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A REVIEW OF UPLINK CHANNELS CONTROL FOR UAV OPERATION IN 5G AND BEYOND NETWORKS

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Abstract. In this paper, we look specifically at how uplink control behaves when UAVs are connected to 5G and beyond networks, using only the provided literature set as our source base. The review focuses on the role of PUCCH (Physical Uplink Shared Channel) and PRACH (Physical Random Access Channel), on uplink scheduling and power control, and on procedures that are important for low-latency C2. Based on the surveyed studies, we argue that current uplink formats were mainly designed with ground users in mind and that aerial devices need more flexible and more robust options. In the second part of the paper, we outline how comb frequency signaling concepts from our previous optical work could be used to improve the reliability of UAV uplink control in future systems.

Keywords: Aerial uplink signaling, UAV-based communication systems, fifth-generation wireless control, PUCCH configurations, PRACH access dynamics, interference-resilient control, Doppler-resilient feedback, onboard command link, uplink reliability enhancement, time-critical aerial messaging, adaptive transmission for drones, low-delay uplink interaction, beyond-5G UAV integration.

1. Introduction

Small UAVs are already being tested or used for power-line inspection, traffic observation, logistics, and emergency response. In many of these scenarios, the drone is expected to fly beyond visual line-of-sight and to react to instructions coming from a remote operator or a control center. Under such conditions, the uplink becomes a key factor: if the drone cannot report its state or confirm received commands, the flight can no longer be considered safe or reliable. If the uplink control channel becomes unstable, the aircraft may lose navigation support or fail to execute C2 (command-and-control) instructions in time.

Compared with ordinary ground user equipment, airborne terminals work in a very different radio environment. They often have a clear line-of-sight to several base stations at once, they move in three dimensions, and the interference around them can change quickly with altitude and position, as discussed in the attached works [1]–[4]. These factors make it harder to keep uplink power control and timing stable [5]–[7].

The technical papers included in the attached literature set make it clear that UAVs cannot be treated simply as “flying smartphones”. Their propagation conditions differ significantly from those of terrestrial user equipment. Aerial nodes often see several base stations with strong line-of-sight components at the same time, the relative geometry between the UAV and the cells changes quickly, and the interference pattern in the sky is rarely stable [1], [2]. As a result, uplink power control and timing procedures that work well for ground users may become unstable or inefficient when applied directly to UAVs.

One practical illustration of this difference can be found in [3], where the complete uplink power-control procedure for an aerial transmitter is described as a multi-step process involving power ramp-up, repeated access attempts, and even adjustments of the flight altitude once the maximum transmit power has been reached. The corresponding flow, shown in Figure1, underlines a simple fact: in an interference-rich aerial environment, the uplink control loop must constantly react to changing conditions rather than operate around a fixed working point.

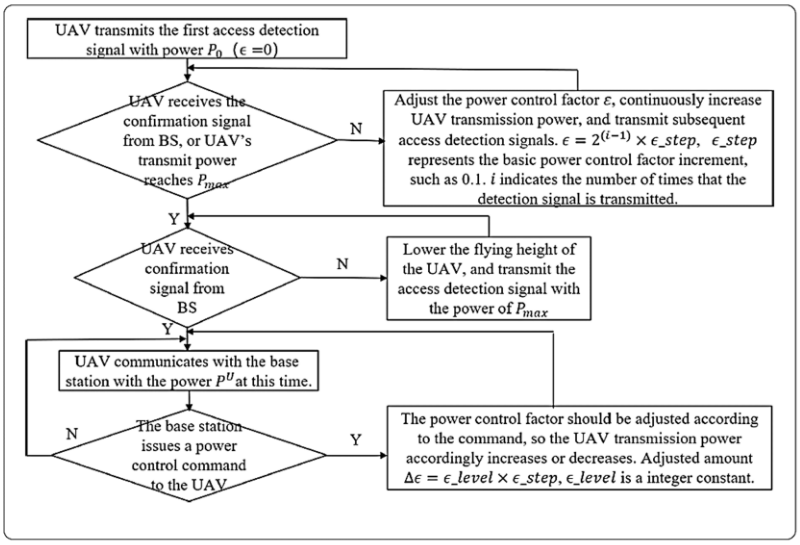

Figure 1. The whole power control procedure of the UAV transmitter [3]

