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System Requirements Specification for Unmanned Aerial Vehicle (UAV) to Server Communication

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***Abstract*—Within this paper, requirements for server to Unmanned Aerial Vehicle (UAV) communication over the mobile network are evaluated. It is examined, whether a reliable cellular network communication can be accomplished with the use of current Long Term Evolution (LTE) network technologies, or, if the 5th Generation (5G) network is indispensable. Moreover, enhancements on improving the channel quality on the UAV-side are evaluated. Therefore, parameters like data rate, latency, message size and reliability for Command and Control (C&C) and application data are determined. Furthermore, possible improvements regarding interference mitigation in the up- and downlink of the UAV are discussed. For this purpose, results from publications of the 3rd Generation Partnership Project (3GPP) and from surveys regarding UAVs and mobile networks are presented. This work shows that, for C&C use cases like steering to waypoints, the latency and the data rate of the LTE network is sufficient, but in terms of reliability problems can occur. Furthermore, the usability of standard protocols for computer networks like the Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) is discussed. There are also multimodal implementations of these protocols like MultiPath TCP (MPTCP) which can be adapted into the UAV's communication system in order to increase reliability through multiple communication channels. Finally, applications for Long Range (LoRa) direct communication in terms of supporting the cellular network of the UAV are considered.**

***Index Terms*—UAV Communication, Quality of Service, LTE, 5G, LoRa**

I. Introduction

According to several sources, there is a growing interest in applications, where Unmanned Aerial Vehicles (UAV) are commercially used [1]–[3]. Those applications are taking place in the area of inspection, agriculture, logistics, and monitoring [4]. Moreover, humanitarian operations, rescue missions, and transport of persons are considered as a utilization of UAVs [2]. Hence, the whole society can profit by future UAV developments.

Normally, the UAV is controlled by the operator within the Visual Line Of Sight (VLOS), but thereby the range is restricted, and autonomous flying is usually not promoted. Therefore, the realization of UAV applications in the sense of the U-Space architecture [5] is needed. To accomplish this undertaking, the mobile network is considered as a communication channel. For visualization, Figure 1 shows

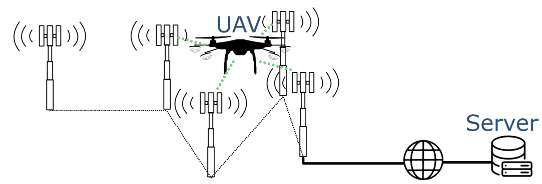

Fig. 1: Illustration of a mobile network based server to UAV communication.

schematically a mobile network based UAV to server communication. As indicated, the UAV is equipped with multiple antennas and receives signals from several base stations (BS) simultaneously. Simplified, the data link between UAV and server consists of an air interface towards at least one BS, and a connection between the BS and the server over the internet. With the mobile network, wide area can be covered [4]. Moreover, the 3rd Generation Partnership Project (3GPP) organization provides new technologies and enhanced support for UAVs [6], [7]. In order to optimize the data transmission, prediction models towards the quality of service (QoS) in cellular networks will be elaborated within this project. These models are based on measurements and their usability for algorithms regarding multimodal communication. Within the present paper, multiple requirements which can be adopted to many kinds of UAV to Server communication are discussed and specified.

The main goal of this work is to answer, whether it is possible to operate a UAV over the Long Term Evolution (LTE) network and which enhancements are needed. Therefore, the general requirements, as data rate, latency, and reliability, for a reliable server to UAV communication, need to be specified. Moreover, it will be examined, which general requirements can be fulfilled by the LTE technology, and where further technologies such as the 5th Generation (5G) standard or Long Range (LoRa) technologies are required or can be useful. Thereby, requirements towards the hardware for an implementation of the mobile communication on the UAV-side are elaborated. Another aspect is finding an appropriate protocol for the data transmission. Therefore, the protocols Transmission Control Protocol (TCP) and User Datagram

Protocol (UDP), which are typically used in computer networks and the internet, are compared. Enhancements of these protocols like their multipath versions are also considered. Within this contribution, related work is discussed to define the requirements. The related work consists of surveys and papers regarding UAVs, LTE, 5G, LoRa, and network protocols. Also, technical specifications and reports by 3GPP are employed. In the following, the requirements for C&C and application data transmission will be evaluated in Section II. In Section III, the threats and possible solutions for operating a UAV over the LTE network are discussed, and the enhancements that come along with 5G and the requirements for an implementation are shown in IV. An overview of the protocols TCP and UDP with a discussion on possible enhancements and their usability in a mobile network based UAV communication is provided in Section V. The LoRa technology is explained in Section VI, whereby a possible exploitation for the UAV use case is presented. Eventually, Section VII gives a conclusion and an outlook towards future work.

