Terahertz Communications

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Ofinno • ofinno.com • April 2021

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Abstract

Higher frequency bands than that being employed in fifth generation (5G) communications, such as terahertz (THz) bands, are envisioned for future communications in the next decade. This article discusses envisioned use cases of THz communications, technical challenges, and the industry's view of THz communications in sixth generation (6G) communications.

Introduction

Higher frequency bands are expected to be employed for 6G communications. This expectation is driven by the desire for a higher data rate and system capacity. In the 5G era, spectrum bands up to 50 GHz have been allocated, standardized, and studied in various regions. A work item supporting 52.6 ~ 71 GHz is under development in the 3rd Generation Partnership Project new radio (3GPP NR) working group for developing 5G standards. It can be foreseen that the 5G standard will continue its evolution after 2020 to further extend deployment scenarios and the operating bands, for example, up to ~ 114 GHz [1].

FIG. 1 illustrates spectrum allocations for possible future 6G communications [2]. According to FIG. 1, while 5G ensured communications via millimeter wave (mmWave) spectrum (e.g., ~114 GHz), new physical layer designs enable high flexibility for 5G communications. The main challenge of using these mmWave frequency bands is balancing the tradeoff between high-output power devices and cost. When facing this challenge, massive multiple-input multiple-output (MIMO) antenna arrays are employed at the transmitters/receivers to generate multiple beams with narrow beamwidth to increase the effective isotropic radiated power (EIRP) and coverage. On the other hand, signal propagation in THz frequency bands have another challenge, namely severe propagation loss due to the fact that the THz signals are easily blocked and attenuated due to their very short wavelength. Consequently, diffraction by obstacles is limited, and signal strength loss due to penetration/absorption by water/air is significant. Furthermore, in dense urban and indoor environments, reflections from the local surfaces, such as buildings and walls, allow Non-Line-Of-Sight (NLOS) coverage the same as an access point node [3].

5G communication systems enable a peak data rate up to 20 Gbps by expending frequency bands to mmWave [4]. However, a desired higher data rate up to Tbps-level and microsecond-level latency are expected in the 6G era. These data rates and latency cannot be achieved by the mmWave based 5G systems. By emerging academic research work and industry development trends, wireless communications via THz frequency band (0.1 ~ 10 THz) have been envisioned in the future for achieving Tbps-level and microsecond-level latency requirements [5]. In the recommendations of International Telecommunication Union Radiocommunication Sector (ITU-R), the 275 GHz–3 THz frequency range is recommended as a main part of THz-based cellular communications. System capacity of future 6G networks will increase by combining the THz frequency bands (275 GHz–3THz) and the mmWave band (30–300 GHz). Since the 275 GHz–3 THz frequency bands have not been allocated for any wireless communication systems globally yet, adopting these higher frequency bands is being considered as a potential solution to accomplish the desired Tbps-level data rate [2].

