Emerging Technologies for Machine-Type Communication Networks

Nian Xia, Hsiao-Hwa Chen, and Chu-Sing Yang

Abstract

Machine-type data traffic volume in 5G networks will grow rapidly with widespread applications of MTC. The MTC devices, including home appliances, sensors, wearable devices, vehicles, and even low-altitude UAVs, will be made smarter with embedded advanced communication modules. However, a massive number of MTCDs with diverse QoS requirements cannot be served well by traditional wireless systems, which were primarily designed for human-type devices. New wireless technologies are needed to support distinct MTC network applications. In this article, five emerging MTC technologies, including Bluetooth 5, WiFi HaLow, LTE-M, NB-IoT, and WURs, are discussed, followed by a survey of 3GPP activities on vehicle-based and UAV-based MTC technologies, such as LTE-V2X and C-UAV for aerial vehicles. In the end, we also address the issues on the new trends for MTC networks with identified research challenges.

Introduction

Next generation wireless systems are expected to provide ubiquitous connections for traditional user equipments (UEs) as well as a massive number of machine-type communication devices (MTCDs). Unlike normal UEs, MTCDs can communicate with each other autonomously without human interventions. More and more machines in our daily life work with communication modules to act as MTCDs. For instance, home appliances with network capabilities can either periodically report their status information or trigger alarming messages to remote MTC servers through uplink (UL), while MTC servers can also deliver commands and software updates via downlink (DL).

To respond to such a vast need, standardization bodies are working hard to develop new technologies for the flourishing MTC applications. Bluetooth Special Interest Group (SIG) introduced Bluetooth 5 for devices that require ultra-low power consumption [1] and Bluetooth Mesh for MTC mesh networks [2]. The IEEE 802.11 task group proposed IEEE 802.11ah, which was also named WiFi HaLow, for both indoor and outdoor Internet of Things (IoT) applications with a massive number of devices [3]. In addition, 3GPP has also been very active in optimizing cellular systems for IoT applications as depicted in Fig. 1. Two distinct 3GPP standards, that is, enhanced MTC (eMTC) and NarrowBand IoT (NB-IoT), were introduced in 3GPP Release 13 and then enhanced in subsequent releases. LTE MTC (LTE-M) was intended for premium IoT applications with high data rates and strict delay requirements, while NB-IoT was designed for low-end IoT applications with low data rates, delay tolerance, massive connections, and extremely wide coverage [4]. Notably, 3GPP Release 15 focused on the enhancements for both LTE-M and NB-IoT to meet not only the requirements of 5G mMTC (massive MTC) in the 3GPP evaluation process itself, but also the demands from new MTC applications [5, 6]. Wake-up radios (WURs) [7] in IEEE 802.11ba can prolong the lifetime of battery-powered devices by introducing a low-complexity wake-up receiver for idle monitoring.

As shown in Fig. 1, 3GPP has also made a lot of effort to accommodate both ground and unmanned aerial vehicles (UAVs) within cellular systems. For ground vehicles, LTE-V2X (vehicle-to-everything) has been standardized in 3GPP Release 14 to compete with IEEE 802.11p-based V2X technologies, that is, DSRC (dedicated short range communications) and ITS-G5 (Europe). In 3GPP Release 15, enhancements on V2X (eV2X) aimed to support advanced V2X users, such as vehicle platooning, autonomous driving, extended sensors, and remote driving [8]. However, how to provide V2X services via 5G new radio (NR) is still open in 3GPP Release 16. Besides ground vehicles, 3GPP is also conducting studies on supporting low-altitude UAVs by LTE and futuristic 5G NR systems [9, 10].

In this article, we first briefly overview five emerging technologies for IoT applications, including Bluetooth 5, WiFi HaLow, LTE-M, NB-IoT, and WUR. Then, we review the standardization works on LTE-V2X and cellular-based UAV (C-UAV) communications, including their service requirements and main features. Then, we will discuss the new trends for MTC networks, followed by the conclusions of this article.

Emerging MTC Technologies

In this section, five emerging MTC technologies for low-power IoT applications are reviewed, including Bluetooth 5, WiFi HaLow, LTE-M, NB-IoT, and WUR.

Bluetooth 5

Bluetooth has been widely used in electronics devices supporting short-range continuous streaming traffic, such as wireless stereo headsets, wireless speakers and mouses. With the popularity of wearable computing applications, Bluetooth SIG introduced Bluetooth low energy (BLE) or Bluetooth 4.0 for devices with ultra-low energy

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The authors are with National Cheng Kung University; Hsiao-Hwa Chen is the corresponding author.

