Atmospheric Ducting Effect in Wireless Communications: Challenges and Opportunities

Fangfang Liu, Jiaxi Pan, Xiangwei Zhou, Geoffrey Ye Li

***Abstract*—Atmospheric ducting has a significant impact on electromagnetic wave propagation. Radio signals that are trapped and guided by the atmospheric duct can travel a much longer distance over the horizon with lower attenuation since the signal power does not spread isotropically through the atmosphere. Atmospheric ducting brings both challenges and opportunities to wireless communications. On one hand, the signals propagating in the atmospheric duct may interfere with a receiver far away as remote co-channel interference. On the other hand, a point-to-point link can be established directly through the atmospheric duct to enable beyond line-of-sight communications. In this article, the formation of the atmospheric duct and its effects on radio wave propagation are first overviewed. Then solutions and standardization activities in the 3rd Generation Partnership Project (3GPP) to mitigate atmospheric duct induced remote interference are presented. Finally, the applications and design challenges of atmospheric duct enabled beyond line-of-sight communications are reviewed and future research directions are suggested.**

***Keywords*—atmospheric duct, ducting channel modeling, beyond line-of-sight, remote interference management**

I. INTRODUCTION

Atmospheric ducting is an anomalous mode of radio wave propagation in the lower layer of atmosphere, where the waves are bent back to the earth surface. Atmospheric ducting usually occurs under certain weather conditions, where the atmospheric refractivity declines rapidly with the increasing of altitude. In this way, the radio waves are ducted back towards the ground since the reflection and refraction are encountered at the upper boundary of the atmospheric duct. The signals trapped in the atmospheric duct can travel over the horizon with much lower path loss in comparison with the normal atmospheric environments[1,2]. The studies on atmospheric ducting have been mainly focused on radio propagation assessment, mitigation, and exploitation for radar systems since the 1940s[3]. However, as the demand of wireless connectivity expands from ground to high rise buildings, air, and even space, radio wave propagation is crucially affected by atmospheric ducting caused by abnormal vertical change of the atmospheric refractivity. This mode of propagation in the atmospheric duct brings both challenges and opportunities for wireless communications.

Atmospheric ducting brings unexpected remote, significant, and dynamic interference, especially for time division duplexing (TDD) cellular networks. With lower path loss, the downlink (DL) signals of base stations (BSs) can travel a long distance far greater than the normal radiation range. As a result, the uplink (UL) reception at a victim BS can be severely interfered by the DL signals from the aggressor BSs far away if the propagation delays go beyond the guard period between UL and DL. This kind of cross link co-channel interference, termed remote interference, can be accumulated from a number of aggressors up to -70 dBm. Remote interference has been observed in commercial time division long term evolution (TD-LTE) networks. Based on the field trial results, half of the provinces in China are influenced by remote interference for over half a year in some places. The distance between the victim and the aggressor ranges from 64 km to 400 km, which is usually within 150 km in most inland areas and sometimes even farther than 300 km in coastal areas[2]. Besides the distance, remote interference is also related to many other dynamic parameters of both the duct and networks, such as the weather conditions, the angle of departure of the aggressor BSs, and the heights of BSs. Therefore, the remote interference is severe and occurs frequently with a large number of distant BSs involved. It would become

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F. F. Liu, J. X. Pan. Beijing Laboratory of Advanced Information Networks, Beijing Key Laboratory of Network System Architecture and Convergence, Beijing University of Posts and Telecommunications, Beijing 100876, China (e-mail: fliu@bupt.edu.cn; panjiaxi2015@bupt.edu.cn).

X. W. Zhou. Louisiana State University, Baton Rouge LA 70803, USA (e-mail: xwzhou@lsu.edu).

G. Y. Li. Imperial College London, London SW7 2AZ, U.K. (e-mail: geoffrey.li@imperial.ac.uk).

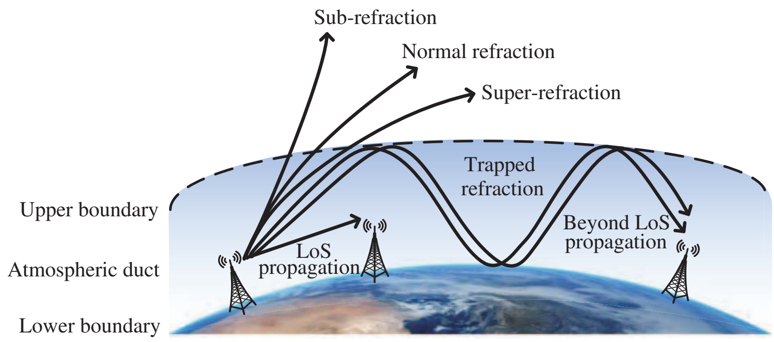

Fig. 1 Different types of electromagnetic wave refraction

even more severe in the fifth generation (5G) new radio (NR) and the future sixth generation (6G) wireless communications, which typically requires a larger number of BSs to cover the same area due to the higher frequency. It is challenging to mitigate the remote interference efficiently over such a large area, which may need inter-BS, inter-system, inter-operator, and even inter-nation coordination.