<table>
<tr><td></td><td colspan="2">mmWave part-1</td><td>30–275 GHz</td><td>10 – 1.1mm</td><td colspan="2" rowspan="2">mmWave</td></tr>
<tr><td rowspan="2">THz</td><td colspan="2">mmWave part-2</td><td>275 – 300 GHz</td><td>1.1 – 1 mm</td></tr>
<tr><td colspan="2">Far IR part-1</td><td>0.3 – 3 THz</td><td>1 – 0.1mm</td><td rowspan="6">Infrared</td><td rowspan="21">Optical</td></tr>
<tr><td rowspan="5"></td><td colspan="2">Far IR part-2</td><td>3 – 20 THz</td><td>0.1 – 0.015 mm</td></tr>
<tr><td rowspan="2">Thermal IR</td><td>Long-wavelength IR</td><td>20 – 37.5 THz</td><td>0.015 – 0.008 mm</td></tr>
<tr><td>Mid-wavelength IR</td><td>37 – 100 THz</td><td>0.008 – 0.003 mm</td></tr>
<tr><td colspan="2">Short-wavelength IR</td><td>100 – 214.3 THz</td><td>3000000 – 1400 nm</td></tr>
<tr><td colspan="2">Near IR</td><td>214.3 – 394.7 THz</td><td>1400 – 760 nm</td></tr>
<tr><td rowspan="6"></td><td colspan="2">Red</td><td>394.7 – 491.8 THz</td><td>760 – 610 nm</td><td rowspan="6">Visible Light</td></tr>
<tr><td colspan="2">Orange</td><td>491.8 – 507.6 THz</td><td>610 – 591 nm</td></tr>
<tr><td colspan="2">Yellow</td><td>507.6 – 526.3 THz</td><td>591 – 570 nm</td></tr>
<tr><td colspan="2">Green</td><td>526.3 – 600 THz</td><td>570 – 500 nm</td></tr>
<tr><td colspan="2">Blue</td><td>600 – 666.7 THz</td><td>500 – 450 nm</td></tr>
<tr><td colspan="2">Violet</td><td>666.7 – 833.3 THz</td><td>450 – 360 nm</td></tr>
<tr><td rowspan="8"></td><td colspan="2">UVA</td><td>750 – 952.4 THz</td><td>400 – 315 nm</td><td rowspan="9">Ultraviolet</td></tr>
<tr><td colspan="2">UVB</td><td>952.4 – 1071 THz</td><td>315 – 280 nm</td></tr>
<tr><td colspan="2">UVC</td><td>1.071 PHz</td><td>280 – 100 nm</td></tr>
<tr><td colspan="2">NUV</td><td>0.750 – 1 PHz</td><td>400 – 300 nm</td></tr>
<tr><td colspan="2">Middle UV</td><td>1 – 1.5 PHz</td><td>300 – 200 nm</td></tr>
<tr><td colspan="2">Far UV</td><td>1.5 – 2.459 PHz</td><td>200 – 122 nm</td></tr>
<tr><td colspan="2">Hydrogen Lyman-alpha</td><td>2.459 – 2.479 PHz</td><td>122 – 121 nm</td></tr>
<tr><td colspan="2">Extreme UV</td><td>2.479 – 30 PHz</td><td>121 – 10 nm</td></tr>
<tr><td></td><td colspan="2">Vacuum UV</td><td>1.5 – 30 PHz</td><td>200 – 10 nm</td></tr>
</table>

FIG. 1 Spectrums for possible wireless communications in 6G [2].

Challenges for Terahertz Communications

Samsung presents their observations on technical challenges of THz communications in a recent white paper [6]. The technical challenges are summarized from the following perspectives.

Severe path-loss and absorption:

Based on the free-space path loss model, signal propagation loss is proportional to the square of the carrier frequency of the signal. For example, a link at 3 THz will cause an additional 20 dB path loss compared with 300 GHz, 40dB additional path loss compared with 30 GHz (which is mmWave spectrum in 5G), and 60 dB additional path loss compared with 3 GHz (which is sub-6 GHz spectrum in 4G). Furthermore, absorption/penetration loss of signal strength by oxygen and water are mostly located in the THz frequency bands. To compensate for the severe power loss, an ultra-massive MIMO antenna array might be utilized to extend coverage by generating very sharp beams.

RF front-end, photonics, and data conversion: The main problem utilizing THz frequency bands for wireless communications is the lack of existing efficient devices. Here efficient devices refer to those devices with high power loss or equivalently low power efficiency. Samsung also mentioned that in the last ten years, researchers have developed advanced chip-scale THz technologies and semiconductor technologies (e.g., based on InP, GaAs, SiGe, and CMOS) for enabling the practical wireless devices operated at low THz band (e.g., ~ 300 GHz), which can generate power in the mW range with acceptable power efficiency.

Antenna, lens, and beamforming architecture: As aforementioned, ultra-massive MIMO antenna arrays in THz frequency bands may result in very focused beams, which indicates that THz links will depend on Line-Of-Sight (LOS) paths and reflected paths, but not on other paths due to scattering and diffracting. This feature suggests that channel characteristics of the THz spectrum for both outdoor and indoor environments should be carefully studied. It is well understood that the design of antenna elements should be based on the wavelength of the carrier frequency. More specifically, the size of the antenna elements should be comparable to the wavelength. The design of antenna elements in THz may face another big challenge since the antenna elements of THz communications should be able to support GHz-wide bandwidth. It is very hard to say what an exact antenna size is suitable for this case.

New waveforms, signals, channels, and protocols: Other than orthogonal frequency division multiplexing (OFDM), a new waveform such as a single carrier may be beneficial for supporting wireless channels with GHz bandwidth, considering reduction of peak-to-average power ratio (PAPR), and the limitations of THz devices.