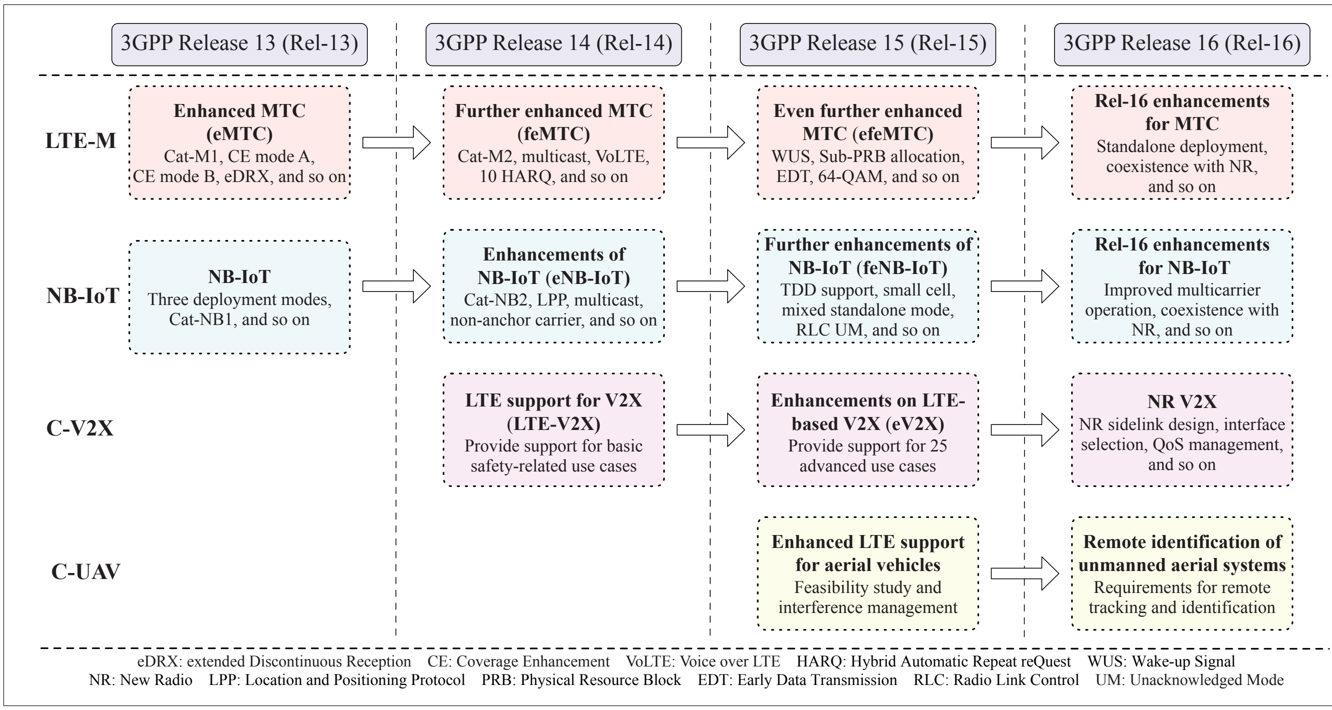

FIGURE 1. 3GPP standardization activities in MTC networks [5, 6, 8–10].

consumption. As a successor to Bluetooth 4.x, Bluetooth 5 broadens BLE use cases by providing extended communication range, increased data rates, and improved broadcasting capacity [1].

In Bluetooth 5, the peak data rate is doubled to 2 Mb/s, and the LE (low energy) 2M uncoded PHY is employed. A higher peak data rate not only conserves energy for devices by reducing device active time, but also accommodates data-hungry services, such as firmware updates. Although the maximum transmit power remains constant, the communication range of Bluetooth 5 has been extended to several hundred meters, which quadrupled the range of Bluetooth 4.x, making it suitable for home and building automation applications. Note that the extended range was achieved by exploiting the LE coded PHY with eight symbols representing one bit. In addition to three primary advertising channels, the remaining 37 data channels can serve as secondary advertising channels for packet broadcasting with large payloads in connectionless applications, where packets are transmitted without handshaking procedures. In the applications with deterministic broadcasting traffic, periodic and deterministic advertising are also supported to reduce overhead. As Bluetooth 5 still operates in the crowded 2.4 GHz ISM band, channel selection algorithm #2 was designed to better combat interferences by employing pseudo random hopping sequences [1]. Moreover, slot available mask (SAM) shares BLE slot activity information with adjacent wireless mobile systems to mitigate interferences.

Bluetooth SIG in [2] developed Bluetooth Mesh, which runs on top of BLE 4.0 or higher for applications that require m:m (namely m to m) communications, such as light control and industry automation. One Bluetooth Mesh network can support up to 32000 devices. As depicted in Fig. 2, devices are classified into nodes, low power nodes (LPNs), friend nodes (FNs), and relay nodes. FNs can store and forward messages for associated LPNs, while relay nodes relay messages only for connected nodes. Publish-subscribe mode is employed for link establishment, while message relaying is controlled by managed flooding and message caching mechanisms.

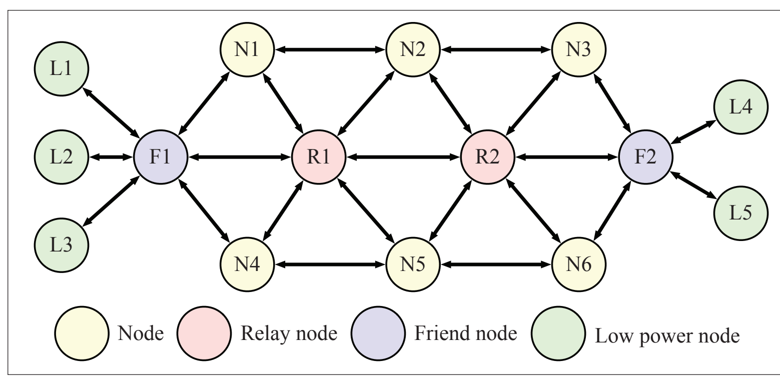

FIGURE 2. An illustration of Bluetooth Mesh topology. Devices are classified into nodes (N1-N6), relay nodes (R1-R2), friend nodes (F1-F2), and low power nodes (L1-L5). For example, friend node F1 stores and forwards messages for associated low power nodes (L1-L3), while relay node R1 can relay messages for connected nodes (F1, N1, N2, N4, N5, R2). Notably, nodes (N1-N6) communicate only with nearby nodes directly and do not forward messages for other nodes.

