCs and UAV-enabled networks. Subsequently, we have highlighted how these two communication paradigms can results complementary to each other. Indeed, by providing good channel condition at both transmitter and receivers, UAV communication could enable the possibility of having a reliable and low-latency communication channel, i.e. consistent reduction of packet error probability and then delay reduction for retransmission. We further pointed out how in order realize UAV-enabled URLLCs, it still results necessary to address some challenges which, depending on the considered application scenario, ranges from jointly optimizing different KPIs to performs some cross-layer optimization. At that pointed, a systematic review and classification of the research activities currently in literature has been provided. Finally, we have illustrated how the large-scale deployment of this communication network while maintaining a secure and real-time implementation represent a future direction in this area.
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