ZTE and China Mobile foresee key technology aspects of THz communications [1]. They share a quite similar view as Samsung in [6], and their concerns are listed briefly as follows:

- Propagation measurement and channel modeling,
- THz signal generation & detection (transceiver design),
- Antenna technologies,
- Ultra-massive MIMO for THz band,
- High-speed baseband signal processing technology, and
- Baseband design.

Because of the new channel characteristics of THz frequency bands and various deployment scenarios, propagation measurement and channel modeling are considered important research topics. So far, designing and manufacturing practical THz hardware, for transferring data at Tbps data rate with acceptable power consumption, are facing many technical challenges. Some of the challenges include: power loss during signal transporting inner device, heat dissipation, phase noise, power loss in analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), and digital input/output (I/O) to DACs and ADCs. THz transceiver design, antenna technologies, ultra-massive MIMO for THz band, and high-speed baseband signal processing technology would play an important role implementing THz communications. Furthermore, novel baseband designs for THz frequency bands may be required, for example, single-carrier waveform, novel modulation and coding schemes, and novel multiple access technologies such as orbital angular momentum (OAM), and non-orthogonal multiple access (NOMA).

For addressing the challenges and promoting the use of THz frequency bands, the Federal Communications Commission (FCC) released spectrum from 95 GHz to 3000 GHz, in March 2019, for the purpose of experimental use and unlicensed applications to promote the research and development of THz wireless communication technologies [6].

Industry Visions on Terahertz Communications

ZTE and China Mobile presented their targeted application scenarios of THz communications for 6G [1]. They classified the application scenarios of terrestrial THz communications into macro-scale, micro-scale, and nanoscale networks based on communication range requirements. FIG. 2 indicates each scenario and its corresponding communication range requirement.

Macro-scale networks are primarily used for applications with a transmission range greater than 10 m. They are usually used for outdoor deployments, which include typical applications such as vehicle-to-everything (V2X) connection and backhaul/fronthaul connection. A high throughput (e.g., ~ 1 Tbps) and a low latency (e.g., < 1 ms) may be expected.

Micro-scale networks are used in applications with a limited transmission range of several meters (e.g., ≤ 10 m). They may be deployed for both outdoor and indoor application scenarios. Indoor deployment of micro-scale networks may support small cells, wireless personal area networks, wireless connections in data centers, and near field communications (NFC), etc. Outdoor deployment of micro-scale networks may support vehicular, small cells, and backhaul connections.

Nanoscale networks may be more suitable for communications within a communication range of less than 1 m (e.g., or cm). The nanoscale network is a new network topology for communications with very short wavelengths. They may support inter-miniature-device links, on-chip and chip-to-chip links, and in-body communications. The main challenges of nanoscale networks include transceiver design for nanoscale devices, channel modeling, physical layer designs such as novel channel coding and modulation schemes, and communication protocols.

In addition to the above scenarios for terrestrial communications using THz frequency bands, outer space communications are also considered as an important application scenario of THz communications. The potential benefits of employing THz frequency bands for outer space scenario include: 1) wider bandwidth available in THz bands, 2) lower atmospheric attenuation and oxygen/water absorption, and 3) less stringent requirements on beam alignment. The main limitation of THz communications in the outer space scenario would be severe path loss due to the long distance between, for example, inter-satellite connections.

Samsung expects that 6G would be designed to utilize up to 3,000 GHz [6]. However as described above, due to hardware limitations in THz bands, efficient devices supporting low THz bands (e.g., ~ 300 GHz) are currently available. How much of the 3000 GHz frequency band 6G will utilize will depend on the hardware improvement in the next decade.

Samsung presented several interesting technologies along with their vision to 6G. FIG. 3 shows a novel metamaterial antenna. As shown in FIG. 3, the metamaterial antenna is capable of radiating directive beams by itself without employing phase shifters for generating directional beams. The metamaterial antenna is engineered to have this property by

Macro-scale networks	Micro-scale networks	Nanoscale networks
10 m ~ few kilometers	≤ 10 m	below 1 m or cm

FIG. 2 EApplication scenarios of THz communications [1].