WiFi HaLow

Unlike Bluetooth 5, WiFi HaLow operates at the sub-1 GHz (S1G) ISM band for achieving better wall penetration characteristics with an extended transmission range up to 1 km and a minimum data rate higher than 150 kb/s. Notably, the coverage range can be further extended by S1G relays that can forward packets for associated stations (STAs). WiFi HaLow is mandatory to support 1 MHz and 2 MHz channel bandwidths, and

S1G STAs can be classified into sensor STAs and non-sensor STAs based on traffic and device characteristics. Sensor STAs have deterministic traffic and device characteristics, that is, payload, traffic volume, and battery powered, while non-sensor STAs do not have such limitations. Similar to channel access, several mechanisms were proposed to reduce energy consumption.

optional to support 4 MHz, 8 MHz, and 16 MHz channel bandwidths. Subchannel selective transmission allows one STA that only supports 1 MHz or 2 MHz channel bandwidth to select the best subchannel from a set of subchannels that belong to a wider bandwidth channel (i.e., 8 MHz).

Each STA is assigned one unique 13-bit association identifier (AID), and at most 8191 STAs can be associated with a S1G access point. Each AID corresponds to one bit in the traffic indication map (TIM), which indicates whether there are any buffered packets for one specific AID or not. Furthermore, a group of STAs can be identified by one group AID.

As the performance of the conventional distributed coordination function degrades significantly with an increasing number of associated STAs, several approaches are used to alleviate congestion as follows:

- Restricted access window (RAW) was proposed to restrict channel access of one RAW to a specific group of STAs.
- Bidirectional TXOP was suggested to reduce the overall number of access requests by allowing an access point and STAs to exchange a sequence of packets in UL and DL for each access opportunity.
- Sectorization divides a serving cell into multiple sectors and restricts channel access to each sector by configuring distinct beams for different sectors.

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- Target wakeup time (TWT) that allows STAs to remain asleep until the negotiated wakeup time.
- Non-TIM operations that allow non-TIM STAs not to wake up for periodical beacons.
- Extended maximum basic service set idle period. Furthermore, shortened frames, such as shortened beacon, can also reduce the overhead of control information and energy consumption.

LTE-M

Next, the enhancements for LTE-M from 3GPP Releases 13 to 15 are discussed with an emphasis on the features in the latest 3GPP Release 15.

Enhanced MTC and Further Enhanced MTC: In 3GPP Release 13, enhanced MTC (eMTC) introduced a new user equipment (UE) category: Cat-M1 with 1.4 MHz bandwidth in both DL and UL for bandwidth-limited and low complexity MTCDs. Coverage enhancement (CE) modes A and B are employed to extend UL coverage by repetitions, while eDRX (extended discontinuous reception) can reduce energy consumption by extending sleeping cycles.

For further enhanced MTC (feMTC) in 3GPP Release 14, the peak data rate for Cat-M1 is increased by extending the transmit block size (TBS) from 1000 bits to 2987 bits. Meanwhile, a new UE category Cat-M2, which occupies 5 MHz bandwidth with the maximum data rates of 4 Mb/s in DL and 7 Mb/s in UL for full-duplex FDD, was introduced. Furthermore, multicast was implemented by modifying SC-PTM (single-cell point-to-multipoint) and up to 128 multimedia broadcast multicast services (MBMS) traffic channels (MTCHs) were supported. Other enhancements in feMTC include enhanced voice over LTE (VoLTE), improved positioning and mobility, 10 DL hybrid automatic repeat request (HARQ) processes, HARQ-ACK bundling, and so on.

Even Further Enhanced MTC in 3GPP Release 15: In 3GPP Release 15, even further enhanced MTC (efeMTC) supports new use cases, such as asset tracking via supporting higher UE velocities and new gap patterns for dense positioning reference signal (PRS). The enhancements in efeMTC are summarized as follows [5].

Wake-Up Signal (WUS): Wake-up signal is transmitted within a configurable time before the page occasion (PO), where the device is paged to maximize sleep time. As UEs avoid frequent wake-ups for listening paging information that is not intended for them, power consumption in idle mode is reduced. However, a low-complexity wake-up receiver is essential.

Sub-PRB Allocation: The minimum resource allocation unit is one physical resource block (PRB), which is underutilized for packets with small payloads. To improve spectrum efficiency in PUSCH (physical uplink shared channel), efeMTC allows sub-PRB allocation with two allocation sizes, that is, 1/2 PRB (six subcarriers) and 1/4 PRB (three subcarriers).

Higher Modulation and Coding Scheme (MCS): 64-QAM is suggested for PDSCH (physical downlink shared channel) in CE Mode A with a larger CQI (channel quality indicator) table to improve spectrum efficiency.

Early Data Transmission (EDT): UEs need to perform a four-step random access procedure before transmitting packets. EDT allows UEs to transmit UL packets with a payload no larger than 100 bytes in Message 3 of the legacy random access procedure for latency reduction and energy saving.

CE-Level-Based Access Barring: Both ACB (access class barring) and EAB (extended access barring) do not differentiate CE levels of UEs. CE-level-based access mechanisms handle different access requests from UEs, considering their corresponding CE levels.

Other enhancements for efeMTC include a new 14 dBm power class, CRS (cell reference signal) muting, flexible starting PRB, system acquisition time reduction, and so on.

Narrow Band IoT

NB-IoT was designed for a massive number of low-cost and low-complexity MTCDs that are distributed in a wide coverage area with small and infrequent packet transmissions. The main fea-

Technology	Operating frequency	Coverage	Channel bandwidth	Data rate	No. of devices	Typical use cases
Bluetooth 5 [1]	2.4 GHz ISM band	~300 m	2 MHz	Up to 2 Mb/s	Unlimited	Wearable applications, home automation
WiFi HaLow [3]	Sub-1 GHz USN band	1 km	1/2/4/8/16 MHz	> 150 kb/s	8191	Home automation, utility monitoring
LTE-M [4, 13]	Licensed band	156 dB (MCL)	Cat-M1: 1.4 MHz; Cat-M2: 5 MHz	Cat-M1: 1 Mb/s (UL/DL); Cat-M2: 7 Mb/s (UL); 4 Mb/s (DL)	~10,000 per cell	Wearable applications, mobile health (m-health)
NB-IoT [4, 13]	Licensed band	164 dB (MCL)	200 KHz	Cat-NB1: 20 kb/s (DL); 60 kb/s (UL); Cat-NB2: 120 kb/s (DL); 160 kb/s (UL)	~50,000 per cell	Industry IoT (IIoT), asset tracking, smart metering, smart parking
LoRaWAN [12]	Sub-1 GHz ISM band	20 km	125/500 KHz	0.3~27 kb/s (CSS); 50 kb/s (FSK)	100,000	Private IoT network, smart metering, environment monitoring

TABLE 1. Comparison of different low-power IoT technologies.

tures of NB-IoT from 3GPP Releases 13 to 15 are also overviewed.