II. General requirements on operating a UAV over the cellular network

In a basic application, an operator, standing on the ground, controls a UAV, which is in the operator's visual line of sight. Moreover, the operator is equipped with a controller, whereby a direct communication towards the UAV is established. The described composition is limited to a few use cases with low range.

A more advanced approach is the usage of the cellular network for the data transfer between the operator and the drone. Several requirements concerning data rate, latency, message size, and maximum packet error loss rate are made. In the literature, the requirements are divided into C&C and application data. For C&C according to 3GPP [6], the latency should not exceed a limit of $50\,\mathrm{ms}$ one way from E-UTRAN Node B (eNB) to the UAV. Furthermore, a data rate for down- and uplink of 60–$100\,\mathrm{kbps}$ and a maximum packet error loss rate of 10^{-3} are required for a reliable communication. Muruganathan, Lin, Määttänen, *et al.* [8] agree to these conditions, whereas Yang, Lin, Li, *et al.* [4] define slightly different limits. In their work, the required uplink rate for C&C is named as $200\,\mathrm{kbps}$, and a network latency of $20\,\mathrm{ms}$ for remote real-time control is determined.

The reasons for the differences in data rate and latency are explained below. The required data rate is dependent on the length of the transmitted data. The reason for the difference in the estimated required latency is that, within the $20\,\mathrm{ms}$, only air-interface and core network latency are included, whereas the $50\,\mathrm{ms}$ contain sending an application layer packet/message [4], [6], [9].

Another approach is shown in Table I. There, the required latency for direct stick steering estimation is based on the update rate of the UAV's on board flight controller [7].

Table I shows that the value of the required latency is less than $40\,\mathrm{ms}$ for a UAV with a flight controller of a cyclic frequency of $25\,\mathrm{Hz}$. In order to decide whether a reliable communication can be established within the LTE network, it is important to define the latency itself and a goal, which latency should be reached. C&C messages over the application layer will be simulated in order to achieve realistic results. Therefore, the latency is defined as the duration of the end-to-end communication including application layer, air-interface and core network. Moreover, the message size in Table I is located at the application layer and excludes overhead of the bottom layers, and the reliability is defined as the probability of successful transmission within the required latency at the application layer while under network coverage [4], [7].

TABLE I: C&C requirements for different UAV control modes defined by 3GPP [7]

Control Mode	**Typical message size**	**End to end latency**	**Reliability**
Steer to waypoints	84–140 bytes	1 s	99.9 %
Direct stick steering	24–140 bytes	40 ms	99.9 %
Automatic flight on Unmanned aircraft system Traffic Management (UTM)	1.5–10 kbytes	5 s	99.9 %
Approaching autonomous navigation infrastructure	4 kbytes	10 ms	99.99 %

The latency goal needs to be defined on the requirements of a selected UAV to facilitate reliable operational control. According to the previous sources, it is approximately 40–$50\,\mathrm{ms}$. For the prediction models in future work, it is planned to exchange generated C&C messages of the size as it is shown in Table I between a server and the UAV. For example, while simulating direct stick steering, the UAV sends $140\,\mathrm{bytes}$ of data and receives $24\,\mathrm{bytes}$ in the update interval of the UAV's controller.

In terms of the application data, the chosen literature consents that in most cases, the required uplink data rate is higher than the downlink data rate [4], [6]–[8]. 3GPP [6] suggests an uplink rate up to $50\,\mathrm{Mbps}$, whereas Yang, Lin, Li, *et al.* [4] go even further with suggesting rates up to $1\,\mathrm{Gbps}$ for augmented reality and virtual reality.

In the next section, requirements and difficulties on integrating a UAV into the cellular LTE network for a UAV to server communication is evaluated. Thereby, it is determined whether a LTE network can provide the general requirements for UAV operations, or further enhancements are needed.

III. Requirements on integrating a UAV into the cellular LTE network

Additionally, the requirements for the integration of a UAV into the cellular LTE network are shown. The following description refers to 3GPP [6]. In this study, an assumption on the requirements for UAVs is made, where the maximum target height is stated to be $300\,\mathrm{m}$ above ground level (AGL) and the maximum horizontal speed is indicated as $160\,\mathrm{km/h}$. In the evaluation, three scenarios regarding E-UTRAN Node B antennas (eNB) are defined [6], [8]:

- Urban-macro with aerial vehicles (UMa-AV)
- Urban-micro with aerial vehicles (UMi-AV)

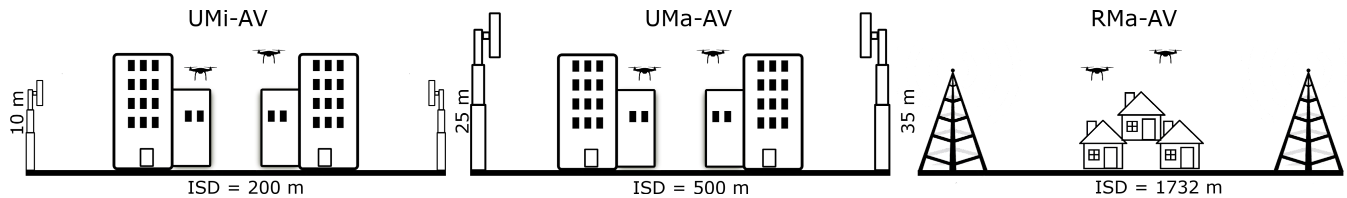

Fig. 2: Visualization of the eNB scenarios based on the work of 3GPP [6] and Muruganathan, Lin, Määttänen, *et al.* [8].