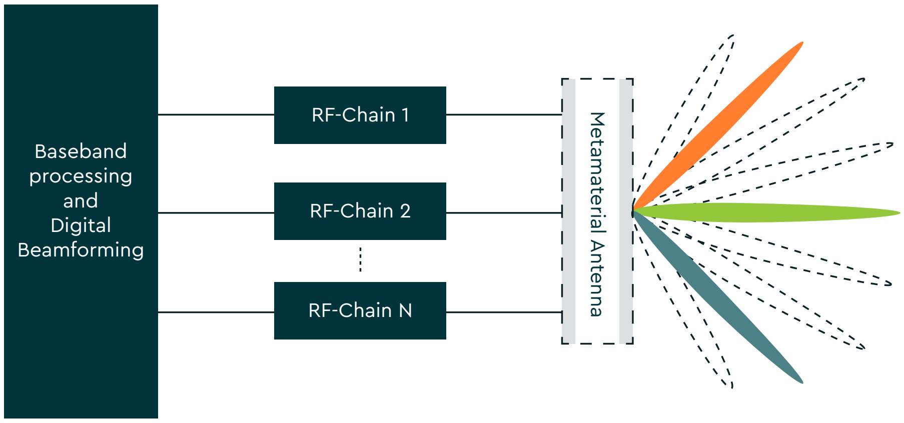

FIG. 3 Metamaterial antenna [6].

arranging multiple tunable elements (PIN diodes, varactor diodes, etc.) in repeating patterns, where the tunable elements are at scales of being smaller than the wavelengths.

Other than metamaterial antenna, OAM multiplexing is also widely recognized as a strong candidate for THz communications in 6G. The basic idea of OAM is to exploit the helical phase front in the propagation direction of electronic-magnetic waves. An OAM mode may generate beams with a distinct number of phase rotations. The phase rotations are orthogonal so that the OAM can create orthogonal channels. The reason OAM is considered as a strong candidate for THz communications is that complex signal processing is not necessary for implementing OAM multiplexing. Considering the LOS channel environments in THz frequency bands, the OAM multiplexing is practical for deployment to achieve the desired point-to-point (P-to-P) higher-rate transmission. FIG. 4 summarized a comparison between MIMO-based technologies and OAM multiplexing for fixed wireless links [7]. FIG. 5 illustrates OAM multiplexing with different OAM modes [6].

	Massive MIMO	LOS MIMO	OAM Multiplexing
Type	P-to-MP	P-to-P	P-to-P
Channel	LOS / NLOS	LOS	LOS
Antenna configuration	linear array	linear array	circular array
Antenna size	large / medium	large	large
Streams per user	single	multiple	multiple
Circuit complexity	high / medium	medium	medium
Mobility tracking	eligible	not eligible	not eligible
Robustness for coaxial distance vitiations	good	bad	good
Robustness for axis misalignments	good	bad	bad

FIG. 4 Comparison among MIMO technologies and OAM multiplexing for fixed wireless links using mmWave bands [7].

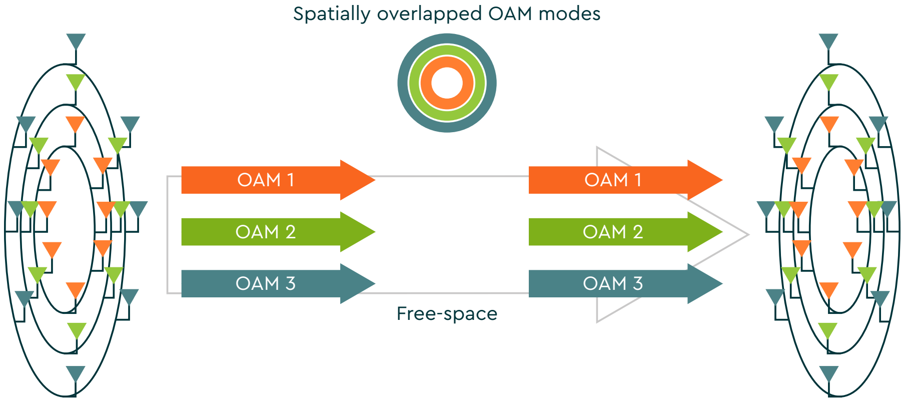

FIG. 5 OAM multiplexing with different OAM modes [6].

Ericsson has presented views on the use of different frequency bands in 6G [8]. Sub-6 GHz bands are shared with 6G. 24 ~ 52 GHz bands which have been standardized by 5G and likely to extend up to 100 GHz, will be covered by 6G. 7 ~ 24 GHz bands, which are currently used for other purposes than cellular communications, may be exploited for 6G via advanced spectrum sharing mechanisms. Beyond 100 GHz, bands show very challenging propagation characteristics. Therefore, bands greater than 100 GHz may be mainly of interest for specific scenarios requiring extreme system throughput/data rates, such as in a dense network.