Atmospheric ducting can be also exploited for wireless communications, since the atmospheric duct behaves advantage in establishing infrastructure-less, long-distance, and directly-connected wireless links. The signals trapped in the atmospheric duct can propagate over the horizon, which makes the atmospheric duct appropriate for beyond line-of-sight (LoS) communications[1]. A point-to-point beyond LoS link can be established conveniently where conventional cellular, satellite, high frequency (HF) radio, or optical fiber communications are not feasible due to limited coverage, restricted capacity, and/or too expensive deployment costs[4]. It is specifically a good candidate for naval applications to realize effective and secure communications since the atmospheric duct is almost persistent in oceanic and coastal regions. Meanwhile, it has been demonstrated that the atmospheric duct can also support high data rate applications, utilizing such as diversity, multiple input multiple output (MIMO), and cognitive radio technologies to improve capacity[5,6]. Moreover, various wireless nodes will be hopefully integrated in the future 6G networks like unmanned aerial vehicles (UAVs) in the air and maritime devices in the sea[7], which may respectively increase the occurrence probability of the ducting propagation with greater heights and more suitable weather conditions. Therefore, beyond LoS communications based on atmospheric ducting not only serves as a flexible alternative to traditional wireless communications, but also a promising technology component to achieve global coverage in the future air-ground-sea integrated networks.

To address the challenges of the remote interference and the opportunities of beyond LoS communications, the formation of atmospheric ducting and its effects on radio wave propagation are first overviewed. The trapping region for a transmitter located in the atmospheric duct is derived and the path losses in mmWave and THz frequency bands are investigated. Then present some remote interference mitigation techniques and introduce the standardization activities on remote interference management (RIM) for 5G NR in the 3rd Generation Partnership Project (3GPP). After that, a promising approach for beyond LoS communications is discussed to make use of the atmospheric duct as a transmission medium and applications and design challenges are presented. Finally, some research directions are identified.

II. Formation and Effects of Atmospheric Ducting

In this section, to describe how and where atmospheric ducting takes place, the formation conditions of atmospheric ducting are first provided and a trapping region for a transmitter in the duct is derived. Then the effects of atmospheric ducting on wireless communications are investigated through channel modeling.

A. Formation Conditions

Electromagnetic waves propagating in the atmosphere are mainly affected by absorption, refraction, reflection, and scattering. Different from normal refraction in standard atmosphere, atmospheric ducting can be referred to as trapped refraction as shown in Fig. 1, which is a kind of anomalous propagation like waves spreading in a metal waveguide. The formation of atmospheric ducting mainly depends on two kinds of conditions. One is the weather conditions for the occurrence of the atmospheric duct, and the other is the transmission conditions including the locations of the transmitters and receivers, the angles of departure at the transmitters, and the working frequencies.

The occurrence of the atmospheric duct is one of the essential conditions, which is generally described by the vertical variation of the modified refractivity with altitude. When negative gradient of the modified refractivity with respect to the altitude happens, the atmospheric duct occurs with certain

Tab. 1 Different types of the atmospheric ducts

	Evaporation duct	Surface duct	Elevated duct
Occurrence	In coastal and maritime areas	Often in clear nights or after rains	Caused by monsoon and motions of cloud clusters
Probability of occurrence	Up to 90% of the time	Up to 40% of the time	Up to 50% of the time
Height of upper boundary	< 40 m	< 300 m	< 3000 m
Applications and challenges	Enable beyond LoS communications with high availability	Cause strong remote interference to the TDD terrestrial communication systems	Affect the satellite communications

thickness and strength. Here the modified refractivity is defined by M as

$$M = N + \frac{z}{a_e} \cdot 10^6 \approx N + 0.157z, \tag{1}$$

where N is the radio refractivity, which is related to the meteorological parameters, such as the atmospheric pressure, temperature, and humidity, z is the altitude in meters, and a_e is the curvature radius of the earth in meters[8]. The negative gradient of the modified refractivity, denoted as

$$\partial M / \partial z < 0, \tag{2}$$

mainly results from temperature and humidity inversions, i.e., temperature increasing along with the altitude, while water vapor pressure doing the opposite. The duct thickness is determined by the altitude difference between the upper and lower boundaries of the duct, and the duct strength by the difference between the maximum and minimum modified refractivities in the duct.

