Off-Network Communications for Future Railway Mobile Communication Systems: Challenges and Opportunities

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The authors provide a comprehensive summary and analysis of off-network use cases in FRMCS. Then they give an overview of existing technologies (GSM-R, TETRA, DMR, LTE-V2X, and NR-V2X) that may support off-network communication.

Abstract

GSM-R is predicted to be obsoleted by 2030, and a suitable successor is needed. Defined by the International Union of Railways, the Future Railway Mobile Communication System (FRMCS) contains many future use cases with strict requirements. These use cases should ensure regular communication not only in network coverage but also in uncovered scenarios. There is still a lack of standards on off-network communication in FRMCS, so this article focuses on off-network communication and intends to provide reference and direction for standardization. We first provide a comprehensive summary and analysis of off-network use cases in FRMCS. Then we give an overview of existing technologies (GSM-R, TETRA, DMR, LTE-V2X, and NR-V2X) that may support off-network communication. In addition, we simulate and evaluate the performance of existing technologies. Simulation results show that it is possible to satisfy the off-network communication requirements in FRMCS with enhancements based on LTE-V2X or NR-V2X. Finally, we give some future research directions to provide insights for industry and academia.

Introduction

Over the past 40 years, the world has rapidly evolved from 1G to 5G. The emergence of new technologies means the obsolescence of old technologies, and the Global System for Mobile Communications-Railway (GSM-R), which is based on 2G, is no exception. The International Union of Railways (UIC) group started looking for a replacement of GSM-R in 2015. In 2018, they established a structured outline named Future Railway Mobile Communication System (FRMCS). FRMCS is intended to replace the soon-to-be obsolete GSM-R and is also oriented to future railway applications, such as automated train operation, remote control, and future fully self-driving trains [11]. This will require a more reliable and higher transmission rate communication system.

The issue of dedicated railway frequencies for FRMCS was raised as early as 2017, which boosted the development of FRMCS. In 2020, the European Conference of Postal and Telecommunications Administrations — Electronic Communications Committee (CEPT-ECC) decided to use the paired frequency bands 874.4—880.0 MHz and 919.4—925.0 MHz, and the unpaired frequency band 1900—1910 MHz for railway mobile radio. In 2021, China planned to use 2.1 GHz as the operating band for future 5G railway communication.

Based on the FRMCS user requirements specification [1] and use cases [2], the Third Generation Partnership Project (3GPP) studies and summarizes all the cases in FRMCS [3]. In addition, the 3GPP further elaborates the off-network use case scenarios and refines their performance requirements in [4]. Off-network communication refers to a direct communication mode between transmitter and receiver without passing the network.

The research on railway off-network communication is in the very preliminary stage. The study in [5] proposes a new train autonomous driving communication system based on 5G train-to-train (T2T) communication. The authors in [6] modified the Long Term Evolution Vehicle-to-Everything (LTE-V2X) for T2T communication and proposed a train-centric communication-based train control (CBTC) system. Most of these studies focus on automatic train control (ATC), but there are many scenarios of off-network communication in FRMCS, which have not been comprehensively studied. The article [7] uses terrestrial trunked radio (TETRA) technology for T2T communication and performs channel measurements at 450 MHz. The authors of [8, 9] take practical measurements of intelligent transport systems (ITS-G5) in T2T scenarios and propose a geometry-based stochastic channel model (GSCM) for T2T communication in an open field environment. Although the existing works assume various existing technologies for railway off-network communication, there is still a lack of rigorous evaluation to judge whether they satisfy the requirements of off-network use cases in FRMCS.

This article first provides an overview of the off-network use cases in FRMCS, and introduces the existing technologies that may be used for future railway off-network communication, including GSM-R, TETRA, digital mobile radio (DMR), LTE-V2X, and New Radio-V2X (NR-V2X). The performance of existing technologies is compared through simulation. Based on the simulation results, it is suggested that the enhancements on...
LTE-V2X or NR-V2X may satisfy the off-network communications requirements for FRMCS, which provides some potential directions and references for standardization. Finally, some possible research directions to improve transmission performance are given to provide insights for the future.

**Use Cases and Requirements of Off-Network Communication for Railways**

Figure 1 shows the use cases of off-network communication in FRMCS, and the performance requirements of off-network use cases are summarized in Table 1 [4].