NB-IoT in 3GPP Releases 13 and 14: NB-IoT can be deployed on LTE operating bands, LTE guard bands, or any bands with a 180 kHz channel bandwidth. To obtain an ultra-low device complexity and an extremely wide coverage, narrowband physical channels and signals for both DL and UL are used. Meanwhile, only half-duplex FDD (HD-FDD) is supported for complexity and cost reduction. Moreover, 20 dB gain in MCL (maximum coupling loss) can be obtained over the legacy GPRS (144 dB). Similar to Cat-M1, NB-IoT also introduces a new UE category: Cat-NB1 with its TBS reduced to 680 bits in DL and 1000 bits in UL.

In 3GPP Release 14, the enhancements of NB-IoT (eNB-IoT) introduce another UE category: Cat-NB2 with its TBS increased to 2586 bits in both DL and UL and two HARQ processes. LPP (location and positioning protocol), which includes both cellular and non-cellular positioning methods, is adopted as the positioning protocol. Similar to feMTC, eNB-IoT also supports multicast and the number of MTCHs is 64. A lower 14 dBm power class is introduced for the use of smaller form-factor batteries as well as device cost reduction. Non-anchor carrier operations can configure up to 15 non-anchor carriers in SIB (system information block) for paging, random access, and multicast purposes [11].

NB-IoT in 3GPP Release 15: Further Enhancements of NB-IoT: Similar to efeMTC, further enhancements of NB-IoT (feNB-IoT) also support WUR (FDD) and relaxed cell re-selection monitoring for power saving, system acquisition time reduction and EDT (FDD) for latency reduction, and CE-level based access barring for access control. Other distinct features of feNB-IoT are briefly described below [6].

TDD-based NB-IoT: NB-IoT in Releases 13 and 14 can operate in FDD mode only. NB-IoT's support for TDD is specialized in 3GPP Release 15 for extending deployment cases. TDD-based NB-IoT can incorporate the features of FDD-based NB-IoT in Releases 13 and 14, while other features in 3GPP Release 15 can be enabled in both FDD-based and TDD-based NB-IoT without specific clarifications.

Small Cell Support: As defined by the power classes for NB-IoT eNBs, different types of NB-IoT small cells with distinct transmission power levels can be deployed.

Cell Range Expansion: Limited by cyclic prefix (CP) length, the cell range of NB-IoT is up to 40 km. By introducing a new NPRACH (narrowband physical random access channel) format that contains a subcarrier spacing of 1.25 kHz and a CP of 800 ms, the cell range of FDD-based NB-IoT is extended to 120 km.

RLC Unacknowledged Mode (UM): NB-IoT and eNB-IoT can only support acknowledged mode and transparent mode. feNB-IoT introduces RLC (radio link control) UM, which removes Acknowledgments for delay-tolerant IoT packets.

Mixed Standalone Operations: In 3GPP Releases 13 and 14, standalone anchor carriers can be configured only with standalone non-anchor carriers. However, one standalone carrier in 3GPP Release 15 FDD-based NB-IoT can be scheduled with one in-band or guard band carrier, regardless of where the anchor carrier resides.

Latency Reduction: If UEs are not polled, feNB-IoT allows UEs to quickly release RRC (radio resource control) connections upon HARQ-ACK messages are sent.

Improved Measurement Accuracy: Narrowband secondary synchronization signal (NSSS) and MIB-NB (narrowband master information block) can serve as alternatives to narrowband reference signal (NRS) in measuring NRSRP (narrowband reference signal received power). In addition, power headroom reports (PHR) denotes the difference between the maximum allowable transmission power and the estimated transmission power. The granularity of PHR is increased to 16 levels.

The aforementioned emerging MTC technologies and LoRaWAN are compared in Table 1. LoRaWAN is a network protocol maintained by the LoRa alliance for IoT applications [12]. Chirp spread spectrum (CSS) and frequency-shift keying (FSK) can obtain different data rates. The number of supported devices for Bluetooth 5 depends on hardware implementations.

Wake-Up Radios

IEEE 802.11ba is an active working group, focusing on wake-up radio (WUR) operations for low power consumption and low latency data reception of fixed, portable, and mobile STAs that operate at a license-exempt band below 6 GHz. One WUR STA is equipped with primary connectivity radio (PCR) and WUR. PCR is responsible for data exchange, while WUR occupies a narrow 4 MHz channel bandwidth to wake up PCR. IEEE 802.11ba supports two data rates, that is, 62.5 kb/s and 250 kb/s. In addition to traditional STAs, WUR can also be adopted by STAs for energy-sensitive MTC applications, such as smart homes, warehouses, outdoor cattle farms, sensor network synchronized wakeup, wearable devices unsynchronized wakeup, and so on.

Functional requirements of WUR in the draft IEEE 802.11ba standard include:

- Less than 1 mW energy consumption with a low latency for WUR in active mode
- Not significantly degrade legacy performance
- The same transmission range as PCR
- Support for 2.4 GHz, 5 GHz, and license-exempt sub-1 GHz
- Coexistence with legacy IEEE 802.11 devices [7].