Nokia shows a similar view with Ericsson [3]. FIG. 6 depicts Nokia's frequency spectrum view in the future 6G era. Based on current knowledge and available THz devices, up to 300 GHz frequency bands may be adopted in 6G. As the carrier frequency increasing, the expected communication range gets shorter. This is intuitive because of the severe path loss of higher frequency bands. By involving sub-terahertz and terahertz bands for future wireless communications, a much wider signaling bandwidth is expected. Artificial intelligence (AI)-based access (e.g., in time, frequency, code, space, and power domain), such as spectrum access, may be adopted for achieving more dynamic and smarter radio resource management. Due to limited deployment scenarios for sub-terahertz frequency bands and sensing-based operations, AI-based spectrum access may not be necessary for the sub-terahertz frequency bands (e.g., 30 GHz ~ 300 GHz in FIG. 6). More spectrum will be available as the frequency increases. It is observed that there is a turning point describing the rank of MIMO links. In mmWave frequency bands, a relatively short wavelength enables a small antenna size, therefore, high-rank MIMO links can be supported

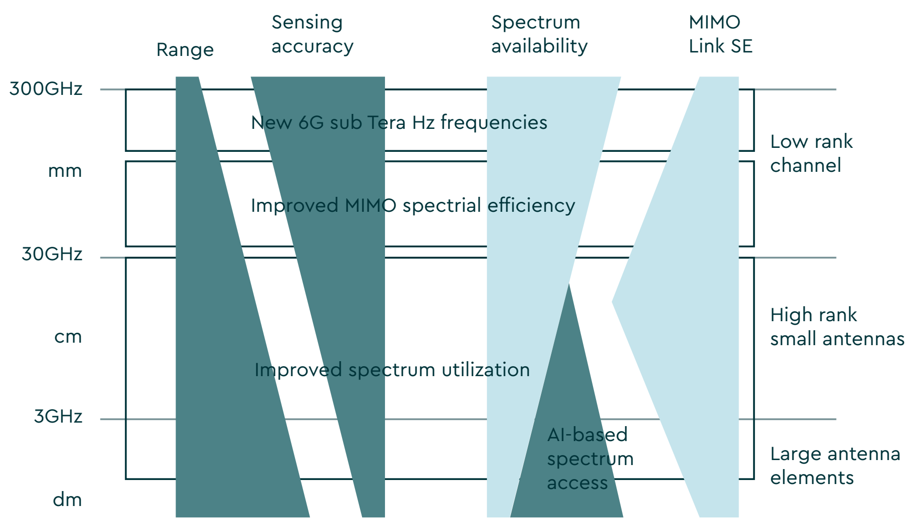

FIG. 6 The THz spectrum resources for future wireless communications [3].

by employing massive MIMO antenna arrays. As the carrier frequency increasing even higher to THz frequency bands, the antenna size can be further reduced considering shorter wavelengths in THz frequency bands compared with that in mmWave frequency bands. Ultra-massive MIMO antenna arrays may be used for THz communications. However, as shown in FIG. 6, the channel rank becomes lower in THz frequency bands. One possible reason is that for compensating the severe path loss in THz frequency bands, more antenna elements may be required for achieving significant beamforming gain.

FIG. 7 illustrates NTT DoCoMo's opinion on spectrum utilization in 6G [9]. DoCoMo assumes that up to 300 GHz may be considered for 6G. The Single carrier may become dominant compared with OFDM. Power-efficient devices and technologies will be the most important issue in 6G. Optimizing the selected application of multiple bands, reexamining the frequency reuse method between cells, upgrading the duplexing method, and reexamining the utilization method of the low frequency band may be critical for practically implementing THz communications. Interestingly, DoCoMo thinks outer space communication may employ relatively lower frequency bands for guaranteeing coverage, which is quite different from the view of Samsung who thought THz frequency bands may be beneficial for outer space communications.