- Rural-macro with aerial vehicles (RMa-AV)

As visualized in Figure 2, by UMi-AV, antennas at a height of $10\,\mathrm{m}$ with an inter-site distance (ISD) of $200\,\mathrm{m}$ are simulated. UMa-AV antennas are mounted at $25\,\mathrm{m}$ above the ground with an ISD of $500\,\mathrm{m}$, and RMa-AV antennas are placed at $35\,\mathrm{m}$ height with a ISD of $1732\,\mathrm{m}$ [6], [8].

Due to the height, user equipment (UE) on aerial vehicles can experience interference problems. One cause for this issue is that aerial UEs receive downlink interference from a larger number of cells, because of their high line of sight propagation probability [6]. In Figure 3, the percentage of UEs over the number of interference cells within a Reference Signal Received Power (RSRP) gap of $6\,\mathrm{dB}$ is illustrated. Moreover, the results for the different eNBs in a height of $50\,\mathrm{m}$ are shown.

The figure shows that, the height of the UAV in which the most interference cells are recognized depends on the eNB. At a UAV height of $50\,\mathrm{m}$, with RMa-AV, up to 10 strong interference cells are detected, whereas at UMi-AV only 7 and with UMa-AV 8-9, strong interference cells are perceived. Moreover, in the case of the UMa-AV, it is shown by 3GPP that with increasing heights, the number of strong interference cells also rises [6]. Another aspect is that, if the eNB antennas are downtilted, aerial UEs flying higher than antenna height, are served by side lobes, which can

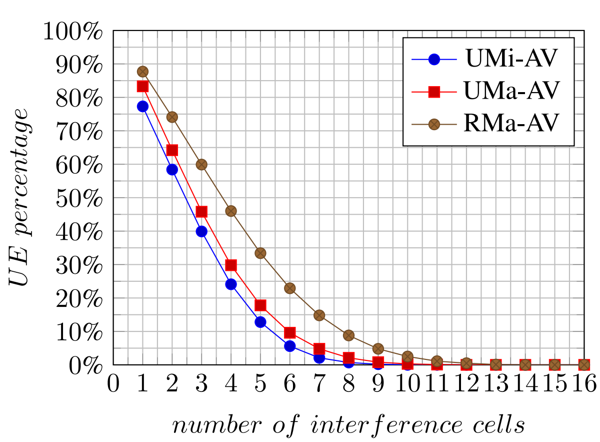

Fig. 3: Comparison of the three scenarios UMa-AV, UMi-AV, and RMa-AV on the percentage of UEs with at least N strong interference cells (within an RSRP gap of $6\,\mathrm{dB}$) with same-type UEs at a UE height of $50\,\mathrm{m}$ based on the work of 3GPP [6]

lead to a use of a faraway base station and thus to path loss [8]. The described interference problem in the downlink leads to higher resource utilization, whereby the spectral efficiency of the network is decreased, and the terrestrial UEs are negatively influenced [6]. Regarding the uplink, aerial UEs cause interference when uploading data to the eNB and have a negative impact on all UEs perceiving the interference [6]. Similar results are shown by the simulations from Azari, Rosas, Chiumento, *et al.* [10]. There, the coverage probability of the cellular network decreases with rising altitudes of the UAV evoked by interference due to the line of sight propagation probability. Furthermore, it is evaluated that both, terrestrial UEs and UAVs, can benefit from lowering the height and increasing the down-tilt angle of the eNBs.

Hayat, Bettstetter, Fakhreddine, *et al.* [11] found in an experimental evaluation an increase in RSRP drops of different eNBs with higher altitudes of the UAV and thus support line of sight propagation probability and interference. This leads to more handovers and a degradation of the throughput. The TR 36.777 by the 3GPP organisation describes different approaches for solving the issues in the cellular network caused by aerial UEs. Those potential enhancements are divided into downlink interference mitigation and uplink interference mitigation [6]. The potential improvements according to 3GPP [6] for avoiding downlink interference are usage of:

- Full Dimensional Multiple Input Multiple Output (FD-MIMO)
- Directional antennas
- Receive beamforming
- Intra-site Joint Transmission Coordinated Multi-Point (JT CoMP) operation
- Coverage extension and coordinated data and control transmission

FD-MIMO provides a large number of active antennas at the eNB arranged in a 2D planar array. Due to a large number of antennas, the inter-user interference in the downlink can be decreased. Furthermore, with active antennas, 3D beamforming can be utilized [6]. This means the vertical and horizontal direction of the beam can be controlled [12]. It is evaluated that, with FD-MIMO, the throughput loss of terrestrial UE can be reduced while aerial UEs are active [6]. As a result, a modem used in a UAV application should support MIMO. Indeed, FD-MIMO has to be implemented at the eNB by the mobile provider as well.