WUR requires modifications of the PHY and MAC layers for transmitting and receiving wake-up frames. A new WUR mode is introduced to STAs and an access point can wake up a specific STA or a group of STAs that support WUR by wake-up frames. In each scheduled WUR duty cycle, STAs stay active for a preconfigured duration.

Vehicle-Based and UAV-Based MTC Networks

In the above section, we reviewed the technologies for energy-sensitive IoT applications with relaxed delay and throughout requirements. Although IoT applications form a large portion

Category	eV2X use case		Latency (ms)	Data rate (Mb/s)	Packet payload (bytes)	Communication range (m)	Messages per second	Reliability (%)
Vehicle platooning	Information sharing (V2V)	Lowest automation	25		300–400		30	90
		Low automation	20		6500	350	50	
		High automation	20	65		180		
		Highest automation	10		50-1200	80	30	99.99
	Information reporting (V2V, V2I)		500		50-1200		2	
	Information sharing (V2I)	Lower automation	20	6000		350	50	
		Higher automation	20	50		180		
Advanced driving	Cooperative collision avoidance		10	10	2000		100	99.99
	Information sharing (V2V, V2I)}	Lower automation	100		6500 (V2V); 6000 (V2I)	700	10	
		Higher automation	100	53 (V2V); 50 (V2I)		360		
	Emergency trajectory alignment (V2V)		3	30	2000	500		99.999
	Intersection safety information provisioning (V2I)			50 (DL); 0.25 (UL)	450		50	
	Cooperative lane change (V2V)	Lower automation	25		300–400			90
		Higher automation	10		12000			99.99
	3D video sharing (V2N)			10 (UL)				
Extended sensor	Sensor and state map sharing		10	25				95
	Collective perception of environment	Lower automation	100		1600	1000	10	99
		Higher automation	3	50		200		99.999
			10	25		500		99.99
			50	10		1000		99
			10	1000		50		99.99
	Video data sharing (V2V)	Lower automation	50	10		100		90
		Higher automation	10	700		200		99.99
			10	90		400		99.99
Remote driving	Information sharing (V2N)		5	1 (DL); 25 (UL)				99.999

TABLE 2. Service requirements for advanced eV2X applications [14].

of existing MTC applications, MTCDs are not limited to conventional IoT devices and some MTCDs may require a high throughput with an ultra-low latency. For example, ground vehicles or UAVs with communication capabilities can communicate with each other autonomously without human interventions. Hence, both ground vehicles and UAVs can be viewed as two specific types of MTCDs. Acknowledging the distinct features and requirements between conventional and specific MTCDs, we see that customized technologies were developed for vehicles and UAVs. In this section, state-of-the-art activities on LTE-V2X and cellular-based UAV (C-UAV) communications are reviewed.

LTE-V2X Communications

V2X, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N), serves as the underlaying communication technologies for intelligent transportation systems (ITS). Before 3GPP joins the competition with the rollout of LTE-V2X in 3GPP Release 14, IEEE 802.11p-based V2X technologies, such as ITS-G5 (Europe) and DSRC (USA), were developed about 10 years ago. When compared to 802.11p-based V2X technologies, LTE-V2X can reuse existing infrastructures, provide ubiquitous coverage, and support guaranteed services with high reliability.

LTE-V2X defines two operating modes, including LTE-V-Direct and LTE-V-Cell. LTE-V-Cell mode reuses the existing Uu-interface, which is the radio interface between the network and the UEs, while LTE-V-Direct adopts the PC5 interface, which was initially tailored for ProSe (proximity-based services) in 3GPP Release 12 with another terminology "sidelink." LTE-V-Direct operates at the dedicated ITS spectrum (5.9 GHz) with 10 or 20 MHz channel bandwidth, while LTE-V-Cell selects distinct frequency bands for FDD-LTE and TDD-LTE with channel bandwidths that are identical to normal UEs. In 3GPP Release 14 LTE-V2X, several enhancements to the PC5 interface mostly for safety-related applications were suggested, that is, dense demodulation reference signal (DMRS) for combating Doppler effects with high velocities, time synchronization, and sidelink resource allocation Modes 3 and 4 [8].

In addition to safety-related use cases, 3GPP in Release 15 identified 25 advanced enhanced V2X (eV2X) use cases that fall into the following categories: vehicle platooning, advanced driving, extended sensors, and remote driving. Service requirements for advanced eV2X use cases [14] are summarized in Table 2. In addition, new features for eV2X in Release 15 are briefly explained as follows.

Carrier Aggregation (CA): Both intra-band and inter-band CA operations are supported to increase throughput. In the PC5 interface, intra-band CA for at most three contiguous carrier components (CCs) has been regulated, while the support of up to eight CCs is reserved for future releases. LTE-V2X inter-band CA operations allow concurrent transmissions over the Uu and PC5 interfaces.

Transmit Diversity: eV2X supports two-port non-transparent transmit diversity using a small cyclic delay diversity (CDD) method with the following two exceptions: 1) communicating with a Release 14 V2X UE, and 2) having a high collision probability for Release 14 V2X UEs.

Unmanned aerial vehicles (UAVs) were initially proposed for military applications. With the hardware cost reduction and advances in communication technologies, low-altitude UAVs have been adopted in civilian applications, that is, flying cameras, search-and-rescue operations, agriculture irrigation, package delivery, infrastructure inspection, and so on.

Short TTI (Transmission Time Interval): As the legacy TTI in LTE is 1ms, the feasibility of a short TTI for LTE-V2X was evaluated.

64-QAM Support: Notably, one Release 15 V2X UE is mandatory to support 64-QAM reception and optional to support 64-QAM transmission.