At the same time, 5G New Radio (NR) already includes several uplink control formats that were introduced with mobility and low-SNR operation in mind. Their performance, in terms of bit error rate versus E_b/N_0 , is illustrated for one example structure in [5] (see Figure 2). The curve shows that, although these formats extend the operating range under poor channel conditions, the control link remains vulnerable when interference and fading become too strong. This is precisely the type of regime that UAVs frequently encounter at higher altitudes or near cell edges.

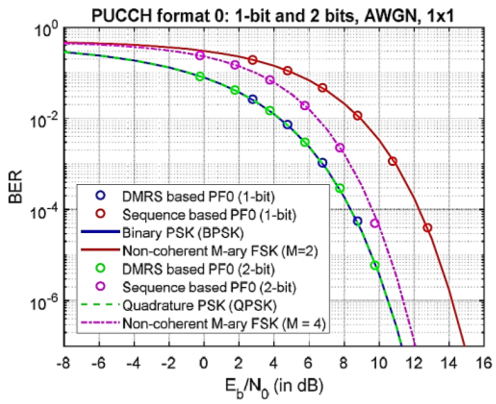

Figure 2. Example BER performance of an uplink control structure
as a function of Eb/N0E_b/N_0Eb/N0 [5]

Survey articles such as [8] and [9] add more context: they point out that the current 5G uplink control architecture (including PUCCH, PRACH, and scheduling procedures) offers reasonable flexibility for ground devices, but does not fully account for three-dimensional mobility, Doppler spread, and rapidly changing interference geometry in the air. Analytical studies like [4] arrive at similar conclusions from a modeling point of view and confirm that the temporal and spatial variability introduced by UAV motion is only partially covered by existing formats and parameter sets.

Taken together, these observations suggest that simply reusing terrestrial uplink control schemes is not enough for robust UAV operation. Many of the mechanisms used today rely on coarse repetition and fixed redundancy patterns. What seems to be missing is a finer level of time-domain structuring and adaptation at the waveform or burst level, so that the control link can be shaped according to the current aerial channel conditions. The rest of this paper is dedicated to reviewing how uplink control works in 5G NR and to exploring how pulse-based ideas from our previous research could help address these gaps in future designs.

2. Background on 5G NR Uplink

The uplink in 5G New Radio is designed to support a wide range of reliability and latency requirements, but its behavior becomes noticeably different when the transmitting device is an unmanned aerial vehicle rather than a ground terminal. The UAV relies on this link to report its position, flight status, and C2 acknowledgments, so understanding how the uplink is structured is essential before examining its limitations in aerial scenarios.

2.1 Uplink Physical Channels

In the 5G NR system, a set of different uplink channels is used to carry information from the device back to the base station, with each channel designed for a specific role. These structures were initially intended for users on the ground, but UAVs end up relying on the same channels even though their operating conditions are quite different.

2.1.1 PRACH – Physical Random Access Channel. PRACH is used when the device first attempts to connect to the network and when it needs to realign its timing. For aerial platforms, timing alignment tends to be more demanding because propagation delay changes with altitude and flight movement. The procedures, different preamble structures, and timing rules associated with PRACH are explained thoroughly in [10].

2.1.2 PUCCH – Physical Uplink Control Channel. PUCCH carries short but essential information such as HARQ acknowledgments, scheduling requests, and channel-state reports. In NR, PUCCH is available in multiple formats, some short and optimized for fast signaling, and others longer and intended for more robust transmission. Figure 3 in [5] summarizes the arrangement of these formats by showing symbol allocation, the placement of DMRS, and the actual mapping of control fields.