**Shunting Communication:** Shunting movements include changing the locomotive of a train, coupling/uncoupling wagons, and changing the order in which wagons are arranged in a train. All shunting movements are done within a station and require cooperation between shunting members via radio, which contains data, voice, and video communications over the network or off-network.

**Remote Control of Engines:** The driver can remotely control the engine of the train via a ground-based system or an onboard system located at the other end of the engine. It is typically used for shunting operations in depots, shunting yards, or banking, and should support off-network communication due to the uncertainty of the network.

**Train Integrity Monitoring:** Accidental separation of train cabins is a hazardous event, and to avoid that situation, the driver can use this system to check the movement of the tail of the train while it is running. Since the track is not always covered by the network when the train is running, the system should also be capable of off-network communication.

**Trackside Maintenance Warning System:** To ensure the safety of the staff and the regular operation of the train, this system must promptly and accurately notify the staff of the upcoming train during the trackside maintenance period. Since the warning system is usually deployed temporarily and the network does not entirely cover the rail tracks, the system needs to have off-network communication capabilities.

**ATC and Autonomous Train Operation (ATO):** This system is expected to be used primarily for urban rail transportation such as subways. It allows trains to determine their movement autonomously based on direct communication between trains. For the safe operation of trains, even if the network is unavailable, the trains need to transmit speed, location, and other information in real time, so this system needs to have the ability to communicate off the network.

**Virtual Coupling:** Virtual coupling is when multiple trains in close distance move together as they are physically coupled. When the virtual coupling is formed, the distance between the trains is about 300 m (urban railway). This scenario is similar to vehicle platooning in V2X, where trains directly share control information (acceleration and braking, etc.) in real time. It can significantly reduce the distance between trains and increase the efficiency of railway transportation. Due to the high demand for latency, it is the only scenario that sets off-network communication as the default mode even when the network is available.

**Train Ready for Departure:** This scenario is
used to ensure that passengers can safely board the train and that the train can safely leave the platform. It consists primarily of driver-to-control-
er communication, conductor-to-driver commun-
ication, and platform camera video transmission. If the platform is in a remote area without a net-
work, off-network communication is used.

**Monitoring and Controlling Critical Infra-
structure**: This system is designed mainly for video
communication and is usually used for intersection
monitoring, train detection, signals, indicators, and
so on. It should also be available in remote areas
where there is no network coverage.

As shown in Table 1, most of the off-network
communication use cases have strict performance
requirements, which require a minimum latency
of 10 ms, a maximum data rate of 10 Mb/s, and
a maximum reliability requirement of 99.9999
percent. In addition, the communication range
is typically within 3 km, except for the track-
side maintenance warning system, which needs
to achieve reliability of 99.9999 percent over a
communication range of more than 8.5 km and
is extremely difficult to achieve with the existing
technologies.

In general, the provisions of these off-network
use cases are full of challenges. We need to an-
swer the question of whether any existing tech-
nology can satisfy these stringent requirements. If
no, we should find a successor or enhance exist-
ing technologies.

**Overview of Existing Technologies**

This section provides a brief introduction to the
existing technologies that may be used to support
off-network communication. Among these tech-
nologies, GSM-R, TETRA, and DMR have been
applied in some scenarios in the field of railway
communication, while LTE-V2X and NR-V2X are
technologies that can be used for off-network
communication in the field of vehicular net-
working. The comparison of existing technologies is
given in Table 2.

**GSM-R [10]**: GSM-R works near the 900 MHz
frequency band, the access scheme is time-divi-
sion multiple access (TDMA), and the channel
bandwidth is 200 kHz. It can achieve data rates of
9.6 kb/s and 14.4 kb/s per channel using cir-
cuit switched data (CSD) mode and high-speed
circuit-switched data (HSCSD) mode, respectively.
In addition, it can achieve data rates of 21.4
kb/s per channel when the general packet radio
service (GPRS) with packet switched data (PSD)
is used.

GSM-R typically uses 1 W mean output power.
The data TCHs use convolutional code as the
channel coding scheme, and the modulation
scheme of GSM-R is Gaussian minimum shift key-
ing (GMSK) with parameter BT = 0.3 and modula-
tion rate of 270.83 kb/s, and a Viterbi algorithm is
used for demodulation.