Generally, the atmospheric duct can be divided into three types with different characteristics: evaporation duct, surface duct, and elevated duct, as shown in Tab. 1[1,9]. The evaporation duct on the sea and coast surfaces is of great potential to enable beyond LoS communications thanks to its high availability. The surface duct occurs with lower probability but higher upper boundary, and it influences the terrestrial communication systems especially TDD networks tremendously. In the following, the evaporation duct and surface duct will be focused on since they significantly affect wireless communications in a low atmosphere. As a matter of fact, the evaporation duct can be considered as a special case of the surface duct.

When the surface duct occurs under certain weather conditions, radio waves are not necessarily trapped unless the transmission conditions of location, angle, and frequency are met[10]. For a transmitter located in the duct, only the rays that have angles of departure below a critical value, referred to as the maximum trapping angle, can be trapped. In addition, the frequency of the wave must be above a critical value which is referred to as the minimum trapping frequency. The maximum trapping angle and the minimum trapping frequency are determined by the duct thickness and the duct strength,

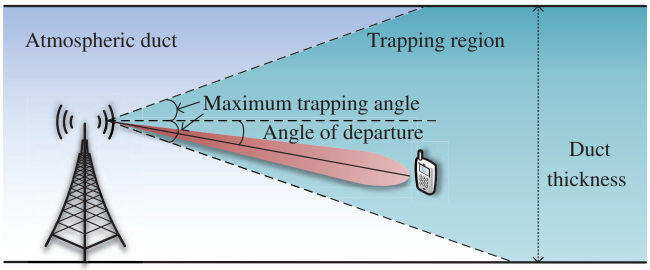

Fig. 2 Trapping region for a transmitter located in the atmospheric duct

which are generally around 0.4°[10] and 0.3 GHz[2], respectively. Obviously, for the location and frequency conditions, most ground and maritime communication nodes, and even UAVs in the air can easily meet. These nodes are usually located below the upper boundary of the surface duct with several hundreds of meters and communicate through waves above the minimum trapping frequency. As for the angle condition, it becomes increasingly frequent that the angle of departure is below the maximum trapping angle, since more and more techniques such as three dimensional beamforming and UAVs communications are widely exploited to make full use of the spatial wireless resources vertically. Therefore, the transmission conditions for atmospheric ducting are more and more easily satisfied with various wireless nodes deployed from ground and sea surface to the air in the future networks.

For more specifically to describe where atmospheric ducting happens, the trapping region can be derived for a transmitter located in the duct which meets the weather and transmission conditions, as illustrated in Fig. 2. Given the location of the transmitter, the trapping region for the transmitter is within the ducting boundaries such that the angle of departure is smaller than the maximum trapping angle for the radio wave. The signals transmitted within the trapping region will be guided by the duct and propagate with a long distance. As a result, if a nearby receiver is located in the trapping region, the signals sent by the transmitter to the nearby receiver will be trapped and may generate unwanted interference to a remote receiver. On the other hand, if a remote receiver beyond LoS is located in the trapping region, the signals sent by the transmitter should be concentrated within the trapping region so that a reliable beyond LoS communication link can be established. Hence, it would be very useful to coordinate the trapping regions of each transmitter for both the remote interference mitigation and beyond LoS communications.

B. Effects of Atmospheric Ducting

Here, how radio waves propagate in the atmospheric duct is reviewed with channel modeling and propagation delay.

1) Channel Modeling: The main challenge is to analyze the impacts of the trapped refraction on wave propagation, which are different from the normal channels in the free space. Capable of handling the complex boundary conditions of the trapped refraction, parabolic equation (PE) methods derived from Maxwell equations are widely utilized to characterize the atmospheric ducting channels[1]. The PE methods can model the multiple parameters quantitatively, including the duct thickness, the duct strength, frequency, transmitter and receiver heights, and polarization[11-13]. In this way, the atmospheric ducting channels can be investigated by the PE methods including path loss, small-scale fading, and channel correlation.

Path loss in the atmospheric ducting channel can be obtained based on the PE methods by

$$PL = 20\lg(4\pi/|u(x,z)|) + \lg(d) - 30\lg(\lambda), \tag{3}$$

where $u(x,z)$ is the reduced field component, x and z are respectively the horizontal and vertical axes representing range and altitude, d is the range from the transmitter and λ is the wavelength[11]. The path losses in the atmospheric duct and the free space are respectively illustrated in Fig. 3. Both numerical results of path loss derived from the PE methods and the corresponding regression lines for the atmospheric ducting channels are shown[11]. For sub-6 GHz, mmWave, and THz frequency bands, the atmospheric ducting channels have 10~20 dB lower path loss than the free space at 3.5 GHz, 66 GHz, and 275 GHz, respectively. Thus waves in the duct travel over the horizon with much lower attenuation, which can extend the communication range especially for the lower frequencies.

