MAC-Layer Protocol for Ultra-Reliable Multi-Hop Communication in DECT-2020 NR IIoT Networks

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***Abstract*—DECT-2020 New Radio (NR) is a Radio Interface Technology (RIT) that meets the IMT-2020 requirements for Ultra-Reliable Low-Latency Communications (URLLC) and massive Machine-Type Communications (mMTC). ITU-R approval was gained by the end of 2021, and it remains the only non-cellular 5G technology to date. This work presents an enhanced Medium Access Control (MAC) protocol that utilizes the mesh-networking capability of DECT-2020 NR, extending the procedures and MAC messages beyond the standard. The protocol dynamically assigns radio devices (RDs) the role of intermediate nodes for routing data to RDs in locations prone to outages, thereby reducing the outage rate to below 1% and expanding the network's coverage area. Furthermore, event-based simulations demonstrate the protocol's potential to enable ultra-reliable 5G private networks, positioning DECT-2020 NR as a promising candidate for evolving into a 6G wireless technology in future releases of the standard.**

***Index Terms*—URLLC, TDMA, DECT-2020, MAC, 5G, 6G, Future Wireless Networks, New Radio, Coverage, Outage Rate.**

I. Introduction

DECT-2020 NR is a RIT developed and maintained by the European Telecommunications Standards Institute (ETSI). It targets applications that lie between the extremes of URLLC and mMTC. DECT-2020 NR is ideal for presence monitoring, audio streaming, smart city developments, and industrial and consumer IoT [2], [4]. It offers local deployment options without the need for dedicated network infrastructure or extensive network planning, due to its inherent capability to form mesh networks, where radio devices make autonomous routing decisions. However, while detailed network planning is not required, seamless and ubiquitous coverage remains crucial for reliable wireless communication. Therefore, addressing coverage-related challenges and finding effective solutions is essential. Coverage enhancement strategies are discussed in [14], proposing solutions such as Heterogeneous Networks (HetNets), relaying, and cloud-based mechanisms for next-generation wireless technologies. Network coverage and the network capacity trade-off are investigated in [9] along with the deployment costs. In [10], coverage analysis is presented along with network throughput and techniques such as mm-Waves and Coordinated Multi-Point (CoMP). The potential of device-to-device communications and Unmanned Aerial Vehicles (UAVs) to extend coverage is discussed in [11], while solutions for coverage challenges, such as cell radius expansion, are addressed in [12].

Most of the literature cited in this work focuses on the concept of coverage area in cellular communications or related domains. DECT-2020 NR, once deployed, enables autonomous and automatic operations, reducing maintenance efforts, and making it an attractive technology for private 5G/6G networks. However, achieving seamless coverage is challenging because no prior planning is involved. In our previous work [1], we discuss enhancing coverage specifically for DECT-2020 NR and propose a MAC protocol to improve coverage performance by exploiting path diversity through an intermediate node acting as a relay device. The protocol leverages the ability of each RD to operate in both Fixed Termination (FT) and Portable Termination (PT) modes simultaneously, i.e., FT/PT mode. In this work, we extend our previously proposed MAC protocol, originally designed to reduce outage probability using the FT/PT mode functionality of an RD as an intermediate node. The extension introduces multi-hop communication to meet stricter reliability requirements and enhance coverage within a given Region of Interest (ROI) for private 5G/6G networks, such as in industrial environments with logistics robots and IoT devices equipped with DECT-2020 NR nodes. Our MAC protocol exploits the path diversity between multiple RDs to route data for an RD in an outage location, achieving an outage rate of less than 1%, i.e., over 99% coverage in the ROI as per IMT-2020 guidelines mentioned in [15]. The remainder of the paper is structured as follows:

In Section II, we briefly explain the modes of operation of an RD in DECT-2020 NR and the MAC layer of DECT-2020 NR. The system model is presented in Section III, where the coverage area and outage probability are also defined. The proposed MAC protocol is explained in Section IV, and simulation results are presented in Section V. Section VI concludes the paper, and Section VII contains the acknowledgments.