The next technique that provides a benefit according to 3GPP [6] is the usage of directional instead of omnidirectional antennas. Due to the direction of the antennas, fewer cells are detected by the UE, whereby the interference coming from a broad range of angles can be reduced. There are different approaches on aligning the antenna. One of them is placing the antenna to the direction of travel. Another option is to steer the antenna towards the serving cell to accomplish an ideal line of sight or with errors due to practical constraints non ideal line of sight.

Moreover, the results shown by Kelif and Simon [13], where a model is developed that replaces omnidirectional antennas by directional ones for terrestrial UEs, demonstrate positive effects in most cases using directional antennas. Thus, for the integration of a UAV into the LTE network, directional antennas may be used for the UAV, and the approach on mounting the antennas to the direction of travel should be evaluated.

Another solution regarding interference mitigation deals with beamforming. At the receiver, several antennas are used to avoid receiving interference, called receive beamforming [6], [14]. To accomplish the described technique several antennas need to be mounted to the UAV, and the selected modem should be able to support receive beamforming.

The other suggested solutions on mitigating downlink interference like intra-site JT CoMP, coverage extension, and coordinated data and control transmission cannot be implemented by the UAV operator. Instead, they have to be applied by the communication providers [6].

For avoiding interference caused in the uplink and thus degrading the performance for terrestrial UEs, 3GPP [6] also describes similar approaches like FD-MIMO and the use of directional antennas for the mitigation of this phenomenon.

In addition, power control-based mechanisms are introduced, which only pertain the uplink. Here, recommendations are the introduction of a height dependent path loss compensation factor α_{UE} in the power control loop, a UE specific P_0 parameter, and closed loop power control [6], [8]. The survey by Lin, Yajnanarayana, Muruganathan, *et al.* [15] also suggests customized power control parameters for the UAVs to mitigate uplink interference. Consequently, the power control-based mechanisms are implemented by the manufacturer of the LTE modem. While selecting a modem, these aspects need to be considered.

Interference can also occur within the LTE connection and the direct communication between the UAV and the operator, which is usually carried out on $2.4\,\mathrm{GHz}$ inside the Industrial, Scientific, and Medical (ISM) bands. Thereby, the uplink of the LTE modem can cause interference to the ISM receiver and vice versa [16]–[18]. The easiest way to avoid this interference is to disable the direct connection, transmitting the operator data over the LTE network. A further option which can be applied in our use case would be the limitation of the transmission power [17].

Another important aspect that needs to be examined are the operating frequencies of LTE in Europe, especially in Germany. For optimizing the performance of the data transfer over the cellular network, the selected modem needs to support all frequency bands that are available. In Germany, the LTE frequency bands are located between $800\,\mathrm{MHz}$ and $2600\,\mathrm{MHz}$.

These frequency bands are split up into smaller bands, which are used by the three providers Telefónica Germany GmbH & Co. OHG, Vodafone GmbH, and Telekom Deutschland GmbH [19]. As a result, for optimizing the QoS, the available providers will be accessed.

Drawing a conclusion towards the requirements on integrating a UAV into the cellular LTE network, one modem for each addressed provider needs to be selected, which can operate at the frequency bands of the desired country (here Germany), supports FD-MIMO, and beamforming. Moreover, several directional antennas may be used.

Next up, it will be evaluated whether the general requirements can be accomplished. With LTE-Advanced, a theoretical rate of $3\,\mathrm{Gbps}$ in the downlink and an uplink rate of $1.5\,\mathrm{Gbps}$ is possible [20]. According to Yang, Lin, Li, *et al.* [4], in a physical test with a UAV, $1080\,\mathrm{p}$ image transmission with a rate of $4\,\mathrm{Mbps}$ can be attained with LTE-Advanced. Thus, the general requirements for the data rate from Section II can be met.