Besides, the shadow fading in the atmospheric ducting channels is best fitted by log-Weibull distribution also known as Gumbel distribution, which is quite different from the log-normal distribution for the normal channels[10]. Meanwhile, the atmospheric ducting channels hold similar small-scale fading fitting Rayleigh distribution within 85%~90% confidence level, and fading correlations in space and polarization which can be implemented to enhance the capacity in the atmospheric duct[5]. Some geometry-based stochastic models are investigated to describe the ducting channels, considering the beyond LoS, LoS, and reflection paths together[14].

Comparing to the normal wireless channels, the atmospheric ducting channels are with lower path loss, a different shadow fading distribution, and similar small-scale fading.

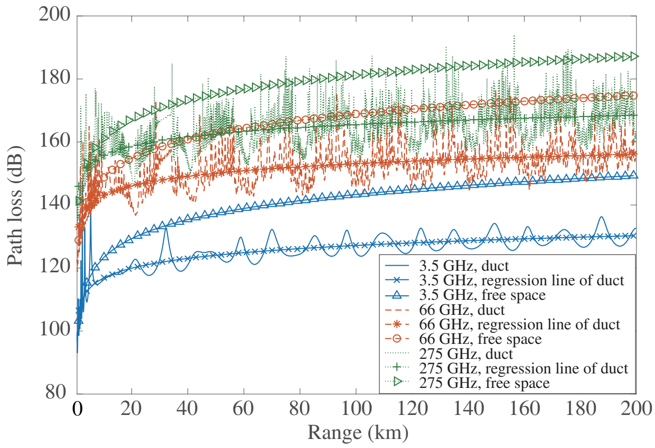

Fig. 3 Path loss in the atmospheric duct and free space at 3.5 GHz, 66 GHz, and 275 GHz

Correspondingly, effective channel estimation algorithms are worth investigating.

2) Propagation Delay: Large propagation delay will be introduced in the atmospheric ducting channels, in which the waves may travel hundreds of kilometers for the lower path loss. Different from the delay introduced by routing or topology changes in multi hop networks, the propagation delay in the ducting channels is generally within a point-to-point link, which is generally not well studied in the existing terrestrial networks. It makes ducting communications are more suitable for non real-time services or delay-tolerant applications. Meanwhile, the signaling overhead of information exchange delay for such as channel estimation, interference mitigation, and resource management would be substantial. Hence, it would be very attractive to introduce some intelligent technologies like semantic communications[15] and distributed learning[16] into ducting communications to enable more effective transmission with smaller data size and delay consequently.

Moreover, persistent connectivity is also a big challenge in the ducting channels. Since the formation conditions for the ducting channels are more rigorous than the normal ones, the connectivity is generally fragile to the dynamic changes of the weather or transmission conditions. It is preferable to estimate the probability of occurrence and the duration of the atmospheric duct through the meteorological parameters, in order to obtain more channel state information in the duct.

III. ATMOSPHERIC DUCT INDUCED REMOTE INTERFERENCE

To address the unexpected interference induced by the atmospheric duct, the characteristics of the remote interference are analyzed first in this section. Then remote interference mitigation techniques and 3GPP standardization activities are introduced.

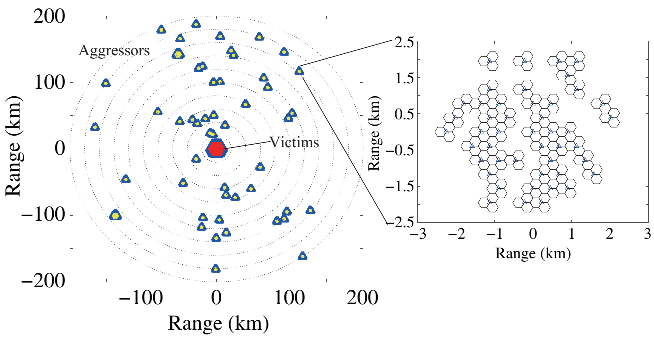

Fig. 4 Simulation scenario

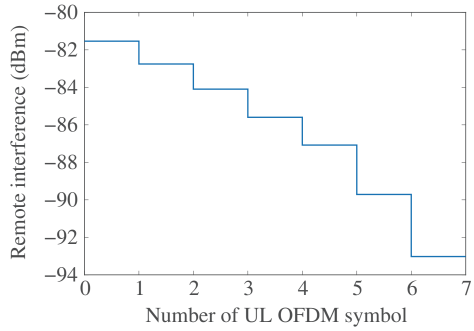

Fig. 5 The remote interference level at a victim BS versus the number of UL OFDM symbols

A. Characteristics of the Remote Interference

The remote interference at a victim BS has a sloping characteristic, i.e., the closer the UL signal is to the guard period, the higher the interference level it experiences since the remote interference is accumulated from a number of remote BSs with different propagation ranges and delays[2].