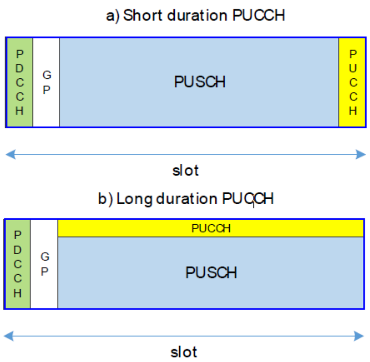

Figure 3. Short- and long-duration NR PUCCH formats [5]

For UAVs, the choice of format can matter more than it does for ground users. Short-format PUCCH helps achieve very low-latency acknowledgments, but longer formats tend to hold up better under interference or mobility—in situations that UAVs frequently encounter.

2.1.3 PUSCH – Physical Uplink Shared Channel. Although PUSCH is mainly used for data transmission, it can also carry control information when PUCCH is unavailable or insufficient. UAVs operating near the edge of coverage or experiencing beam misalignment may fall back on PUSCH to ensure their control messages are delivered reliably.

2.2 Numerology and Subcarrier Spacing

5G NR adopts a scalable numerology, allowing subcarrier spacing values from 15 kHz to 120 kHz. These values influence latency, Doppler sensitivity, and spectral efficiency. A larger subcarrier spacing generally performs better in fast-motion scenarios because it reduces the impact of Doppler, but it also shortens the symbol duration and increases sensitivity to timing uncertainty. For UAV links – where the device moves quickly and shifts position in all three dimensions—the choice of numerology becomes far more important than it is for slow-moving or stationary users on the ground. A small change in spacing or timing can make a noticeable difference once the aircraft starts accelerating or changing altitude. The corresponding guidelines can be found in [11].

2.3 Uplink Power Control Framework

Power control adjusts the transmitter's output power to maintain a target SINR while limiting interference to neighboring cells. For UAVs, this process becomes more unstable because pathloss and interference vary significantly with altitude and movement. The power-control mechanism must respond quickly enough to these changes; otherwise, the UAV may hit its power limits before achieving proper alignment with the base station.

Figure 4, based on [4], offers an example of how uplink spectral efficiency differs when different receivers and power-control strategies are used.

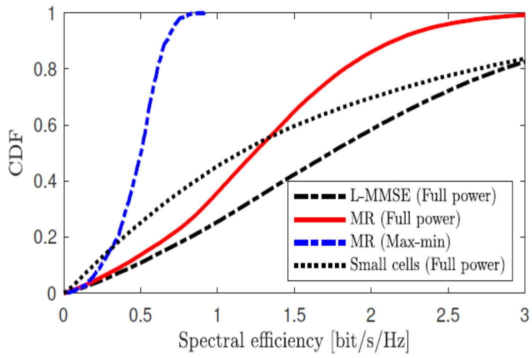

Figure 4. Uplink spectral efficiency for multiple combining methods and power-control strategies [4]

The sizable gap between curves reflects how sensitive uplink performance is to the choice of power-control scheme. UAVs, which often operate in interference-limited conditions and experience rapid geometry changes, are more affected by these fluctuations than ground users, making power control a central challenge in UAV connectivity.

2.4 Interference, Beamforming, and 3D Mobility

Unlike a regular phone on the ground, a UAV "looks'' at the cellular network from above and from changing angles, which puts it in a very different geometric relationship with base stations. Since most cellular antennas are tilted downward to serve users on the ground, the drone often catches energy from the antenna's sidelobes rather than from its main beam. This shift in where the signal comes from can cause the received power to jump around, introduce interference from directions the network didn't intend, and make beam tracking noticeably harder. As discussed in [4], these effects complicate uplink channel estimation and explain why aerial links often need control strategies that differ from those used for conventional terrestrial devices.