**TETRA [11]**: TETRA operates at 300 MHz to
1 GHz, the access method is TDMA, and the
channel bandwidth is 25 kHz. The peak rate of
the data traffic channel is 7.2 kb/s. The aver-
age power of 0.56 W to 10 W is the common
power range used by TETRA. The channel coding
scheme for data traffic channels is rate-compat-
ible punctured convolutional (RCPC) code. The
channel coding scheme, and the modulation
scheme of GSM-R is Gaussian minimum shift key-
ing (GMSK) with parameter BT = 0.3 and modula-
tion rate of 270.83 kb/s, and a Viterbi algorithm is
used for demodulation.

**DMR [12]**: DMR operates in part of the fre-
quency range from 30 MHz to 1 GHz, with a
TDMA access scheme and a channel bandwidth
of 12.5 kHz. The channel coding scheme of DMR
is forward error correction (FEC) codes, including
Golay code, Hamming code, block product turbo
code (BPTC), and trellis code. The trellis code is
used for data channels. The modulation scheme
of DMR is 4-frequency shift keying (4FSK), and the
average transmission power range is 1–40 W.
The single-channel transmission rate can reach
4.8 kb/s.

**LTE-V2X [13]**: Since there are many similari-
ties between railway communication and vehicle
communication, V2X may be a good direction.
LTE-V2X Mode 4 can directly communicate via
sidelink without network support.

LTE-V2X operates in the 5.9 GHz (n47) band

| Scenario                                      | End-to-end latency | Reliability      | Data rate       | Communication range |
|-----------------------------------------------|--------------------|-----------------|-----------------|--------------------|
| Shunting voice communication                  | ≤ 10 ms            | 99.9999%        | 10 kb/s up to 300 kb/s | ≤ 1.5 km               |
| Shunting data communication                   | ≤ 500 ms           | 99.9999%        | 10 kb/s up to 500 kb/s | ≤ 1.5 km               |
| Shunting video communication                  | ≤ 100 ms           | 99.9%           | 10 Mb/s         | ≤ 1.5 km               |
| Remote control of engines data communication   | ≤ 10 ms            | 99.9999%        | 100 kb/s up to 1 Mb/s | ≤ 1 km                 |
| Remote control of engines video communication  | ≤ 100 ms           | 99.9%           | 10 Mb/s         | ≤ 1 km                 |
| Train integrity monitoring data communication  | ≤ 1 s              | 99.9%           | 10 kb/s up to 500 kb/s | ≤ 2 km                 |
| Trackside maintenance warning system communi-
  cation                                        | ≤ 500 ms           | 99.9999%        | 10 kb/s up to 500 kb/s | ≥ 8.5 km               |
| ATC and ATO                                    | ≤ 100 ms           | 99.99%          | ≤ 1 Mb/s        | ≤ 3 km                 |
| Virtual coupling critical data communication   | ≤ 100 ms           | 99.99%          | ≤ 1 Mb/s        | ≤ 3 km                 |
| Virtual coupling very critical data communication | ≤ 10 ms          | 99.9999%        | ≤ 1 Mb/s        | ≤ 0.3 km               |
| Train ready for departure data communication   | ≤ 500 ms           | 99.9%           | 100 kb/s up to 500 kb/s | ≤ 1 km                 |
| Train ready for departure video communication  | ≤ 100 ms           | 99.9%           | 100 kb/s up to 500 kb/s | ≤ 1 km                 |
| Monitoring and controlling critical infrastruc-
  ture video communication                      | ≤ 100 ms           | 99.9%           | ≤ 10 Mb/s       | ≤ 1 km                 |

TABLE 1: Requirements of off-network communication use cases.
with a channel bandwidth of 1.4 MHz–20 MHz, and the access method is single-carrier frequency-division multiple access (SC-FDMA). The channel coding scheme of LTE-V2X sidelink is turbo code. The modulation scheme is quadrature phase shift keying (QPSK) or 16-quadrature amplitude modulation (16-QAM), and to support higher transmission rates, 3GPP added 64-QAM in Release 15. The transmit power of LTE-V2X mobile devices is usually set to 23 dBm, supporting a transmission rate of 30 Mb/s, and the transmission delay is generally in the range of 10–100 ms. LTE-V2X Mode 4 uses sensing-based semi-persistent scheduling (SPS) for resource reservation.

**NR-V2X** [14]: 3GPP proposed NR-V2X in Release 16 to supplement LTE-V2X in scenarios requiring high throughput, ultra-reliability, and low latency, and they will coexist and supplement each other in the future. Similar to LTE-V2X Mode 4, NR-V2X Mode 4 uses sensing-based semi-persistent scheduling (SPS) for resource reservation.