However, Yang, Lin, Li, *et al.* [4] show latencies between $200\,\mathrm{ms}$ and $300\,\mathrm{ms}$ for a UAV flying at heights of $50\,\mathrm{m}$ and $100\,\mathrm{m}$. By rising the height, the latency also increases. Thus, according to Table I, direct stick steering cannot be accomplished by using the LTE network. Another issue lies in provisioning the required reliability. In the study of Nguyen, Amorim, Wigard, *et al.* [21], a minimum Signal to Interference plus Noise Ratio (SINR) threshold of $-6\,\mathrm{dB}$ is determined to enable C&C communication. This means, all data points with a SINR below $-6\,\mathrm{dB}$ are considered as outage. For $99.9\,\%$ reliability, the maximum outage is $0.1\,\%$. The results by Nguyen, Amorim, Wigard, *et al.* [21] show an outage for UAVs in the LTE network up to $51.7\,\%$ in a height of $120\,\mathrm{m}$. With multiple retransmissions, the outage probability can be decreased, but in the worst case for a reliability of $99.9\,\%$, $log_{0.517}(0.01) \approx 7$ re-transmissions need to be performed, and thus, a low latency is required. In order to increase the performance and reliability of the UAV to server connection, QoS modeling and prediction need to be investigated in future work. Thereby, the experience in QoS prediction gained by previous projects, regarding vehicle to server communication in the automotive sector, will be used to accomplish these enhancements [22], [23].

In case the QoS prediction in combination with the LTE network does not deliver the expected results, further technologies like 5G and LoRa are evaluated in Section IV and VI.

IV. Enhancements and Requirements for UAVs in the 5G Network

With the launch of the 5G network, many enhancements for UAVs can be accomplished. Firstly, 5G uses mmWave, resulting in high frequencies and thus higher data rates because of broader bandwidths [4], [24]. The frequencies for mmWave are defined by 3GPP in the frequency range (FR) 2 as shown in [25] and lie between $24\,250\,\mathrm{MHz}$ and

52 600 MHz. Although those frequencies are bound to the technical specification 38.101-1 [25] they may be extended later. According to Amorim, Wigard, Kovacs, *et al.* [26], the mmWave spectrum is between 30 GHz and 300 GHz. Thus, higher frequency bands up to 300 GHz may be defined and used in the near future. However, as the frequency increases, the communication range is shortened due to path loss. Therefore, advanced solutions as distance-adaptive, Reflectarrays, or Hyper Surfaces are developed reaching distances of up to 100 m at 60 GHz [24]. Thus, in order to enable a 5G network with high frequencies and sufficient coverage, a larger number of base stations (BSs) is required.

The design of circuits and antennas for mmWave technology is smaller, whereby the UAV needs to carry less weight [24], [26], [27]. According to studies by Yang, Lin, Li, *et al.* [4], Zhang, Zhao, Hou, *et al.* [24], and Ratnam and Molisch [27], massive MIMO with 3D beamforming will be implemented within the 5G technology. With this technique, the beam direction can be controlled towards the UAV. Moreover, information as the flight route of the UAV can be used to form the beam towards the UAV with greater resolution through mmWave [4], [24]. Also, interference can be mitigated by suppressing beams of interfering signals [4], [24], [28]. Regarding massive MIMO in the 5G network, Garcia-Rodriguez, Geraci, Lopez-Perez, *et al.* [29] mention that, BSs can mitigate inter-cell interference by positioning radiation nulls.

In order to be able to use the described enhancements, a modem is required, which supports the frequencies of the mmWave or the 5G network in general. In contrast to LTE, for the 5G network, an adaptive omnidirectional antenna is recommended [29]. Thus, MIMO and precise beamsteering can be enabled.

Another enhancement of 5G is network slicing. This topic is already named by the providers Vodafone [30] and Telekom [31] in the context of building up a 5G network. With network slicing, multiple logical networks are generated on one physical network [4]. Within the logical networks respectively slices, the C&C traffic can be separated from the data traffic or the aerial and terrestrial UEs can be isolated [32]. Furthermore, a UAV should be recognized by the BS to accomplish service optimization for the drone [4], [32].

With a frequency band of 3.5 GHz in the 5G network, according to Yang, Lin, Li, *et al.* [4], data rates of up to 1.3 Gbps in the downlink and 175 Mbps in the uplink are expected, whereas in the 26 GHz band, up to 13 Gbps in the downlink and up to 1.75 Gbps in the uplink are estimated [4]. Thus, the required data rate of 60–100 kbps for C&C traffic can be highly exceeded. Moreover, with the 5G network, ultra reliable and low latency communication (URLLC) is introduced [33], [34]. There, for a message size of 32 bytes, a reliability of $1-10^{-5}$ with a latency of 3.5 ms [34] or even 1 ms [35] in the user plane is announced. With these stated values for the data rate, reliability and latency, the requirements for C&C from Table I in Section II can be fulfilled for any control mode. Although it is likely that those announced values are worse for UAVs due to interference.

The 5G frequency bands are specified by the 3GPP organisation in [25]. Some of these frequencies overlap with previous defined frequency bands of the 3G network. For example, the n1 band of 5G as shown in [25] with an uplink frequency of 1920–1980 MHz and a downlink frequency of 2110–2170 MHz uses the same frequencies as the first operating band of 3G as defined in [36]. Thus, already used frequencies may be reused for the 5G network. The presentation of the 5G auction results in [37] shows an overview of the distribution of the current frequency bands in Germany. The frequency bands depicted by the Bundesnetzagentur [37], which will expire in the year 2040, are the ones sold to the providers in order to be used for the 5G technology.