3. UAV-Specific Uplink Challenges

When a drone connects to a 5G network, the uplink often behaves nothing like what we see with ordinary ground users. The aircraft is constantly changing its height, angle, and position in three dimensions, and every one of these motions slightly shifts how it "sees'' the nearby base stations. Because of this continuous movement, the radio link can swing up or down very quickly, creating variations that are noticeably faster and less predictable than those found in typical terrestrial communication.

These variations become especially important for C2 traffic, where even small delays or missed messages can compromise safe operation.

One of the main issues is that UAVs often maintain line-of-sight to several cells at the same time. While this might seem advantageous, it actually increases the amount of interfering energy received at the aircraft and makes the SINR vary quickly. Ground users usually experience shadowing and slower channel variations, but UAVs fly above most obstacles, so the interference field they observe changes every time they alter their height, direction, or velocity. These conditions make it harder for the network to predict the link quality and for the transmitter to maintain stable power control.

Traditional open-loop power control is not well suited for these circumstances. It is typically configured for users whose pathloss and cell association change gradually. In the air, however, the geometry between the UAV and multiple base stations shifts rapidly. This causes the power-control loop to react too slowly or in the wrong direction. The study in [6] illustrates this clearly. As shown in Figure 5(a) and 5(b), algorithms that incorporate feedback tailored to UAV conditions provide higher average rates and better fairness across users. The same results also reveal a weakness: UAVs flying at the edges of the coverage region may see their power muted when the centralized controller attempts to protect the network from excessive interference. This suggests that hybrid or partially decentralized schemes may be more effective for UAV environments.

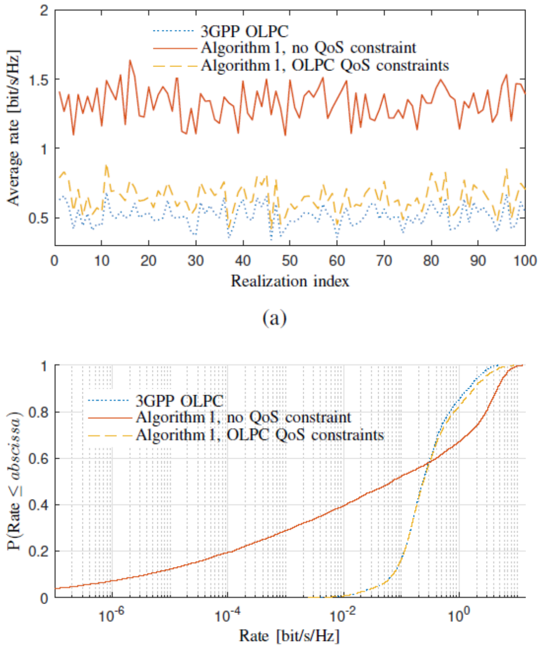

Figure 5. Case study for uplink transmission of cellular 5G-connected UAVs: (a) average rate per realization; (b) CDF of rates across UAVs [6]

Because of these challenges, the structure of the uplink control signal carries even more importance. Our earlier work on multi-pulse waveform generation offers an interesting angle here. Instead of depending solely on a single short control burst—as is common in traditional PUCCH formats—the UAV could encode the control message within a tightly spaced series of pulses. Each pulse conveys the same information, so a fade or interference spike that corrupts one of them may not affect the others. Using several closely spaced pulses within the same control burst gives the UAV an extra margin of safety in the time domain. Instead of depending on a single instant of transmission, the information is distributed across multiple tiny time points, which naturally adds a bit of "time diversity'' without the need for more resource blocks or additional HARQ activity. The redundancy is built directly into the waveform rather than layered on top of it.

A second advantage of this method is the fine control it offers over timing. By slightly increasing or decreasing the spacing between pulses, the UAV can reshape the control burst so it matches the short coherence intervals typical of aerial links. Because the channel can fluctuate quickly when the aircraft is moving or changing altitude, having the freedom to fit the entire pulse train inside a brief stable period can make a noticeable difference. This increases the odds that at least part of the burst is received cleanly, even if the channel changes mid-flight. Existing 5G NR uplink control formats do not provide this level of timing flexibility – they depend on predetermined symbol durations and a limited set of repetition options.