Latency Reduction: T2 value indicates the time interval between packet arrival and transmission. In Release 15, the minimum and maximum T2 values are set to 10 ms and 20 ms, respectively.

Resource Pool Sharing between Modes 3 and 4: Efficient resource pool sharing methods can improve spectrum efficiency. The regulations are listed as follows:
- It supports resource pool sharing between Release 15 Mode 3 V2X UEs and Release 15 Mode 4 V2X UEs;
- It supports resource pool sharing between Release 15 Mode 3 V2X UEs and Release 14 Mode 4 V2X UEs;
- It does not support resource pool sharing between Release 14 Mode 3 V2X UE and Release 15 Mode 4 V2X UE.

Cellular-Based Unmanned Aerial Vehicle Communications

Unmanned aerial vehicles (UAVs) were initially proposed for military applications. With the hardware cost reduction and advances in communication technologies, low-altitude UAVs have been adopted in civilian applications, that is, flying cameras, search-and-rescue operations, agriculture irrigation, package delivery, infrastructure inspection, and so on [15].

An unmanned aerial system (UAS) consists of one UAV controller and one UAV. In an existing non-cellular based UAS, the UAV controller communicates with the UAV via the 2.4/5 GHz ISM band using UAV communication technologies such as WiFi, DJI OcuSync, and so on. However, interferences from adjacent UAVs will severely degrade the throughput and reliability of a UAV when multiple UAVs operate at the same geographical region. Furthermore, the communication range for the non-cellular based UAS is also constrained.

Cellular systems have the advantages for serving low-altitude UAVs (aerial UEs) due to ubiquitous coverage, high reliability, robust security, and seamless mobility. In a typical LTE-based UAS, eNBs can relay messages for UAV controllers and UAVs. Aerial UEs can fly up to 300 m above ground level (AGL) and thus are more likely to obtain line-of-sight (LOS) links with eNBs. Therefore, aerial UEs may suffer more DL interferences from cells than terrestrial UEs do. Approaches in 3GPP [10] for mitigating DL interferences are summarized as follows.

FD-MIMO at eNB Transmitters: eNB transmitters with full-dimensional multiple input multiple

Metrics	Service requirements
Maximum height	300 m (AGL)
Maximum latency	UTM-to-UAS: 500 ms; End-to-end broadcast: 100 ms
Maximum speed	Absolute: 160 km/h; Relative: 320 km/h
Payload	UAV-to-UAV broadcast: 50-1500 bytes
Distance	UAV-to-UAV broadcast: 600 m; UAS identity: 500 m
Message sending frequency	UAV-to-UAV broadcast: ≥10 messages per second; UAS location update and identity broadcast: one message per second
Interoperability support	Different 3GPP networks; 3GPP and non-3GPP networks

TABLE 3. Service requirements for remote identification of UAS [9].

output (FD-MIMO) can steer beams in both azimuth and elevation dimensions, thereby reducing interferences to aerial UEs.

Directional Antenna at Aerial UEs: Aerial UEs can employ directional antennas to combat interferences from undesired directions.

Receive Beamforming at Aerial UEs: When aerial UEs are equipped with multiple antennas, receive beamforming can be exploited to mitigate downlink interferences.

Intra-Site JT CoMP: A site consists of multiple cells. All the cells that belong to the same site can transmit packets jointly to UEs by leveraging joint transmission (JT) coordinated multipoint (CoMP) techniques.

Coordinated Data and Control Transmission: The intra-site JT CoMP method can be generalized to the coordinated data and control transmission approach, where cells that belong to the same or different sites can form a "virtual site" and are coordinated to transmit data as well as control information for aerial UEs.

Similarly, aerial UEs in UL are more likely to interfere cells than terrestrial UEs do. The approaches for UL interference mitigation are discussed as follows [10].

Power Control: Both open loop and closed loop power control methods can be used for uplink interference mitigation. In the open loop approach, the fractional compensation factor and P0 parameter can be specified for aerial UEs. The closed loop power control for aerial UEs can consider serving and neighboring cell measurement reports jointly.

FD-MIMO at eNB Receivers: Similar to eNB transmitters, eNB receivers equipped with multiple antennas can exploit FD-MIMO to mitigate uplink interferences.

Directional Antennas at Aerial UEs: Directional antennas can also alleviate uplink interferences by decreasing power in undesirable directions.

As aerial UEs can fly at a relatively high velocity, enhancements on mobility management, that is, frequent handover and message reporting, are also critical. In addition, existing channel models should be calibrated for terrestrial UEs that are basically connected with eNBs via non-line-of-sight (NLOS) links. Hence, channel models for aerial UEs should be redesigned.

Identification of aerial UEs is also an important task. In addition to the service requirements for remote identification of UAS as shown in Table 3, UAS should also obey regional regulations to ensure that only authorized UAS can fly at permitted flying zones. Furthermore, UAS traffic management (UTM) should notify UAV controllers and can even take over the control of UAVs if necessary. From either commercial or technical viewpoints, terrestrial and aerial UEs should be differentiated by subscription information. Although UAVs can communicate via eNBs, direct UAV-to-UAV communications are essential for coordinations when UAVs are out of cellular coverage. Meanwhile, UAVs and UAV controllers may also need direct communications. However, 3GPP at the present has not specified the technologies for direct UAV-to-UAV communications. The existing PC5 interface can be a good candidate for UAV-to-UAV communications.