The frequency bands of NR include frequency range 1 (FR1) and frequency range 2 (FR2). The bands used by NR-V2X sidelink belong to FR1, which are 5.9 GHz (n47) and 2.5 GHz (n38), respectively. The channel coding scheme of NR-V2X sidelink is low density parity check (LDPC) code. Compared to LTE-V2X, the modulation scheme 256-QAM is added to support higher rate transmission. NR-V2X supports a channel bandwidth of 5–40 MHz, with a maximum transmission rate of 1 Gb/s and an end-to-end latency as low as 3 ms [15]. NR-V2X Mode 2 also uses the sensing-based SPS resource reservation scheme.

**Analysis of latency and transmission rate:** GSM-R, TETRA, and DMR may have a latency of hundreds of milliseconds or even seconds, while LTE-V2X can achieve end-to-end latency of about 20 ms, and NR-V2X is even more advanced, reaching about 10 ms [15]. As shown in Table 1, most scenarios require end-to-end latency within 100 ms, and some critical scenarios even have a strict requirement of 10 ms. Therefore, GSM-R, TETRA, and DMR may not satisfy the latency requirements of these use cases, while LTE-V2X and NR-V2X may satisfy them most of them.

In addition, GSM-R, TETRA, and DMR are narrowband technologies, and they have low data rates, which are insufficient for future off-network use cases of railways. On the contrary, the data rate performance of LTE-V2X and NR-V2X may meet the data rate requirements, which may reach 30 Mb/s and 1 Gb/s, respectively.

**Reliable Communication Distance**

**Evaluation of Existing Technologies**

This section uses Matlab to evaluate the reliable communication distance of each existing technologies in an open field environment. The simulation sets up two trains, one in front of the other, with overhead line masts at regular intervals on the track, in addition to adjacent buildings, trees, and walls. The channel model uses the GSCM consisting of line of sight (LoS) components and multipath components (MPCs). More detailed channel infor-

| Characteristics | GSM-R [10] | TETRA [11] | DMR [12] | LTE-V2X (sidelink) [13] | NR-V2X (sidelink) [14] |
|-----------------|------------|------------|----------|-------------------------|-----------------------|
| Access scheme   | TDMA       | TDMA       | TDMA     | SC-FDMA                 | OFDMA                 |
| Time slot duration | 0.577 ms | 14.167 ms | 30 ms   | 0.5 ms                  | 1/0.5/0.25/0.125/0.0625 ms |
| Transmission power | 30 dBm  | 35 dBm     | 30–46 dBm| 23 dBm                  | 23 dBm                |
| Frequency       | Uplink: 876–915 MHz Downlink: 921–960 MHz | 380–400 MHz 410–430 MHz 450–470 MHz 806–821 MHz 851–866 MHz | 30 MHz–1 GHz | 5855–5925 MHz (n47) | 2570–2620 MHz (n38) |
| Channel bandwidth | 200 kHz  | 25 kHz     | 12.5 kHz | 1.4–20 MHz              | 5–40 MHz              |
| Channel coding (data channel) | Convolutional Code | RCPC       | Trellis Code | Turbo                  | LDPC                  |
| Modulation scheme | GMSK       | χ/4-DQPSK  | 4FSK     | R14: QPSK 16-QAM R15: 64-QAM | QPSK 16-QAM 64-QAM 256-QAM |
| Peak transmission rate (single channel) | 7.2 kb/s  | 4.6 kb/s   | 30 Mb/s  | 1 Gb/s                  |                       |
| Operation mode  | Infrastructure-based Mode only | Infrastructure-based/ Direct Mode | Infrastructure-based/ Direct Mode | Infrastructure-based/ Direct Mode | Infrastructure-based/ Direct Mode |
| Access protocol (direct mode) | —         | Slotted Aloha | Slotted Aloha | Sensing-based SPS | Sensing-based SPS |
| Multi-antenna supporting | N         | N          | N        | Y                      | Y                     |

**TABLE 2. Comparison of existing technologies supporting off-network communication.**

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When the transmit power is increased to 46 dBm, which is usually used for the base station, the existing technologies in the open field environment can satisfy the reliability requirements of 99.99 percent for 3 km communication distance and 99.9999 percent for 1.5 km communication distance.

According to the performance analysis earlier and the results in Fig. 2, the existing technologies with the parameters given by the standard cannot fully satisfy the requirements of the use cases in Table 1. In conclusion, to satisfy the requirements of off-network use cases in FRMCS, new technology or evolution of the existing technology is needed.