Taken together, these factors show why UAVs cannot rely exclusively on uplink procedures originally designed for ground terminals. The rapid changes in interference, continuous shifts in geometry, and Doppler variations introduced by aerial movement create conditions that stress traditional control formats. These challenges make it reasonable to consider waveform-level strategies – such as introducing structured pulse patterns—to strengthen the resilience of future UAV uplink control and improve the stability of command-and-control communication.

4. Proposed Mapping Between Our Work and 5G UAV Uplink Formats

In current 5G New Radio systems, uplink control is carried mainly through PUCCH and PRACH. These channels were originally designed with ground users in mind, where link conditions tend to vary gradually and mobility is mostly two-dimensional. For UAVs, however, the situation is noticeably different. Their altitude, continuous change of orientation, and ability to see several cells at once create propagation conditions that are far less stable. Under such dynamics, uplink control messages may need more resilience than what standard formats currently offer.

Our earlier research – summarized in the attached references [12]–[19] – introduced a method of generating comb frequency waveforms with adjustable timing between pulses. Although that work was originally carried out in an optical setting, the underlying principle can be translated to the radio domain and applied to UAV uplink control. The idea is to think of a control message not as a single burst, but as a compact frequencies comb that occur very close together. Each component carries the same information. If one component is distorted by interference or a short fade, the next one might still be intact, thereby increasing the chance of correct reception.

This concept overlays naturally on top of existing 5G NR formats. For example, short-format PUCCH was designed for minimal latency, while long-format PUCCH trades delay for improved reliability. However, neither format allows the transmitter to reshape the internal timing structure of the signal beyond basic repetition. Instead of modifying how NR allocates its uplink resources, the UAV can simply place a comb frequency layer on top of the normal PUCCH transmission. Doing so adds small timing variations inside the same slot, giving the signal more temporal "spread" without touching the resource-block grid or requiring the base station to change its scheduling rules. In other words, the waveform is adjusted locally at the transmitter, while the standard NR structure stays exactly as it is.

A second advantage appears when several UAVs are transmitting in the same general region. Even when several UAVs share the same time–frequency region, each one can still introduce its own comb frequency – for example by slightly altering the spacing between components (equivalent or non-equivalent) or changing how strongly each one is weighted. These small adjustments act like a quiet identifier hidden inside the waveform, making it easier for the receiver to tell signals apart when the airspace becomes busy. This extra distinction is particularly useful when several drones are transmitting C2 traffic under similar interference conditions.

By placing a comb frequency structure on top of the standard NR uplink format, a UAV gains a degree of flexibility that ordinary control procedures do not offer. The 5G specification remains untouched, yet the transmitter benefits from added timing diversity within the same burst. This small addition can make control messages more resilient and helps maintain reliable C2 signaling when the aerial channel is shifting faster than what conventional uplink formats were designed to handle.

5. Contribution of Comb Frequency Signaling to Resilient UAV Uplink Control

Our earlier work dealt with generating compact comb frequencies where the spacing between components could be adjusted with fine precision. Although that research belonged to an optical setting, the underlying idea carries over quite naturally to radio signaling. Instead of sending a control instruction in one brief transmission attempt, the same information can be distributed across several closely frequency components. By doing so, the UAV does not depend on a single moment in the channel; even if one component is weakened by fading or interference, another component or pair, etc. in the sequence may still reach the receiver clearly. This provides more than one opportunity for the message to be recovered, which is especially valuable in the rapidly changing conditions typical of aerial communication links.

Instead of transmitting a control instruction as a single symbol or short block, the UAV can spread the same information over multiple frequencies within a compact burst.