Thus, the new radio (NR) bands n1, n78 will be used for 5G, and must be supported by the selected modem. Usually, most 5G modems support all of the listed NR-bands shown in [25]. Furthermore, in order to enable the advantages along with the mmWave, the modem should support the 5G technology.

V. Suitable protocols for the UAV use case

There are the two IP-based protocols TCP and UDP that are mainly used in computer networks. TCP is a connection-oriented protocol with three-way handshake, and UDP is a connection-less protocol where datagrams are exchanged, whereby the received data with UDP are unordered, and packet loss can occur.

Regarding the use case of the protocols in a UAV to server communication over the mobile network, TCP seems suitable for most C&C traffic due to its reliability through the acknowledgments and the congestion control mechanisms. Regarding C&C, UDP may be used for direct stick steering due to fewer delays and its real-time capability [38]. Moreover, UDP is suitable for non safety-relevant application data traffic like video transmission, because of the missing handshake and retransmission mechanisms. However, TCP was originally developed for networks with low bit-error rates. At a standard implementation of TCP, the high error rates and frequent disconnections, which occur in wireless networks cause a reduction of the transfer rate, because of congestion control. When packet losses occur through channel errors, the size of the sliding window is cut in half, and recovers by increasing the size at one packet per Round Trip Time (RTT). This mechanism helps to mitigate congestion in wired networks, but causes lower transmission rates in wireless networks [39], [40].

There are different approaches to reduce these issues with TCP in wireless networks. The Snooping TCP protocol provides a snoop agent at the network-layer of the fixed host to hide packet loss from the congestion control mechanism [40], [41]. Another approach is the Forced Acknowledgment TCP (FACK-TCP) protocol, where the slow-start mode of TCP is suppressed [41]. Versatile TCP (V-TCP) on the other hand customizes the congestion control algorithm, so that connection failures detected by the network layer do not cause congestion mitigation [42].

The mentioned TCP extensions need high implementation effort and are therefore not considered further. On the contrary, UDP has no congestion control algorithms implemented. Consequently, the data rate is not reduced when packet loss occurs [39]. Therefore, UDP behaves similar in wireless networks compared to wired ones, but with an increase in the loss rate.

In order to reduce packet loss of UDP, algorithms are proposed, which use a Negative-acknowledgment (NACK) mechanism when loss occurs. If a NACK is received, the lost data will be resent [43]. A similar approach is proposed in the NACK-Oriented Reliable Multicast (NORM) protocol. Besides NACK, there is also a congestion control scheme implemented to share the network bandwidth with protocols such as TCP [44]. Similar to the TCP enhancements, the suggested UDP expansions require higher implementation efforts.

For the prediction model of the mobile network interfaces in future work, QoS measurements need to be performed. Moreover, in order to review future results with the QoS prediction, the QoS parameters throughput, latency, and reliability from Section II need to be determined by the used protocol. Therefore, the QoS parameters of TCP and UDP are compared in the following. With TCP, the throughput, RTT, jitter, receive windows size, and packet loss can be obtained. Thereby, the throughput is the difference of the data rate and the transmission overhead like IP-address, or the portnumber. The RTT is the time difference between sending a segment and receiving the acknowledgment flag as shown in Equation (1). To get an estimation of the latency defined as the one way delay in Section II, the RTT may be cut in half, but this approach is not precise, because different paths for the opposed directions can be used. The calculation of the one way delay is shown in Equation (2), where t_s is the time, when the packet was sent, and t_r is the time, when the receiver gets the packet. The jitter is the variation of the delay showing whether the connection is stable, or if the network condition is often changing. The jitter can be calculated as the mean value of the difference in transition time of two consecutive packets as shown in Equation (3), where n is the number of packets used for the average. Moreover, t_t is the difference between send- and receive time of a transmitted packet including kernel delays. In contrary to the one way delay, the system clocks of the sender and receiver need no synchronization for the jitter calculation [45]. The receive window size and packet loss are connected in the way that, when packet loss increases, the window size is reduced. Thus, both are indicators for the reliability of the connection, whereby the reliability can be calculated with packet loss directly [46]–[48].

$$RTT = t_{ACKr} - t_s, \quad (1)$$

$$OWD = t_r - t_s \approx \frac{RTT}{2}, \quad (2)$$

$$Jitter = \frac{1}{n} \sum_{i=0}^{n} (t_{t\ P\ i+1} - t_{t\ P\ i}). \quad (3)$$

With UDP on the other hand, throughput, jitter, and packet loss can be measured without further enhancements, because of its protocol characteristics. For a measurement of the RTT, an echo server is required to acknowledge sent messages or mirror them [38].