**Impact of Different Parameters**

Based on the results of Fig. 2, it is better to choose a lower frequency and an appropriate transmission power to achieve reliable transmission over long distances. Figure 3 simulates the BLER performance of existing technologies at different communication distances by setting the frequency to 450 MHz, the bandwidth to 1.4 MHz, and the transmit power to 23 dBm, 30 dBm, and 46 dBm, respectively.

Figure 2 shows that the BLER performance of LTE-V2X and NR-V2X with 5.9 GHz is inferior to other low-frequency technologies. While Fig. 3 sets the frequency of LTE-V2X and NR-V2X to 450 MHz, their performance is significantly improved, even better than GSM-R, TETRA, and DMR. The reason might be that the LDPC code used in NR-V2X and the turbo code used in LTE-V2X have more significant coding gain than the convolutional, RCPC, and trellis codes used in GSM-R, TETRA and DMR, respectively, but also might introduce additional latency through coding delays, which will be further investigated in future work. Therefore, it is suggested to operate LTE-V2X or NR-V2X at a lower frequency to achieve long-distance transmission.

As shown in Fig. 3, with the same settings of other parameters and the higher transmission power, better performance is obtained. When the transmit power is increased to 46 dBm, which is usually used for the base station, the existing technologies in the open field environment can satisfy the reliability requirements of 99.99 percent for 3 km communication distance and 99.9999 percent for 1.5 km communication distance as seen in Table 1. But the open field environment is only one realistic scenario, and there are also non-line-of-sight (NLoS) environments where greater fading is caused by obstruction. The performance of these techniques under NLoS environments would be worse than that in an open field environment. Therefore, even if the power is increased to 46 dBm, they may not satisfy the requirements of NLoS scenarios. Hence, blindly increasing the transmission power is not feasible. Instead, if the existing LTE-V2X or NR-V2X is further enhanced, 30 dBm may be a more suitable power, which is now commonly used for train communication.

According to the analysis in Fig. 3, when using the 30 dBm power commonly used in trains, LTE-V2X and NR-V2X are insufficient to support the use cases in Table 1 in terms of reliable communication distance even with lower frequency. However, appropriate enhancement of LTE-V2X and NR-V2X can be achieved with acceptable performance.
and NR-V2X may have the potential to fulfill these strict requirements. Therefore, besides adjusting the frequency and transmission power, we will further enhance them by adding multiple-input multiple-output (MIMO) and a retransmission scheme in the next part and simulate them at the possible frequency bands of FRMCS to analyze their performance.

**RELIABLE COMMUNICATION DISTANCE OF LTE-V2X AND NR-V2X AT FRMCS FREQUENCY BAND WITH MIMO AND RETRANSMISSION**

Figure 4 simulates the LTE-V2X and NR-V2X technologies at the possible future FRMCS bands 900 MHz, 1.9 GHz, and 2.1 GHz, and adds 430 MHz for comparison with Fig. 3. $2 \times 2$ MIMO is used to improve the performance further assuming that the antenna spacing is large enough so that antennas are not correlated with each other. The minimum mean square error (MMSE)-based beamforming technique is used, and the $2 \times 2$ channel coefficients are generated by the extension of GSCM. In addition, since LTE-V2X only supports blind retransmission, Fig. 4 uses three blind retransmissions, and the transmission power is set to 30 dBm.

In Fig. 3, when the transmission power is 30 dBm with the frequency of 450 MHz, LTE-V2X and NR-V2X can only achieve a reliability performance of 99.9999 percent at less than 1 km communication distance. With the addition of MIMO and retransmission, Fig. 4 shows that they can achieve a reliability performance of 99.9999 percent over 6 km communication distance at 430 MHz in the open field environment, which is a significant improvement and is sufficient for most of the off-network communication use cases in Table 1.

In addition, by adding MIMO and a retransmission mechanism, the performance of LTE-V2X at 450 MHz, 900 MHz, 1.9 GHz, and 2.1 GHz can satisfy the reliability requirements of 99.99 percent for 3 km communication distance and 99.9999 percent for 1.5 km communication distance, as mentioned in Table 1. NR-V2X also can satisfy these requirements at 450 MHz and 900 MHz. However, all performance evaluations are based on an open field environment. For NLoS scenarios, further evaluations will be done in future work.