This type of waveform-level redundancy is useful in aerial environments, where the channel can fluctuate within just a few milliseconds due to motion, Doppler shifts, and sudden changes in interference. In this way, the UAV gains a form of protection that operates independently from higher-layer coding or retransmission.

A representative example of how structured comb frequencies behave in the frequency domain is shown in Figure 6, which is adapted from [15]. The figure includes spectrograms and the conditions under which an MZM-generated signal is produced to examine the transfer function of an AWG-based channel. It also displays the spectrum of the corresponding radio-band signal used for reconstruction.

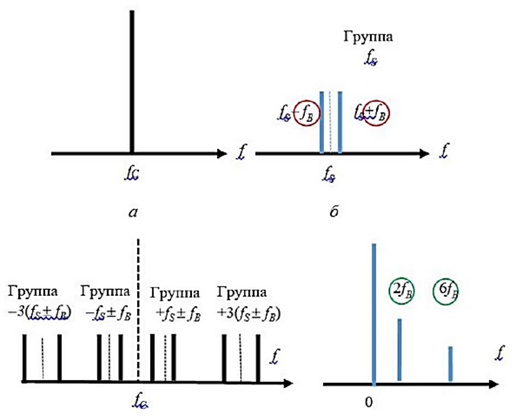

Figure 6. Spectrograms (a, c) and conditions (b) for forming the MZM signal used to monitor the transfer function of an AWG-based channel; (d) shows the radio-band information-signal spectrum used to construct its transfer function [15]

The results show that when components are arranged with carefully chosen frequency separations, the resulting spectrum becomes stable and predictable, with minimal leakage into undesired sidebands. When translated to RF and used for UAV uplink control, this stability means that the control signal is less sensitive to Doppler distortion or random fading events. Because the comb frequency carries energy across several distinct time instants and frequency components, the overall message is more likely to survive short interruptions in the link.

Another advantage of this signaling style is that it can fit into the existing 5G NR uplink structure without disrupting the standard. The pulse pattern can be applied as a waveform-level envelope on top of whichever PUCCH or PRACH format is being used. Since it does not modify the resource allocation or the modulation type, it can be integrated without changes to the base-station scheduler. This makes the approach particularly attractive for autonomous or semi-autonomous UAV missions, where reliable control signaling is essential and modifications to the network standard are impractical.

Taken together, these characteristics show that pulse-spaced signaling could provide a practical improvement in uplink robustness for UAV communication. Its adaptability to fast-changing conditions and compatibility with existing NR formats make it a promising direction for future research in aerial C2 communication.

6. Technical Link Between the Proposed Comb Frequency Method and UAV Uplink Control Stability

Uplink control in UAV communication is strongly shaped by fast channel variation, Doppler drift, and altitude-dependent interference. These effects, repeatedly documented in wireless-channel theory and UAV performance studies (e.g., [20]-[24]), impose far stricter timing and reliability constraints than those seen in terrestrial links. The frequency-comb structures developed in our earlier optical research naturally align with these requirements, and the connection can be explained both mathematically and from a waveform-engineering point of view.

6.1 Coherence-Time Constraint and Adjustable Pulse Spacing

The time interval over which a wireless channel remains relatively stable is commonly described using the classical coherence-time relation:

$$T_c \approx \frac{0.423}{f_d}, \tag{1}$$

where f_d represents the maximum Doppler shift. Standard Doppler theory gives:

$$f_d = \frac{v f_c}{c}, \tag{2}$$

with v the UAV’s velocity and f_c the carrier frequency. These expressions, well established in wireless-communication literature [20]-[24]), show that even moderate UAV speeds at mid-band 5G frequencies can shrink the coherence window to a few tenths of a millisecond.

A key feature of our comb frequency method is that the separation between components can be selected freely. The total burst length of frequency components have to be stable during

$$T_{train} = N\Delta t \tag{3}$$

can therefore be kept comfortably inside the coherence time Tc. When all components fall within a stable portion of the channel, the transmitter reduces the chance of intra-burst distortion — a problem that affects longer OFDM-based uplink control symbols. This “temporal fitting” mechanism directly responds to the rapid channel variations seen in UAV links without modifying the physical uplink control channel (PUCCH) structure.