II. DECT-2020 New Radio

An RD in the DECT-2020 NR network with transmission and reception capabilities can be operated in either FT mode, PT mode, or in both modes simultaneously as an FT/PT [4]. The particular RD mode depends on the local requirements and can be switched during operation by an autonomous decision of the RD. According to the DECT-2020 NR technical specification [4], local resources—such as time, i.e., time slots or sub-slots, and frequency channels—are coordinated by the RD in FT mode, which announces information regarding connection initiation and communication with it. The RDs in PT mode, however, follow the FT's instructions and connect to it. The MAC layer in DECT-2020 NR enables RDs to access the wireless medium via random access or scheduled time resources while providing logical channels for higher-layer

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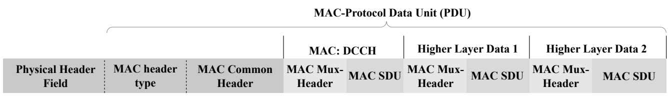


Fig. 1: Physical Header Field and Protocol Data Unit (PDU) of MAC layer.

data transfer. It consists of a Physical Header Field, which configures physical layer parameters, e.g., Modulation and Coding Scheme (MCS), number of antennas, transmit power, etc., and a MAC Protocol Data Unit (PDU) carrying MAC messages, Information Elements (IEs), and higher-layer data [5]. The MAC header type indicates the communication type, e.g., unicast, multicast, or broadcast, while multiplexing headers manage data integration within the MAC PDU, where MAC-own messages and IEs are multiplexed in the Dedicated Control Channel field (DCCH) [5] as shown in Fig. 1.

III. System Model

We focus on achieving ultra-reliable communication using DECT-2020 NR for private 5G/6G networks, utilizing scheduled TDMA/FDMA communication resources. The downlink (DL) supports data transmission from the FT, i.e., $RD_{\text{FT,G}}$, connected to a private server acting as a gateway, while the uplink (UL) is limited to link quality feedback. We consider a private network with one RD in FT mode, i.e., $RD_{\text{FT,G}}$, and N RDs in PT mode, i.e., RD_{total}, where $RD_{\text{total}} = \{RD_{\text{PT},1}, RD_{\text{PT},2}, RD_{\text{PT},3}, ..., RD_{\text{PT},N}\}$ as shown in Fig. 2. $RD_{\text{FT,G}}$ manages resource allocation, schedules RDs, and initiates communication. Operating in the DECT band (1880–1900 MHz) with a 6.912 MHz bandwidth, i.e., the maximum available bandwidth, the system faces outage risks due to mobile RDs and varying channel conditions. This outage risk must be mitigated in the system deployment.

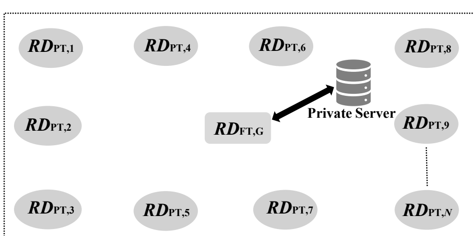


Fig. 2: DECT-2020 NR system model.

This research examines two large-scale propagation models for coverage and outage probability assessment [1]: the log-distance path-loss model and log-normal shadowing. In the log-distance model [1], the free-space path-loss distance (d_0) is 1 m, with a path-loss rate γ of 1.6 for indoor environments [13]. Log-normal shadowing captures non-deterministic effects like blockage, reflection, and scattering [1], [13]. The total path-loss combines log-distance path-loss and log-normal shadowing, represented as ψ_{dB}, a zero-mean Gaussian variable with standard deviation $\sigma_{\psi_{\text{dB}}}$ [1], [13]. Typically, $\sigma_{\psi_{\text{dB}}}$ is 12 dB for implicit indoor models and 6 dB for explicit ones [8].

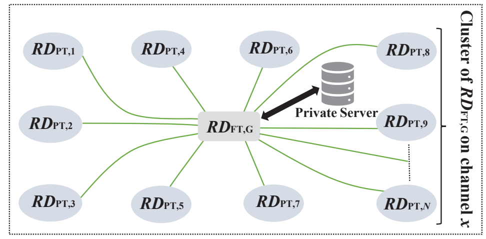


Fig. 3: Initial Cluster Formation of $RD_{\text{FT,G}}$.