The sloping characteristic of the remote interference is investigated through simulation for the scenario with 3.5 GHz carrier frequency, 20 m BS height, and 450 m inter-site distance. A group of victim BSs are located at the origin covering a radius of 11.25 km area in Fig. 4. The total number of victim BSs is 976, which are randomly activated. Within a range of 200 km, two groups of aggressor BSs with a radius of 4.5 km coverage and another 48 groups of aggressor BSs with a radius of 2.25 km coverage are randomly located around the victim BS group. Fifty percent BSs are randomly activated in each aggressor BS group in total 2 515. Other parameters, including the angle of departure, antenna gain, and user terminal height, are as in Ref. [17]. Here the maximum trapping angle is set as 0.4°. Remote interference happens when the angle of departure of the aggressor is smaller than 0.4°. In Fig. 5, the remote interference level at a victim BS with different number of UL orthogonal frequency division multiplexing (OFDM) symbols is shown. Each stair of the sloping curve corresponds to one OFDM symbol. From the figure, the accumulated interference from the aggressors declines from -81.54 dBm to -93.02 dBm as the number of the OFDM symbols increases. Moreover, nearly 80% of BSs in the victim group suffer interference ranging from -90 dBm to -70 dBm. Therefore, severe co-channel remote interference is induced by the atmospheric duct.

B. Remote Interference Mitigation Solutions

Remote interference can be mitigated at the aggressor and at the victim so that the victim does not fall into the trapping region of the aggressor and vice versa. In general, interference mitigation can be done in time, frequency, spatial, or power domain.

1) Time Domain Solution: Time domain interference mitigation can be done either in a semi-static or dynamic manner. As a straightforward way, the victim and the aggressor can be semi-statically configured with a long guard period. The obvious drawback is the large overhead if the worst case is considered. Therefore, dynamic schemes can be considered. The victim can refrain from scheduling transmission on the UL resources suffering from the remote interference. On the other side, the aggressor can be muted on the DL resources that cause the remote interference. However, the aggressor needs to be aware of the number of UL resources that interfered at the victim.

2) Frequency Domain Solution: Frequency domain interference mitigation can also be done in a semi-static or dynamic manner. The aggressor and the victim can be semi-statically configured with orthogonal frequency resources or even non-overlapping bandwidth all time at the cost of the spectral efficiency loss. As a dynamic solution, the victim can refrain from scheduling only on the frequency resources suffering from high interference.

3) Spatial Domain Solution: The remote interference can be avoided with careful network planning, such as mounting the antennas at lower altitudes. Alternatively, the victim or the aggressor can adjust the down-tilt so that the remote interference level is tolerable. However, this may reduce the cell coverage and potentially increase the deployment cost. As a dynamic solution, the victim can apply receive beam nulling, interference rejection combining, or beam selection. The victim can also schedule UL transmission in the beam directions less interfered. The aggressor can also transmit in the beam directions that will cause less remote interference to the victim.

4) Power Domain Solution: The remote interference can be mitigated by increasing UL transmission power at the victim or reducing DL transmission power at the aggressor on the resources interfered and interfering, respectively. However, this will either lead to higher interference to neighbor cells for the victim or have an impact on the cell coverage for the aggressor.