New Trends in MTC Networks

A typical MTC deployment scenario, including home automation, ITS, and smart farming, is depicted in Fig. 3. Bluetooth 5 and Bluetooth Mesh can interconnect various types of home appliances. Energy-sensitive MTCDs that are deployed in either indoor or outdoor environments, can be connected via various types of low power wide area (LPWA) interfaces, that is, WiFi HaLow, NB-IoT, LTE-M, LoRa, and so on. In ITS applications, LTE-V2X vehicles can exchange information directly with nearby LTE-V2X vehicles and pedestrians. Alternatively, roadside units (RSUs) can relay messages in V2V and V2P communications. In smart farming applications, multiple UAVs can be scheduled to handle the tasks, such as routine pesticide spraying and patrolling, while various types of sensors that are distributed in the farmland can periodically report perceived data via LPWA interfaces.

Radio Access Technologis in MTC

In one specific MTC application, several radio access technologies (RATs) may be qualified candidates at the same time. How to choose the most appropriate technology is an important issue, which should consider multiple factors jointly, including cost, reliability, energy efficiency, and so on.

Licensed Versus Unlicensed LPWA Technologies: Unlicensed LPWA technologies, such as WiFi HaLow and LoRaWAN, can be flexibly deployed by individuals or corporations, while licensed LPWA technologies, such as LTE-M, can reuse the existing infrastructures deployed by network operators. In rural areas, cellular IoT networks are not available and unlicensed LPWA technologies can provide connectivity for MTCDs. However, unlicensed LPWA technologies are not as reliable as licensed technologies due to the interferences from other technologies that coexist at the same frequency bands. Meanwhile, regional regulations on the ISM bands, such as duty cycle restriction, will affect the actual number of serving devices in unlicensed LPWA networks [12]. In contrast, licensed LPWA technologies can provide a guaranteed service at the expense of additional subscription expenses.

LTE-V2X versus IEEE 802.11p-based V2X: IEEE 802.11p-based DSRC is a mature technology that has been promoted for safety-related information sharing among vehicles in the USA. However, the

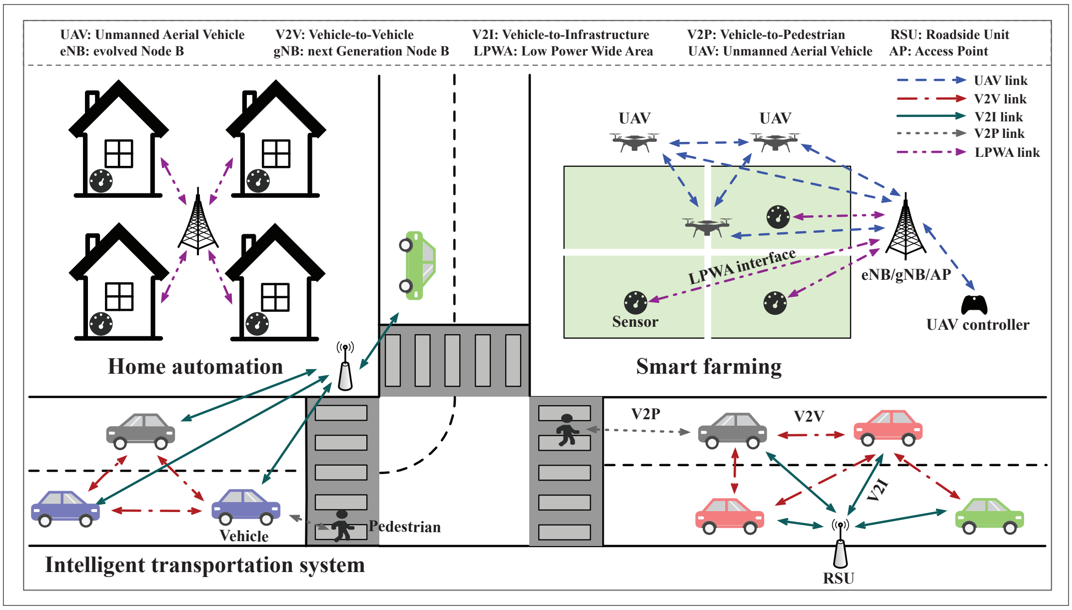

FIGURE 3. A typical MTC network deployment scenario.

density of IEEE 802.11p-based vehicles is severely constrained by the legacy distributed coordination function access method. LTE-V2X has no such limitations and can provide a larger communication range than DSRC. Hence, a longer response time can be reserved for driving assistance. By leveraging existing infrastructures such as RSUs, LTE-V2X enjoys a better expansibility for supporting advanced V2X applications than IEEE 802.11p-based V2X.

ISM-based versus Cellular-based UAVs: Existing ISM-based UAVs communicate with UAV controllers via either conventional 2.4/5 GHz WiFi technologies or customized technologies, such as DJI LightBridge and OcuSync. Dedicated technologies can provide higher data rates and longer communication ranges than WiFi technologies at the expense of compatibility. Cellular-based UAVs can support NLOS operations beyond a single-cell coverage with an ultra-low latency and guaranteed data rates. Moreover, multiple cellular-based UAS can operate at the same region simultaneously without sacrificing the performance of each UAS.

5G New Radio in MTC: In 3GPP Release 15, 5G NR focuses on fulfilling the requirements for enhanced mobile broadband (eMBB). The works on massive MTC (mMTC) are postponed to 5G Phase II. Moreover, 5G NR is expected to support new MTC use cases such as industry IoT (IIoT). As 3GPP has no intention to introduce other IoT technologies, LTE-M and NB-IoT have been evolving to meet IMT-2020 requirements on mMTC. However, the coexistence of NB-IoT and LTE-M within 5G NR still requires more effort.

Although LTE-V2X and eV2X can respectively support basic safety-related and advanced eV2X applications, both LTE-V2X and eV2X operate based on LTE. With the introduction of 5G NR, NR-V2X is expected to provide more advanced V2X services with ultra-low latency, high throughput, and reliability requirements by incorporating 5G technologies such as massive MIMO and millimeter wave (mmWave).