1) Outage Probability and Coverage Area: The outage probability $\rho_{\text{out}}(P_{\text{min},d})$ is the probability that the received power $P_{\text{r}}(d)$ at distance d falls below the minimum required power P_{min} [1]. Based on the total path-loss model [1] and the derivation in [13], it is given by:

$$\rho_{\text{out}}(P_{\text{r}}(d) < P_{\text{min}}) = 1 - Q\left(\frac{P_{\text{min}} - \left(P_{\text{t}} - PL(d_0) - 10\gamma \log_{10}\left(\frac{d}{d_0}\right)\right)}{\sigma_{\psi_{\text{dB}}}}\right), \tag{1}$$

where P_{t} is the transmit power, PL is the log-distance path-loss [1], and $Q(\cdot)$ is the Q-function [13]. The coverage area in an ROI consists of locations where the received power exceeds or equals P_{min}.

IV. Proposed MAC Layer Protocol

The proposed MAC protocol for a private DECT-2020 NR 5G/6G network with one gateway and mobile RDs in PT mode aims to reduce outage risks. It targets an outage rate below 1% according to the IMT-2020 guidelines, with distinct modules detailed in separate subsections.

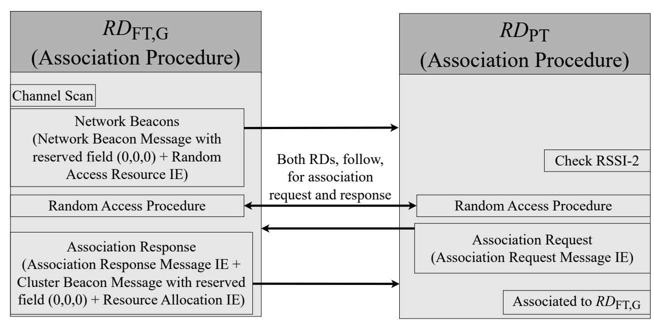
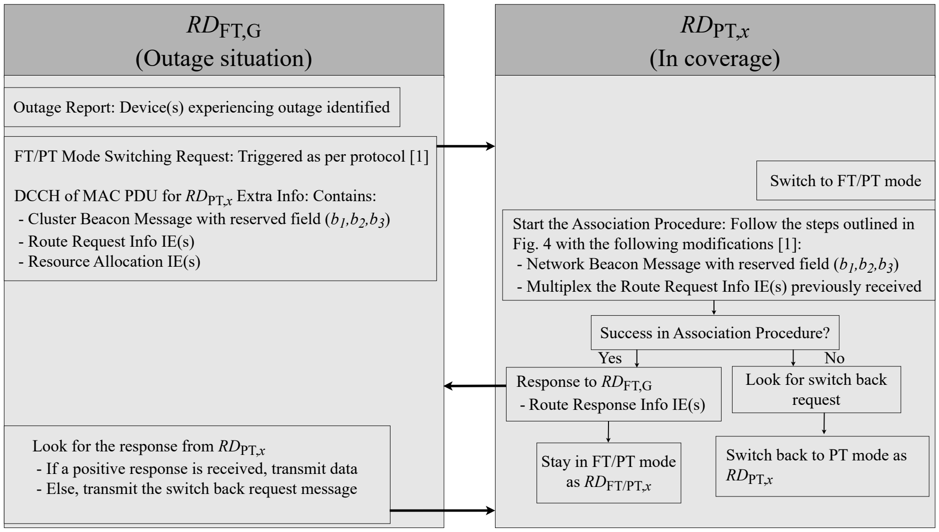


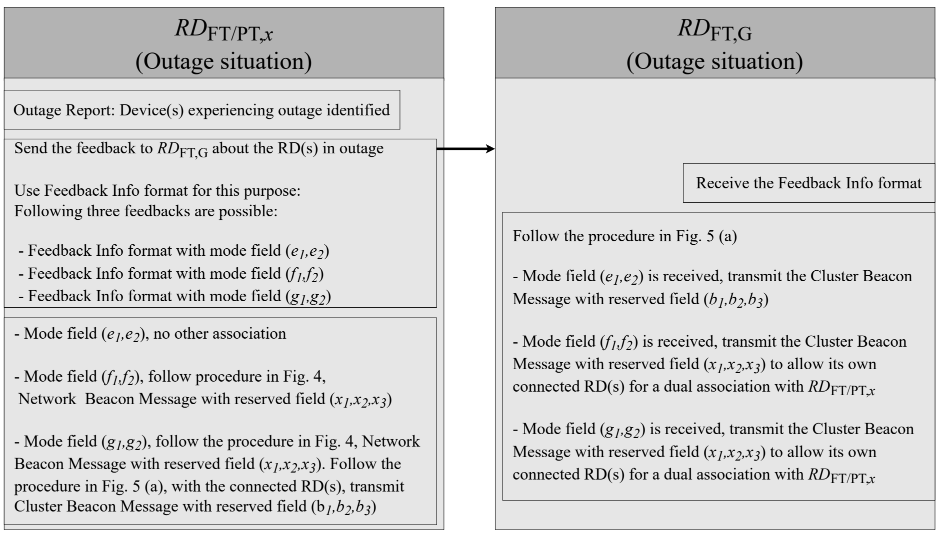
Fig. 4: Initial Association Protocol.