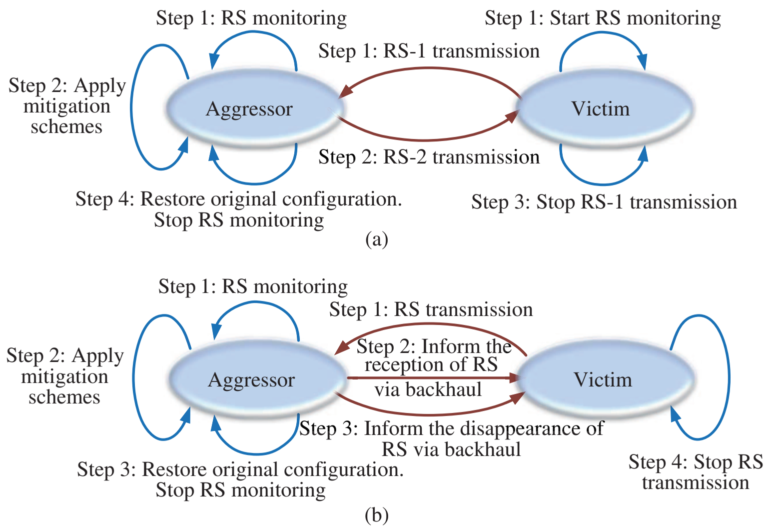

Fig. 6 Illustration of RIM framework: (a) Framework 1; (b) Framework 2

In principle, there is large flexibility to select different remote interference mitigation approaches at either the aggressor or victim side in either a semi-static or a dynamic manner and in time, frequency, spatial, or power domain. Besides, polarization domain can also be explored to mitigate the co-channel remote interference[18]. Currently, the time domain solution is widely adopted in commercial TD-LTE networks by reconfiguring the guard period from three to nine OFDM symbols, which however reduces the DL capacity by 15.7%. Therefore, more sophisticated and efficient interference mitigation schemes are of great significance to minimize the performance loss.

C. Standardization of RIM in 3GPP

There has been no standardized mechanism to handle the remote interference in TD-LTE. However, RIM is required as a mandatory feature by the operator based on the experience learned from time division-synchronous code division multiple access (TD-SCDMA). In 5G NR, the impact of atmospheric ducting is expected to be even more severe than TD-LTE due to the larger number of BSs required at a higher frequency. Moreover, with the popularity of NR deployment on TDD spectrum over the world, the problem becomes worse since the remote interference will occur not only in one country but also across borders. Therefore, it was widely recognized within 3GPP to have a standardized solution to improve the network robustness.

In order to minimize manual intervention during the RIM procedure, two main RIM frameworks have been proposed in 3GPP as shown in Fig. 6. In both frameworks, there are essentially three key steps. (1) The victim informs the aggressor about the presence of the remote interference. (2) The aggressor applies the interference mitigation scheme. (3) The aggressor informs the victim about the change of the remote interference. The key difference between the two frameworks is that RIM Framework 1 is solely based on over the air signaling while RIM Framework 2 requires information exchange between the aggressor and the victim through backhaul with core network involvement.

To support different functions in both RIM frameworks, a unified RIM reference signal (RS) design and resource configuration have been specified. The fundamental tasks of RIM RS are three folds: (1) providing information on whether the atmospheric ducting phenomenon exists; (2) assisting the aggressor to identify how many UL symbols are interfered; (3) carrying information to enable the information exchange through backhaul.

Particularly, two types of RIM-RS have been specified. The first type corresponding to RS-1 in Framework 1 and RS in Framework 2 is used by the aggressor to identify the victim and the number of interfered symbols. It may additionally be used to indicate from the victim to the aggressor whether enough remote interference mitigation has been achieved or not so that a progressive remote interference mitigation scheme can be applied to the aggressor. The second type of RIM-RS corresponding to RS-2 in Framework 1 is sent by the aggressor after it has applied the RIM scheme, to indicate to the victim that atmospheric ducting still exists.

With the assist of RIM frameworks and the RIM-RS design, more intelligent, effective, secure, and universal remote interference mitigation solutions become possible.

IV. Atmospheric Duct Enabled Beyond LoS Communications

Atmospheric duct enabled beyond LoS communication has been considered as a promising technology in coastal and maritime areas due to the high availability of the evaporation duct.

The applications and design challenges for the air-ground-sea integrated networks in 6G are discussed in this section.

A. Application Areas

A point-to-point communication link can be established directly through the atmospheric duct. Hence, atmospheric duct enabled beyond LoS communications outperform traditional relay based communications in terms of delay, the risk of interception or detection, and cost efficiency. It is extremely attractive to utilize ducting links instead in military communications and maritime communications between islands and the mainland[1,4,14].

In military communications, atmospheric duct enabled beyond LoS communications to have lower transmission delays of a few milliseconds than satellite communications of around 500 ms. Meanwhile, they can work in a wide frequency range with high capacity, especially between 2 GHz and 20 GHz, versus HF radio communications in a limited frequency band. Furthermore, the risk of interception or detection can be reduced under hostile conditions utilizing beams with low elevation angles in a long single-hop span, which outperforms satellite communications as well as most existing two- or multi-hop relay systems. All these advantages are meaningful for tactical operations, such as rapid strategic deployment in emergency, saving valuable mission time, extended operation range of radars, and secure protection from hostile jamming[1]. Therefore, atmospheric duct enabled beyond LoS communications is a promising technology for the modern military application providing timely, precise, reliable, and secure transmission.