Interference Mitigation

The radio propagation characteristics in frequency bands below 1 GHz make it attractive for IoT applications to cover a wide area. Several promising MTC technologies, such as WiFi HaLow, LoRaWAN, ZigBee, and Sigfox, may coexist at the unlicensed 900 MHz ISM band, but severe co-channel interferences can degrade the performance. Upon detecting the energy level above a predetermined threshold, WiFi HaLow may adopt the following methods for interference mitigation:

- Defer transmissions for a particular interval
- Change operating channels or subchannel selective transmission channels
- Use sectorized beamforming
- Change the schedule of RAW and TWT service periods.

Moreover, reducing the duty cycles of coexisting technologies can be an alternative approach to combat interferences. Although one centralized controller with spectrum sensing capabilities can collect spectrum usage information, how to precisely identify each interfering technology is still a challenging issue. Machine learning based approaches may help distinguish different technologies by mining out their hidden features to learn the behaviors of each technology.

Interference mitigation approaches in C-UAV communications have been discussed above. In vehicle-based MTC, IEEE 802.11p-based V2X and LTE-V-Direct share the same 5.9 GHz ITS frequency band. As regional communication regulators such as ETSI show their neutrality on both technologies, vehicles on the roads may install V2X modules that use one or both V2X technologies. Vehicles with both technologies can exchange messages with nearby vehicles via their desired technology in a TDMA manner. Acknowledging that IEEE 802.11p-based V2X and LTE-V-Direct cannot interwork with each other, we should be aware that interferences between them cannot be negligible. When interference signals are detected, transmission rates can be adjusted for interference mitigation by sacrificing non-safety related messages and prioritizing safety-related messag-

State-of-the-art research activities on LTE-V2X and cellular-based UAVs were also reviewed. The hybrid V2X solution, which combines LTE-V2X and IEEE 802.11p-based V2X, may be one potential approach to improve reliability and mitigate interferences from each other in practical deployments.

es. Similar to C-UAV communications, directional antenna techniques can be exploited to combat interferences by strengthening desired signals in the preferred direction with a narrow beam, while constraining the signals in other directions. LTE-V2X vehicles can switch to LTE-V-Cell mode and use the Uu interface rather than the PC5 interface for interference mitigation.

Conclusions

In this article, five emerging MTC technologies from different standardization groups were reviewed first, including Bluetooth 5 (Bluetooth SIG), WiFi HaLow (WiFi alliance), LTE-M (3GPP), NB-IoT (3GPP), and WUR (WiFi alliance). Although Bluetooth low energy (BLE) has dominated the market in personal area networks, Bluetooth SIG has its ambitions to embrace new applications such as home and building automation with the latest Bluetooth 5 and Bluetooth Mesh standards. WiFi HaLow has been standardized, but it is still at its initial phase before it will be integrated to commercial WiFi products. WiFi HaLow still has a chance to compete with other LPWA technologies as it can support a wide range of IoT applications with diverse requirements. LTE-M and NB-IoT are two complementary and competing technologies for LPWA applications with the backup from network operators. However, the additional usage fee may prevent price-sensitive customers from choosing LTE-M and NB-IoT. WURs can reduce the energy consumption of STAs without sacrificing latency.

State-of-the-art research activities on LTE-V2X and cellular-based UAVs were also reviewed. The hybrid V2X solution, which combines LTE-V2X and IEEE 802.11p-based V2X, may be one potential approach to improve reliability and mitigate interferences from each other in practical deployments. The stringent requirements of safety-related V2X applications and autonomous driving also pose new challenges for cellular systems. Cellular-based UAVs extend the service range of cellular systems to vertical domains and make it possible for air traffic control agencies to monitor and control flying UAVs over UTM in real time. Finally, we discussed different MTC RATs and interference mitigation methods.

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Biographies

Nian Xia (brastme@gmail.com) received his B.Sc. degree in electrical engineering from Northeastern University, Shenyang, China, in 2012, and his M.Sc. degree from the Institute of Computer and Communication Engineering, Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan in 2014, where he is currently pursuing his Ph.D. degree. His research interests include machine-type communications and device-to-device (D2D) communications.

Hsiao-Hwa Chen [S'89, M'91, SM'00, F'10] is currently a Distinguished Professor in the Department of Engineering Science, National Cheng Kung University, Taiwan. He obtained his B.Sc. and M.Sc. degrees from Zhejiang University, China, and a Ph.D. degree from the University of Oulu, Finland, in 1982, 1985, and 1991, respectively. He has authored or co-authored over 400 technical papers in major international journals and conferences, six books, and more than 10 book chapters in the areas of communications. He served as the general chair, TPC chair, and symposium chair for many international conferences. He served or is serving as an editor or guest editor for numerous technical journals. He is the founding Editor-in-Chief of Wiley's *Security and Communication Networks Journal*. He is the recipient of the best paper award at IEEE WCNC 2008 and the recipient of the IEEE 2016 Jack Neubauer Memorial Award. He served as the Editor-in-Chief for *IEEE Wireless Communications* from 2012 to 2015. He was an elected Member-at-Large of IEEE ComSoc from 2015 to 2016. He is a Fellow of IEEE and a Fellow of IET.

Chu-Sing Yang (csyang@mail.ee.ncku.edu.tw) received his B.Sc., M.Sc., and Ph.D. degrees from National Cheng Kung University, Tainan, Taiwan, in 1976, 1984, and 1987, respectively, where he is currently a professor with the Institute of Computer and Communication Engineering, Department of Electrical Engineering. He has been serving as the chairman of the Taiwan Association of Cloud Computing since 2017. He participated in the design and deployment of the TaiWan Advanced Research and Education Network and served as the Deputy Director of the National Center for High-Performance Computing from 2007 to 2008. His research interests include software-defined networking, machine-type communications, cloud computing, and cyber-security.