A. Initial Association with $RD_{\text{FT,G}}$

$RD_{\text{FT,G}}$ initiates the communication on free time resources after a channel scan following the association procedure described in [1]. Initially, all the channels are considered free due to the presence of only one FT in the network, i.e., $RD_{\text{FT,G}}$. In [1], we proposed that the $RD_{\text{FT,G}}$ initiates the association procedure by transmitting network beacons on a dedicated channel. In these beacon transmissions, the Random Access Resource IE is multiplexed with the Network Beacon Message to announce resources such as UL random access resources for association requests and DL resources for association responses, thereby completing the random access procedure



(a)



(b)

Fig. 5: Proposed protocol for mitigating outage risks in DECT-2020 NR network.

for initial association with the RDs in RD_{total} [1], [5]. The minimum periodicity of the network beacons was set to 10 ms in [1], and this value is still used in the current solution. By utilizing network beacons with 10 ms periodicity, instead of cluster beacons as traditionally used according to the DECT-2020 NR technical specification [5], channel congestion during the association process is effectively reduced. It allows RDs to perform scanning and transmit beacons on a dedicated channel, thereby minimizing interference [1]. Additionally, it supports the coordination of random access resources among RDs—a mechanism implicitly tied to FT/PT mode switching as described in prior work [1]. The association procedure from the perspective of $RD_{\text{FT,G}}$ is shown in Fig. 4. The RDs in RD_{total} send the association request using the Association Request Message IE on the announced UL random access time resources if the detected network beacon exceeds the required Received Signal Strength Indicator (RSSI)-2 threshold. The RSSI-2 requirement depends on receiver sensitivity and the quality margin, with a 20 dB margin to account for small-scale fading [1]. Initially, we assume that all RDs in RD_{total} meet the minimum RSSI-2 requirement and receive a positive acknowledgment (ACK) through the Association Response Message IE from $RD_{\text{FT,G}}$ on the announced DL time resources. All RDs are assumed to complete their association with $RD_{\text{FT,G}}$ following the Random Access Procedure [1]. In the association response, we propose multiplexing the Cluster Beacon Message and Resource Allocation IE with the Association Response Message IE using unicast header. Multiplexing the Cluster Beacon Message in this manner is a valid approach, as the DECT-2020 NR technical specification permits the inclusion of different messages within a MAC PDU. The Cluster Beacon Message sets the time reference, while the Resource Allocation IE specifies scheduled DL and UL resources for RD_{total}. The initial association procedure is shown in Fig. 4 and the cluster of $RD_{\text{FT,G}}$, e.g., on channel x is shown in Fig. 3. Once the association is complete, further communication is carried out with the help of cluster beacons, according to their roles as described in [5]. The scheduled time resources for the RDs in RD_{total} are repeated each frame until the *scanStatusValid* timer ends [1]. We assume no interference occurs in the allocated time resources due to the absence of nearby interfering networks. Each RD is allocated equal time resources. For a particular RD, $RD_{\text{PT},k}$, the required time resources are $X_{\text{tr},k} = DL_{\text{tr},k} + UL_{\text{tr},k}$, where $k = 1, 2, 3, ..., N$, DL_{tr} and UL_{tr} are DL and UL time resources, respectively, and $DL_{\text{tr}} > UL_{\text{tr}}$ as shown in Fig. 3. After successful allocation of time resources, the data transmission starts, following the procedure in [5].

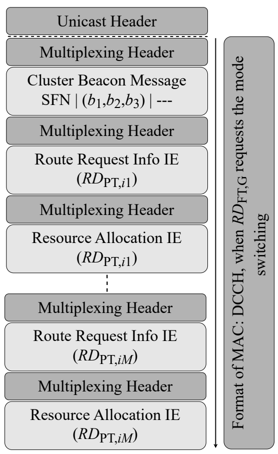


Fig. 6: Control information in the DCCH of MAC PDU when a mode switching request is initiated.