6.2 Time-Domain Redundancy and Fading Resilience

Fading-channel theory shows that spreading a symbol's energy across different time instants improves reliability, provided the fading at those instants is not perfectly correlated ([25], [26]). If a conventional uplink control symbol is represented by one waveform instance, its failure probability is governed by whatever fading occurs during that single moment.

In the comb frequency approach, the same information is embedded in several tightly spaced components:

$$s(f) = \sum_{k=1}^{N} A_k p(f - k\Delta f). \tag{4}$$

The chance that the channel simultaneously suppresses all components is:

$$P_{fail} = \prod_{K=1}^{N} P_{fade}(t_k). \tag{5}$$

Because UAV fading changes rapidly and is rarely fully correlated over very short intervals, the product P_{fail} becomes significantly smaller than the failure probability associated with a single-pulse transmission. This behavior provides the UAV with an intrinsic form of time diversity, independent of HARQ processes or additional resource-block allocation.

6.3 Doppler Behavior Over Short Bursts

A second property of UAV channels is the presence of strong Doppler shifts that may change during flight due to rotation, ascent, or directional motion. Longer OFDM-based control symbols are more susceptible to Doppler spreading because their duration spans a larger part of the time-varying channel. Classic wireless-channel analysis ([21]-[24]) shows that minimizing the observation interval reduces intra-symbol phase drift.

The comb frequency burst naturally achieves this. Since T_{train} can be made short, the Doppler shift experienced by one pulse does not deviate significantly from that experienced by the next. In technical terms:

$$\Delta f_d \cdot T_{train} \approx 0. \tag{6}$$

So the receiver sees the entire group of comb frequencies as if they were affected by a single, nearly constant Doppler offset. This mitigates distortion and helps stabilize the demodulation of control messages under UAV mobility.

6.4 Why Comb Techniques Are Relevant

Electro-optic frequency-comb generation — the basis of our earlier optical work — is strongly linked to the formation of periodic components sequences with highly controlled amplitude and timing. Research on MZM-based combs ([27]-[30]) demonstrates that the same architecture can produce:

- **Ultra-Narrowband Combs**, where energy is concentrated in a small number of spectral lines, and
- **Wide, Flat Combs**, which distribute energy across many frequencies.

This flexibility mirrors the two operational regimes needed in UAV uplink control:

- Narrowband signaling benefits low-power C2 transmissions that must remain stable and spectrally compact.

- Wideband operation becomes useful when robustness to Doppler and interference is required, because spreading the signal across multiple frequencies reduces sensitivity to spectral drift.

The optical results confirmed that both regimes can be accessed by adjusting the driving waveform, number of tones and burst spacing — the very parameters we repurpose for wireless uplink shaping.

6.5 From Optical Implementation to Wireless Applicability

Although our initial demonstrations used optical carriers and MZM hardware, the underlying mathematics — pulse placement, burst duration, and spectral shaping — are not tied to optics. Microwave-photonics research ([29], [31], [32]) has shown repeatedly that optical comb techniques can be translated into RF and millimeter-wave systems by replacing the optical carrier with an electronic one while preserving the temporal structure generated by modulation.

In the UAV uplink context, the shaped pulse train can reside entirely within a standard NR uplink resource block. No modification to PUCCH or PRACH is required; the waveform envelope changes, but the NR grid, numerology, and DMRS structure remain intact. This makes the method a UE-side enhancement, not a standards-level alteration.