Regardless of TCP or UDP, for one way delay measurement, a clock synchronization between sender an receiver is required. For synchronization, a GPS clock can be used. Therefore, a GPS module needs to be attached to both the sender and receiver. By sending timestamps, the one way delay can be calculated as the difference between send time and receive time [49], [50]. Another solution for clock synchronization is provided by the Network Time Protocol (NTP). With NTP a synchronization between the clocks of a server and client over the internet is possible [51]. In Wide Area Networks (WAN) such as the internet, an accuracy of low tens of milliseconds can be delivered. By using GPS receivers, higher accuracies are possible [52]. Thus, for one way delay measurements, GPS modules are required, even if NTP is used to achieve a sufficient accuracy. Moreover, with NTP, additional traffic is generated, which can distort the QoS measurement.

To further extend the capabilities of the protocols for their use in mobile network communication, Multipath versions of TCP and UDP are considered. An approach for this undertaking is using MultiPath TCP (MPTCP). With MPTCP, a connection between a client and a server can be established while transmitting the data over different physical media simultaneously [53]–[55]. MPTCP may be chosen over comparable solutions like the Stream Control Transmission Protocol (SCTP) or Concurrent Multipath Transfer extension for SCTP (CMT-SCTP). According to Jagetiya, Ramakrishna, and Haider [56], SCTP has no application compatibility, no simultaneous use of multiple paths, and no backward compatibility to TCP, whereas MPTCP supports those features. This means that applications, which previously used the TCP protocol work the same way while using MPTCP, because the protocol is operating at the transport layer [54], [55]. In a study by Becke, Adhari, Rathgeb, *et al.* [57], a comparison between CMT-SCTP and MPTCP is conducted. The result of this study shows that, within the investigated scenario, MPTCP can perform significantly better than CMT-SCTP [57]. Finally, MPTCP is chosen, because it will be implemented in the upstream Linux kernel and thus, it will be further developed and maintained [55].

For establishing a MPTCP connection, both devices on the client and the server side need to support MPTCP [54]. In a MPTCP connection, additional TCP sessions called subflows are established, if multiple network interfaces are available, causing parallel transmission of the application data over the subflows. The data to the subflows is aligned dynamically, whereby the priorities of the subflows can be changed in the userspace. If one device is not capable of MPTCP, the protocol will fall back to TCP [54], [55].

A possible use of MPTCP, within integrating a UAV into the mobile network, is generating one subflow for each addressed mobile provider in order to improve communication reliability. Therefore, one network interface for each subflow is required. With dynamically changing the subflow priority according to the predicted QoS, which will be implemented in future work, the functionality of the QoS prediction algorithm can be evaluated.

On the other hand for UDP, a Multipath version is not specified by the IETF yet, but suggestions are made to provide a solution for unreliable traffic [58]. Amend, Bogenfeld, Cvjetkovic, *et al.* [58] show an implementation of the IP extended Multipath DCCP protocol for transmitting UDP traffic. The Datagram Congestion Control Protocol (DCCP) is a standardized protocol, which provides congestion control for unreliable datagram connections [59]. The protocol stack for Multipath DCCP is similar to MPTCP by implementing subflows and being transparent to higher and lower levels [60]. Boutier and Chroboczek [61] and Liu, Lei, Zhang, *et al.* [62] also present a Multipath UDP called solution. The approach by Boutier and Chroboczek is a user-space implementation of Multipath UDP based on Mosh, but currently under development. The other approach by Liu, Lei, Zhang, *et al.* [62] is more promising with support for UDP and TCP, although there are TCP based mechanisms like acknowledgements and flow control implemented.

As a conclusion, TCP is designed for reliable data transmission due to its congestion and flow control algorithms. Regarding QoS parameters, TCP covers the required parameters from Section II, although for one way delay measurements further effort is required. Moreover, Multipath TCP will be added to the upstream Linux Kernel, and thus provides high usability. On the contrary, UDP is suited for applications that do not require reliable or ordered transmission. Nevertheless, UDP is suitable for real-time based applications that require low latency [38]. Towards the QoS parameter, UDP does not provide acknowledgements, whereby RTT and thus latency measurements require additional implementation effort. Approaches for a Multipath UDP application have been made, but none is standardized yet. For the UAV use case, one protocol will probably not be sufficient to fulfill the needs for both the C&C and application data. One way could be using MPTCP for C&C traffic, while applying our future QoS model, and for application data, the standard UDP protocol may be utilized. Another approach to enable direct stick steering may be using UDP for both C&C data and application data.