B. Mitigation of outage risks in the network

Due to the mobility of the RDs in RD_{total} or varying channel conditions, the RDs may experience an outage situation. We analyze two scenarios. First, RDs directly connected to $RD_{\text{FT,G}}$ as shown in Fig. 3, experience an outage. Second, RDs in FT/PT mode, e.g., intermediate routing RDs, or the RDs connected to them, encounter an outage. The protocol addresses both scenarios: how RDs switch to FT/PT mode and how RDs in outage identify FT/PT-mode RDs. It also ensures network adaptation to prevent outages, even if intermediate nodes, i.e, RDs in FT/PT mode, or their connected PTs experience an outage. Each scenario is explained in separate subsections.

1) Direct Connection Scenario: When the RDs are directly connected to $RD_{\text{FT,G}}$ as shown in Fig. 3, $RD_{\text{FT,G}}$ manages an outage report in case one or more RDs experience an outage, identifying the affected RDs [1]. The identified RDs in outage are given by a set RD_{outage}. This set is obtained by subtracting the set of RDs fulfilling P_{min} requirement, i.e., RD_{coverage}, from RD_{total}.

$$RD_{\text{outage}} = RD_{\text{total}} - RD_{\text{coverage}}, \tag{2}$$

Furthermore, the disjoint sets RD_{outage} and RD_{coverage} are represented as

$$\begin{aligned} RD_{\text{outage}} &= \{RD_{\text{PT},i_1}, RD_{\text{PT},i_2}, RD_{\text{PT},i_3}, ..., RD_{\text{PT},i_M}\}, \\ RD_{\text{coverage}} &= \{RD_{\text{PT},j_1}, RD_{\text{PT},j_2}, RD_{\text{PT},j_3}, ..., RD_{\text{PT},j_{N-M}}\}, \end{aligned} \tag{3}$$

where, M represents the total RDs in outage, $i_1, i_2, i_3, ..., i_M$ are the indices of the RDs in RD_{total} facing an outage, $0 < M < N$ and RD_{coverage} contains the remaining RDs fulfilling the P_{min} requirement with $j_1, j_2, j_3, ..., j_{N-M}$ as their indices. In the outage scenario, following our proposed protocol mentioned in [1], the $RD_{\text{FT,G}}$ requests the RDs in RD_{coverage} to switch to FT/PT mode to route the data for the RDs in RD_{outage}. For $RD_{\text{PT},x}$ such that,

$$RD_{\text{PT},x} \in RD_{\text{coverage}}, \quad \text{where } x \in \{j_1, j_2, \ldots, j_{N-M}\}$$

following steps are taken as shown in Fig. 5 (a). $RD_{\text{FT,G}}$ initiates the FT/PT mode switching request per protocol mentioned in [1]. In DL transmission to $RD_{\text{PT},x}$, $RD_{\text{FT,G}}$ multiplexes Cluster Beacon Message with reserved field (b_1, b_2, b_3) to initiate the request of mode switching, Route Request Info IE(s)—as proposed and detailed in our previous work [1] containing the address(es) of RD(s) in RD_{outage} , and Resource Allocation IE(s) containing information about the previously allocated time resources to the RD(s) in RD_{outage}, in the MAC PDU of $RD_{\text{PT},x}$. The address(es) of RD(s), along with their previously allocated time resource(s) are later used by $RD_{\text{PT},x}$ to receive the data for routing and to transmit feedback to the $RD_{\text{FT,G}}$ if one RD or more RDs in RD_{outage} get associated to $RD_{\text{PT},x}$. The format of DCCH in the case of mode switching request is shown in Fig. 6. Extra control information for the $RD_{\text{PT},x}$, e.g., Resource Allocation IE of $RD_{\text{PT},x}$, etc., can also be multiplexed if needed, which is allowed and described in DECT-2020 NR technical specification [5]. The mode switching request is transmitted with the unicast header. $RD_{\text{FT,G}}$ repeats this [1],

$$\forall x \in \{j_1, j_2, \ldots, j_{N-M}\}, \quad RD_{\text{PT},x} \in RD_{\text{coverage}}.$$