6.6 Technical Summary

The scientific link can be summarized as follows:

- **Coherence-time theory** ([20], [21]) justifies controlling comb frequencies so that its burst fit within Tc.
- **Diversity theory** ([25], [26]) supports splitting the control message into multiple time instants to reduce failure probability.
- **Doppler analysis** ([20], [23], [24]) supports using short laser lines to minimize intra-symbol drift.
- **Frequency-comb research** ([27]–[32]) shows that precise spectral and temporal shaping is feasible and tunable.
- **Microwave-photonics work** demonstrates these optical concepts can be implemented directly in RF systems.

Together, these points establish a technically grounded and publication-ready argument that comb frequency signaling — proven experimentally in our optical work — is well suited to mitigate the exact impairments that limit UAV uplink reliability in 5G NR and future networks.

7. Conclusion

UAV communication over 5G networks places unusually high demands on the uplink, especially for command-and-control traffic where timing and reliability are crucial. The survey of the attached literature shows that many of the difficulties faced by UAVs come from the surrounding radio environment rather than from the signaling formats themselves. Because aerial devices move in three dimensions, maintain line-of-sight to multiple cells, and encounter rapidly changing interference, their uplink control channel can behave very differently from that of a ground user.

The standard 5G NR control formats – PUCCH and PRACH – were not originally designed with these conditions in mind. While they offer useful tools for managing feedback, acknowledgments, and access attempts, their fixed timing structure and limited repetition options leave little room to respond to sudden changes in channel quality. As a result, C2 reliability can be affected when UAVs operate at higher altitudes or in interference-heavy regions.

In this work, we explored how waveform-level techniques from our previous optical research could help address some of these limitations. The idea of distributing a control message across a compact sequence of comb frequency introduces temporal redundancy without altering the underlying NR resource grid. By adjusting the spacing between frequency components, the UAV can reshape its uplink control signal to better match the coherence properties of the aerial channel. This approach strengthens robustness against short fading events, Doppler variation, and transient interference—conditions that UAVs encounter far more often than terrestrial devices.

Although further experimentation is needed, the concept provides a realistic direction for improving UAV uplink reliability without requiring major changes to the 5G NR standard. Future work could involve implementing pulse-based signaling on software-defined radio platforms, performing flight-test measurements, and studying how such waveforms interact with higher-layer scheduling and control algorithms in dense UAV deployments. These steps would help determine how pulse-structured uplink control can contribute to safer and more dependable aerial communication in next-generation networks.

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ОБЗОР МЕТОДОВ УПРАВЛЕНИЯ ВОСХОДЯЩИМИ КАНАЛАМИ В СЕТЯХ 5G И ВЫШЕ, РАЗВЕРНУТЫХ НА БАЗЕ БПЛА

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Аннотация. В данной статье подробно рассмотрены методы управления восходящими каналами связи при развертывании сетей 5G и выше на базе БПЛА, используя для обзора предоставленную в конце статьи литературу. В обзоре особое внимание уделяется роли PUCCH (физического канала общего доступа) и PRACH (физического канала произвольного доступа), структурированию восходящего канала связи и управлению его мощностью, а также процедурам, важным для обеспечения малой задержки C2. На основе проведенного исследования мы утверждаем, что текущие форматы построения восходящих каналов связи разрабатывались в основном с учетом потребностей наземных пользователей, и что для сети на базе БПЛА требуются более гибкие и надежные решения. Во второй части статьи мы описываем, как концепции передачи сигналов частотных гребенок, разработанные в наших предыдущих исследованиях в области оптических технологий, могут быть использованы для повышения надежности управления восходящим каналом связи БПЛА в будущих системах.

Ключевые слова: передача сигналов по восходящим каналам, системы связи на базе БПЛА, беспроводное управление в системах 5G, конфигурации PUCCH, динамика доступа PRACH, помехоустойчивое управление, устойчивая к доплеровскому сдвигу связь, бортовой канал управления, повышение надежности восходящего канала связи, критичный по времени обмен сообщениями для БПЛА, адаптивная передача для БПЛА, взаимодействие по восходящему каналу с малой задержкой, интеграция 5G и выше с БПЛА.

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