In conclusion, enhancement of LTE-V2X and NR-V2X by adding MIMO and retransmission has the potential to satisfy all the off-network use cases’ requirements in Table 1 at 900 MHz and 450 MHz except for the trackside maintenance warning system. For the consideration of policy permission, 900 MHz might be a more suitable frequency band for FRMCS off-network communication. The 900 MHz currently used by GSM-R may be refarmed for off-network communication in FRMCS.

**OPPORTUNITIES AND CHALLENGES**

In this section, some potential research directions and challenges are presented to provide insight for future research.

**System Parameters Consideration:** Frequency, transmission power, bandwidth, and modulation coding scheme significantly affect the performance of the system. A reasonable setting is required to meet the system requirements.

**Multi-Air Interface and Multi-Antenna:** When the off-network communication mode is introduced, the placement and orientation of the antenna cannot be well optimized for train-to-ground communication, and at the same time for train-to-train communication. When performing mode switching, antenna adjustment will inevitably cause communication interruptions. Similar to the Uu interface (on-network mode) and PCS (sidelink) interface (off-network mode) in LTE-V2X/NR-V2X, adding a new air interface for railway-off-network mode is a good solution (the two air interfaces are independent of each other and can operate simultaneously). The existing Uu/PCS seamless switching optimization scheme has been relatively mature, which has great reference value for future research on mode switching in railway.

Multiple antennas need a trade-off between diversity and multiplexing, and the high-speed movement of trains can make channel estimation inaccurate. Another key challenge is how to optimize and deploy the antennas.

**MAC Protocol Design:** If V2X is used for FRMCS off-network communication, the higher transmit power of the PC5 interface will make coexistence with cellular link (Uu) in the same band challenging. In addition, since there is no centralized control center for off-network communication, suppressing interference from other users in the same frequency band and avoiding collisions when reserving the channel are also key challenges. The power control algorithm, channel division protocol, and random access protocol of the MAC layer can be used to avoid these problems. Therefore, the MAC protocols dedicated to the railway environment need to be designed for FRMCS.

**Channel Measurement:** Accurate channel measurement can help better understand the signal propagation conditions, which can benefit system design and parameter setting. There have already been works on T2T channel measurement, such as [7–9]. However, the future railway off-network communication scenarios are diverse, and there might be several different potential frequencies. Hence, more channel measurements can be done for different scenarios with different frequencies.

**Off-Network Communication Assisted by Relay or Satellite Communications:** Some extreme scenarios, such as the trackside maintenance warning system, which requires reliability of 99.9999 percent within a communication range of 8.5 km, need some other technologies.
to assist communication. Existing technologies cannot achieve the long-range reliable communication requirements of a trackside maintenance warning system with only one-hop transmission. Relay technology for multi-hop communication can be adopted to improve communication distance and reliability. In addition, satellite communication technology can also be used to support this use case.

Mission-Critical Framework (MCX): The FRMCS system builds on the 3GPP MCX framework, which complements the transport technology by functions for authentication, functional addressing, and so on. A key challenge is that the MCX framework is typically centralized and has not been used for off-network communications as of today. 3GPP expects to use ProSe direct communication to provide MCX, but lacks a set of standards and requires a lot of future research.

System-Level Simulation: This article performs link-level simulations of the data channel for existing technologies. In the future, more comprehensive system-level simulations are needed to evaluate the overhead and latency, including evaluation of the MAC layer as well as control channel overhead, among others.

Coexistence of Multiple Technologies: Most of the existing railway communications are based on GSM-R, and it will be a long process to completely replace the current GSM-R to its successor (e.g., LTE-R or 5G-R), so they will coexist for a long time in the future. The coexistence of multiple technologies is also a challenge in terms of interference and allocation of bandwidth resources.

Conclusion

This article briefly introduces off-network use cases in FRMCS and summarizes the performance requirements of these use cases. Then we provide an overview of existing technologies (GSM-R, TETRA, DMR, LTE-V2X, and NR-V2X) that may support off-network communication and discuss their physical layer characteristics. In addition, we simulate and evaluate the data channel of existing technologies and compare their performance with the requirements of off-network use cases in FRMCS. According to the performance analysis of different technologies, it is challenging for the existing technologies to fully satisfy the requirements of these cases. However, with the help of MIMO and a retransmission scheme, we point out that enhancement of LTE-V2X or NR-V2X operating at 900 MHz has the potential to satisfy the requirements of off-network use cases in FRMCS.

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