After receiving the FT/PT mode switching request, $RD_{\text{PT},x}$ switches to $RD_{\text{FT/PT},x}$ and starts the association procedure as per protocol mentioned in [1]. The network beacons are transmitted by multiplexing the Network Beacon Message with reserved field (b_1, b_2, b_3) and the Route Request Info IE(s) to avoid any irrelevant association [1]. Although these network beacons target the RDs in outage, they are transmitted using a broadcast header rather than a multicast header. Irrelevant associations are prevented via the three-bit Network Beacon Message field, ensuring compatibility and consistency with overall MAC beacon transmission procedures in [5]. The format of DCCH in this case, when an RD switched to FT/PT mode transmits the beacons for the initiation of the association procedure is shown in Fig. 7. The rationale behind using network beacons for association is already explained in IV-A. $RD_{\text{FT/PT},x}$ follows the association procedure as mentioned in section IV-A and shown in Fig. 4. If the association procedure is successful, $RD_{\text{FT/PT},x}$ sends the response to the $RD_{\text{FT,G}}$

about the associated RD(s) using the proposed Route Response Info IE(s) in [1] on their previously allocated time resources announced in the FT/PT mode switching request and from the next frame starts receiving data for routing it to the newly associated RD(s). The response to the successful association can be transmitted either collectively or individually. In the collective case, $RD_{\text{FT/PT},x}$ sends a unified response regarding all newly associated RDs using the proposed Route Response Info IE(s) on the first available time resources. The corresponding DCCH format is illustrated in Fig.8 (a). Alternatively, responses can be sent individually for each RD, as per the resource allocations announced in the original FT/PT mode switching request. The DCCH formats for these individual responses are shown in Fig.8 (b) and (c), respectively. In this context, we consider that a set of RDs, denoted as $\{RD_{\text{PT},y_1}, RD_{\text{PT},y_2}, \ldots, RD_{\text{PT},y_Q}\}$, where $\forall k \in \{1, 2, 3, \ldots, Q\}$, the index $y_k \in \{i_1, i_2, \ldots, i_M\}$. These RDs are assumed to be newly associated with $RD_{\text{FT/PT},x}$ as a part of outage recovery procedure. In case, not a single RD in RD_{outage} associates to $RD_{\text{FT/PT},x}$, it waits for the switch back to PT mode request message from $RD_{\text{FT,G}}$ and switches to PT mode again, if received, as mentioned in [1]. All RDs within RD_{coverage}, that establish a connection with one or more RDs in RD_{outage} form their cluster with the connected RD or RDs [1].

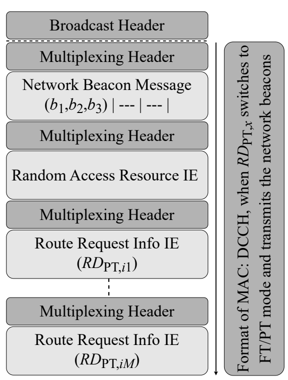


Fig. 7: Control information in the DCCH of MAC PDU for the association procedure when an RD in PT mode switches to FT/PT mode.

2) Intermediate Node Scenario: Once $RD_{\text{PT},x}$ transitions to $RD_{\text{FT/PT},x}$ and forms its cluster, there are three possible scenarios for the number of RDs in its cluster [1]. First, at least one RD is associated with it. Second, Q RDs are associated, where $Q < M$. Third, all RDs in RD_{outage} are associated with it. The three scenarios are shown in Fig. 10. In Fig. 10 (a), $RD_{\text{PT},y} \in RD_{\text{outage}}$ is the only RD connected to $RD_{\text{FT/PT},x}$, where $y \in \{i_1, i_2, \ldots, i_M\}$. In Fig. 10 (b), a set of RDs, i.e., $\{RD_{\text{PT},y_1}, RD_{\text{PT},y_2}, \ldots, RD_{\text{PT},y_Q}\}$, where $\forall k \in \{1, 2, 3, \ldots, Q\}, y_k \in \{i_1, i_2, \ldots, i_M\}$. However, in Fig. 10 (c), all RDs within RD_{outage} are connected to $RD_{\text{FT/PT},x}$. In addition, we consider two more scenarios for the outage given as