Conclusion

This article summarized visions of THz communications from industry and academia perspectives. Many companies expect that low THz frequency bands (e.g., ~ 300 GHz) may be practical to use in 6G, based on current knowledge and limitations of devices. Due to very challenging propagation conditions and hardware limitations, companies think that interest in THz communications rely on some specific scenarios such as dense network deployment, short-range communications, etc. Therefore, AI-based spectrum sharing/access may not be required for THz communications. Some companies as well as some research papers suggest that THz can be utilized for outer space communications such as inter-satellite communications due to the widely available bandwidth, low atmospheric attenuation, and less stringent requirements on beam alignment. On the other hand, some other companies also have concerns about the limited coverage problem in the THz frequency band. Further study is necessary to conclude this case.

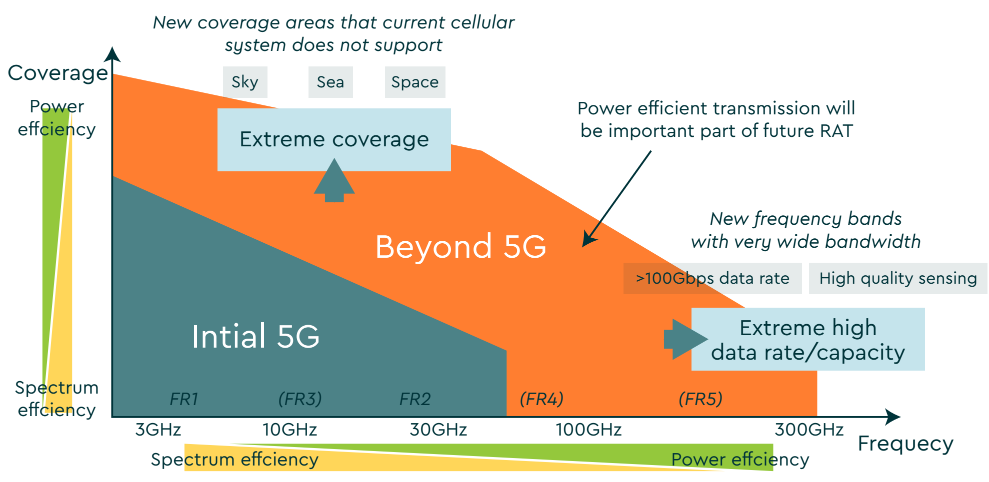

Figure 4-4. Expansion of radio access technology for exploiting new frequency and coverage

FIG. 7 DoCoMo's opinion on spectrum utilization for future wireless communications [9].

Acronym List

3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
ADC	Analog-to-Digital Converter
AI	Artificial Intelligence
CMOS	Complementary Metal-Oxide-Semiconductor
DAC	Digital-to-Analog Converter
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Commission
GaAs	Gallium Arsenide
InP	Indium Phosphide
I/O	Input/Output
ITU-R	International Telecommunication Union Radiocommunication Sector
LOS	Line-Of-Sight
mmWave	Millimeter Wave
mW	Milliwatt
MIMO	Multiple-Input Multiple-Output
NFC	Near Field Communications
NLOS	Non-Line-Of-Sight
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
OAM	Orbital Angular Momentum
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-Average Power Ratio
PIN	Positive-Intrinsic-Negative
P-to-P	Point-to-Point
P-to-MP	Point-to-Multiple Points
SiGe	Silicon Germanium
THz	Terahertz
V2X	Vehicle-to-Everything

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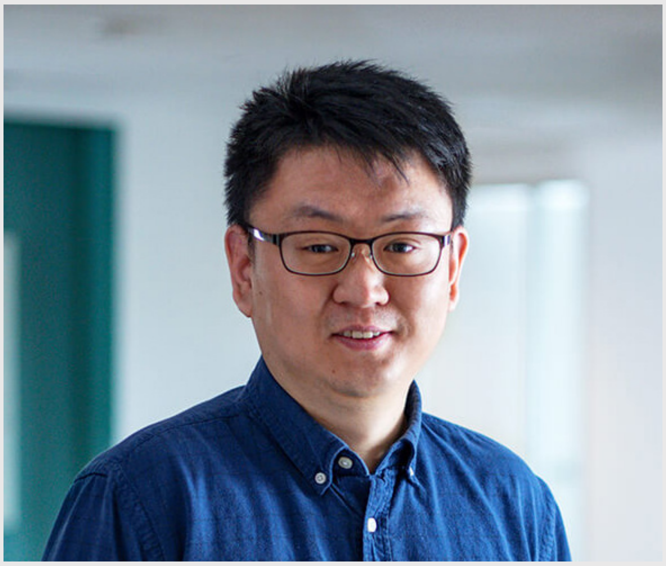

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