VI. Long Range direct communication as a fallback option

For debug and safety purposes, LoRa will be introduced and discussed in the following. LoRa is the physical layer for the LoRaWAN communication protocol. It is designed for Low-Power, Wide-Area Networks (LPWAN). Due to its modulation, LoRa can be used for long range applications by providing optimized battery lifetime. In Europe, a data rate of up to 50 kbps for a single communication channel can be accomplished. In contrast to other Internet of Things (IoT) technologies like NB-IoT and LTE-M [63], [64], LoRa is separated from the cellular network, and thus not dependent on the technology and coverage developments of the mobile providers. The structure of LoRaWAN consists of multiple end nodes sending their data to a gateway called concentrator. After that, the concentrator can forward the collected data to a server over a network technology with higher bandwidth. There are three different device classes, that can be implemented on the end node side [65].

Those classes differ in their sleep time, where they use low energy and are not listening for messages sent by the gateway resulting in high latency for waking up. The devices in Class A are usually in sleep mode and only active when sending new messages. After the transmission, a receive window is open for a few seconds, where data from the gateway can be received. In Class B, the receive windows, and thus the sleeping times are scheduled. When not transmitting, Class C devices listen continuously for messages. The sleep time is reflected in the average energy consumption, where Class A consumes 5 µA, Class B 30 µA, and Class C 10 mA [66].

There are different use cases for LoRa in UAV applications. Firstly, LoRa can be used in the IoT context, where sensor data with low requirements towards bandwidth is transmitted. The idea of Martinez-Caro and Cano [67] is measuring air pollution with sensors attached to a UAV and sending the data via LoRa. Another approach presented by Gunawan, Yahya, Sulaemen, *et al.* [68] is monitoring the GPS location of the UAV by transmitting the positions over a LoRa link. This can be further exploited to find an incapacitated or damaged UAV due to the low energy consumption of LoRa [69].

A further use case of LoRa is enhancing a mobile network-based UAV link as shown by Yuan, Jin, Sun, *et al.* [70]. Thereby, all UAVs of a swarm are equipped with LoRa, WiFi, and LTE links to test which link provides highest reliability and lowest polling delays. It was found that, LoRa should be preferred over WiFi for the C&C link if LTE is not available, because of better results in real life testing regarding reliability and the polling delay, whereby the communication range of LoRa is in comparison to WiFi eight times higher [70]. Similar findings were made by Kainrath, Gruber, Flühr, *et al.* [71], whereby LoRa is combined with GSM/3G. Both implementations differ in terms of LoRa in the way that Yuan, Jin, Sun, *et al.* [70] places the LoRa gateway on the ground, whereas in the configuration by Kainrath, Gruber, Flühr, *et al.* [71], the LoRa gateway is mounted on the UAV and the end node is located on the ground. An advantage of a gateway placed on the UAV is that, data can be received and sent simultaneously. Although the enhancements on the energy consumption are only provided by an end node. Thus, it is more reasonable to put a Class C end node on the UAV with scheduling the sending and receiving windows.

Within our work on providing a reliable UAV to server communication over the mobile network, LoRa can be used to enhance the C&C link, when there is no LTE or 5G network available.

VII. Conclusion and future work

With this paper, the general requirements on operating a UAV over the cellular network were considered at first. Thereby, the requirements were split into demands for C&C and application data in order to take a closer look. In Section III, it was examined that the stated requirements can only be fulfilled partially by the LTE network. Nevertheless, there are enhancements like FD-MIMO or directional antennas, which can be applied within LTE to facilitate a mobile network-based server to UAV communication. Additionally, the upcoming 5G network technology provides further support for UAVs, although for acceptable coverage, many BSs are required due to the high frequencies and the resulting path loss. Another aspect, which was further examined, is the selection of a network protocol for the UAV communication, whereby the multimodal expansion of TCP seems suitable for reliability improvements. Finally, LoRa and its usability within a mobile network-based UAV communication was presented. An extension of the system towards LoRa provides further options for enhancements on the C&C reliability or debugging.

To conclude, multiple modems which support both the LTE as well as the 5G technologies in the regional frequency ranges are required. Moreover, various directional antennas operating in the LTE/5G frequencies can be beneficial. Furthermore, a Class C LoRa device and a gateway are required to provide a LoRa link. For the support of different communication channels, an implementation of UDP in combination with a Multipath protocol like MPTCP should be considered. Regarding the measurements for the QoS prediction a calculation of one way delay is useful. Thus, a GPS receiver is required at the server and UAV side for synchronizing their system clocks. In consequence, all of these technologies need to be combined in a communication platform in order to provide reliable data transmission for a UAV.

In the future, hard- and software for such a communication platform will be designed and integrated to a UAV. During the system design, the findings of this paper will be reviewed to identify and avoid problems in an early stage. However, challenges towards power consumption and weight in relation to the UAV may arise. Moreover, a communication link to the flight controller of the UAV will be required to forward the C&C messages. Furthermore, the orientation of the UAV could be controlled via this interface in order to align the antennas with the serving cell. After the design phase, QoS measurements will be performed with the communication platform attached on the UAV. The measured data will be used to develop QoS prediction models for prioritizing the communication channels according to their predicted quality at a later stage.

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