The civilian applications of atmospheric duct enabled beyond LoS communications have mainly focused on remote communications between islands and mainland over the sea[4]. For example, cost-effective beyond LoS links for offshore gas or petroleum production platforms can be established through the atmospheric duct, where cellular links may not be feasible in open seas, submarine optical fiber links are too expensive to build, and satellite links have high operational cost. Particularly, atmospheric duct enabled beyond LoS communications become more dominant cost-saving candidates if continuous transmission is necessary. An experimental beyond LoS link using the evaporation duct has successfully sent real-time video for ecological system monitoring between the Great Barrier Reef and the Australian mainland, connecting 78 km with 10 Mbit/s more than 80% of time[4].

Furthermore, to extend the coverage of conventional terrestrial communication both from ground to air and from mainland to broad sea, atmospheric duct enabled beyond LoS communications is a key component of the air-ground-sea integrated networks[7]. For example, taking the advantage of ducting propagation, remote, flexible, and cost-effective connections can be established among UAVs in the air, offshore gas or petroleum production platforms in the sea, and the BSs in the mainland. How to construct and control such duct-assisted air-ground-sea integrated networks is an open issue.

B. Design Challenges

The design of atmospheric duct enabled beyond LoS communications has significant differences compared with other communication systems.

1) Duct Link Establishment: In order to set up the beyond LoS communication link, the transmitter and the receiver should be located in the atmospheric duct and the receiver needs to be located in the trapping region of the transmitter. Therefore, it is critical as the first step to identify the presence as well as the property of the atmospheric duct. Since the formation and characteristics of the duct, e.g. thickness and strength, are entirely dependent on meteorological conditions, it is of great importance to understand the relationship between the radio refractivity and its meteorological components. Besides, the channel state information of the ducting channels should be estimated in short enough time, to assure that the ducting channels would not change during the long-distance transmission. With the recent development of machine learning, a more accurate prediction model is promising to involve all the meteorological and transmission parameters together, which serves as a basis for a more effective, efficient, and secure design.

2) Duct Link Management: The protocols for beyond LoS communications, such as the channel access schemes and physical channel structure, are worth studying. It should be noted the overall design shares some similarities with ad hoc networks or wireless sensor networks although this might be a new system. The challenges here are the large propagation delay and the non-persisted connectivity because the communication link may become completely out of service due to weather conditions. A bundle protocol has been designed for delay-tolerant networks to not only reduce the round-trip signaling delay, but also deal with the discontinuous link with hop-by-hop transfers[19-21]. It can be learned from the bundle protocol to transmit more information with fewer handshakes. Hence it is extremely important to optimize the radio parameters so that link establishment and information delivery can be done in an efficient manner.

3) Duct-Assisted Networking: It is attractive to investigate the remote networking among the nodes in the atmospheric duct. Due to the sensitivity to meteorological conditions, the reachability between the network nodes may vary over time. How to manage the network topology and maintain robust connections among different nodes is an interesting topic. Moreover, smart caching can be introduced to handle the large propagation delay by locating important or mostly accessed content among ducting communication nodes. Last but not the least, the hybrid management of the ducting links with other LoS or non-LoS wireless links is a promising area.

V. Future Research Directions

Given the challenges of remote interference and the opportunities of beyond LoS communications, some future research directions oriented toward the new paradigm shifts in the future 6G networks[7] are provided in the following.

A. Improved Ducting Channel Modeling

On one hand, more characteristics of the ducting channels should be investigated. For example, ducting channel modeling for higher frequencies such as mmWave and THz bands is of fundamental importance for 5G and future 6G communications, since these bands are usually sensitive to atmospheric attenuation. In section II, the large-scale path losses in the duct for these bands are studied, where the duct can help concentrate the waves for a longer distance transmission than the free space. Moreover, it is challenging but meaningful to construct more complicated channel models for the dynamically coexisting LoS, non-LoS, and beyond LoS paths, considering the formation conditions of the ducting channels changing with weather or transmission.

On the other hand, how to utilize the ducting channel modeling is still an open problem. It is promising to exploit traditional wireless transmission technologies like multiple antennas and OFDM into the ducting channels[5], of which the performances should be further evaluated. Furthermore, if the transmitters and receivers are mobile, Doppler effect may result in channel fading[14]. In this way, extra transmitting power as fade margin should be investigated to combat the fading caused by the Doppler effect, and mobility management strategies such as joint beamforming and trajectory optimization are necessary for moving UAVs or ships to maintain the ducting links.

B. Intelligent Remote Interference Mitigation

More efficient and intelligent remote interference mitigation schemes should be investigated by making use of machine learning (ML). The remote interference mitigation schemes in a TD-LTE network rely on manual control via an operation, administration, and maintenance (OAM) function. It is inefficient to identify the aggressors and challenging to take appropriate actions in a timely manner. In contrast, the ML-based mitigation schemes can deal with multiple atmospheric and communication parameters autonomously, e.g., atmospheric pressure, humidity, trapping region, channel estimation, beam width design, mobility, and coordination between operators and even across nations. Moreover, considering the large delay introduced by the long-distance transmission of the ducting link, distributed ML methods like federal learning can be exploited by the BSs locally to reduce frequent information exchange significantly.

C. Atmospheric Duct Affected UAV Communications

UAVs have attracted great interest in wireless communications due to its high flexibility and enormous application potential. The maximum altitude of UAV deployment is generally regulated around one hundred meters if there is no specific permit. In this situation, UAVs are usually located in the trapping regions of the ground BSs, where smaller angles of departure are often used. As a result, UAVs, as flying BSs or mobile terminals, may face more severe remote interference than the traditional terrestrial nodes. On the other hand, atmospheric duct enabled beyond LoS communications can be a robust and redundant backup for UAVs networking with end-to-end connectivity, particularly in emergency communication applications.

D. Duct-Assisted Air-Ground-Sea Integrated Networks

The atmospheric duct can connect various flying, terrestrial, and maritime nodes and devices remotely in a cost-saving and flexible way. The trapping region of each transmitter should be well utilized to construct effective ducting links. The three-dimensional beam management in horizontal and vertical directions is essential to make use of the trapping region. Moreover, powered by advanced deep learning, some intelligent solutions for the atmospheric ducting would be further studied to enhance the efficiency of the duct-assisted air-ground-sea integrated networks.

VI. Conclusions

Electromagnetic wave propagation is significantly affected by the atmospheric duct, which is caused by the rapid decrease of tropospheric refractivity under certain weather conditions. Atmospheric ducting brings both challenges and opportunities to wireless communications. Based on the investigation of the characteristics of the atmospheric duct and its influence on radio wave propagation, the concept of trapping region is developed. The trapping region plays an important role in both remote interference management and beyond LoS communications. Future research areas towards 6G include more intelligent and more integrated atmospheric duct affected wireless communications.

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About the Authors

Fangfang Liu [corresponding author] received the B.S. and Ph.D. degrees from Beijing University of Posts and Telecommunications (BUPT) respectively in 2006 and 2012, Beijing, China. She is currently an Assistant Professor with BUPT from 2012. Her current research interests are in edge intelligence for vehicle networks, interference management for 5G and beyond networks, and polarization signal processing.

Jiaxi Pan received the B.S. degree from Beijing University of Posts and Telecommunications (BUPT) in 2019, Beijing, China. She is a M.S. student in BUPT. Her research focuses on wireless resource management and standardization for 5G networks.

Xiangwei Zhou received the B.S. degree from Nanjing University of Science and Technology, Nanjing, China, the M.S. degree from Zhejiang University, Hangzhou, China, and the Ph.D. degree from Georgia Institute of Technology, Atlanta, USA, in 2005, 2007, and 2011, respectively. Since August 2015, he has been with Louisiana State University, Baton Rouge, LA, USA. His research interests are in machine learning for intelligent communications, coexistence of wireless systems, and spectrum-efficient, energy-efficient and secure communications.

Geoffrey Ye Li has been a Chair Professor at Imperial College London, London, U.K., since 2020. Before moving to Imperial College London, he was with Georgia Institute of Technology in Georgia, Atlanta, USA, as a Professor for twenty years and with AT&T Labs - Research in New Jersey, USA, as a Principal Technical Staff Member for five years. His general research interests include statistical signal processing and machine learning for wireless communications. In the related areas, he has published over 500 journal and conference papers in addition to over 40 granted patents. His publications have been cited over 46 000 times and he has been recognized as a Highly Cited Researcher, by Thomson Reuters, almost every year.

Dr. Geoffrey Ye Li was awarded IEEE Fellow for his contributions to signal processing for wireless communications in 2005. He won several prestigious awards from IEEE Signal Processing Society (Donald G. Fink Overview Paper Award in 2017), IEEE Vehicular Technology Society (James Evans Avant Garde Award in 2013 and Jack Neubauer Memorial Award in 2014), and IEEE Communications Society (Stephen O. Rice Prize Paper Award in 2013, Award for Advances in Communication in 2017, and Edwin Howard Armstrong Achievement Award in 2019). He also received the 2015 Distinguished ECE Faculty Achievement Award from Georgia Institute of Technology.

He has been involved in editorial activities for over 20 technical journals, including the founding Editor-in-Chief of IEEE JSAC Special Series on ML in Communications and Networking. He has organized and chaired many international conferences, including Technical Program Vice-Chair of the IEEE ICC'03, General Co-Chair of the IEEE GlobalSIP'14, the IEEE VTC'19 (Fall), and the IEEE SPAWC'20.