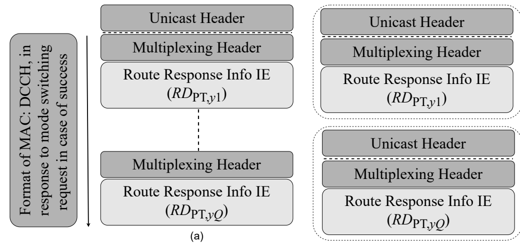


Fig. 8: Control information in the DCCH of MAC PDU following successful mode switching and feedback is sent by the intermediate routing node.

a) Scenario 1: If the intermediate node, e.g., $RD_{\text{FT/PT},x}$ faces an outage then in this case $RD_{\text{FT,G}}$ updates the RD_{outage} by adding $RD_{\text{FT/PT},x}$ and the RDs connected to it and initiates the procedure as mentioned in IV-B1 and shown in Fig. 5 (a). $RD_{\text{FT/PT},x}$ switches back to the $RD_{\text{PT},x}$ and ends the association with the connected RDs.

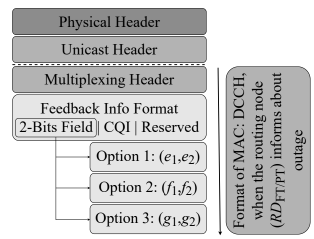


Fig. 9: Control information in the DCCH of MAC PDU, when the feedback is sent by the intermediate routing device regarding an outage.

b) Scenario 2: If any connected RD, e.g., $RD_{\text{PT},y}$, with $RD_{\text{FT/PT},x}$ encounters an outage again, then, as per the proposed protocol, $RD_{\text{FT/PT},x}$ sends feedback to $RD_{\text{FT,G}}$ over the UL time resources previously allocated to $RD_{\text{FT/PT},x}$ for $RD_{\text{PT},y}$, as outlined in section IV-B1, to inform $RD_{\text{FT,G}}$ about the outage. We propose a 12-bit Feedback Info format for this purpose. Two bits are dedicated to the mode in which $RD_{\text{FT/PT},x}$ will assist $RD_{\text{FT,G}}$, four bits represent the Channel Quality Indicator (CQI), and the remaining six bits are reserved to maintain a consistent bit length across different formats as specified in [5]. The four-bit CQI field follows the standard convention used in various other feedback formats, as described in [5]. If the Feedback Info format is sent with mode bits (e_1, e_2), it indicates that the connection is lost, and $RD_{\text{FT/PT},x}$ is switching back to PT mode, making it unavailable as a routing device, e.g., in Fig. 10 (a). Conversely, if Feedback Info format is sent with mode bits (f_1, f_2), it signifies that the connection is lost; however, $RD_{\text{FT/PT},x}$ will remain in FT/PT mode to support multi-hop communication, e.g., in Fig. 10 (a)-(c), that means it will be available for a new association with any RD that associates with the RD went into an outage to support multi-hop communication. Otherwise, if the Feedback Info format is sent with mode bits (g_1, g_2), it indicates the connection is lost, and $RD_{\text{FT/PT},x}$ will trigger its directly connected RDs and be available for a new association with any RD that associates with the RD went into an outage to support multi-hop communication, e.g., Fig. 10 (b) and (c). If $RD_{\text{FT,G}}$ receives the Feedback Info

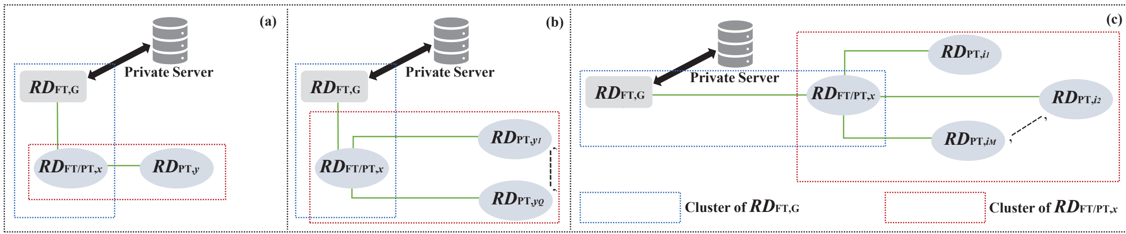


Fig. 10: Different possibilities of RDs in the cluster of an RD, e.g., $RD_{\text{PT},x}$ switched to FT/PT mode as $RD_{\text{FT/PT},x}$.

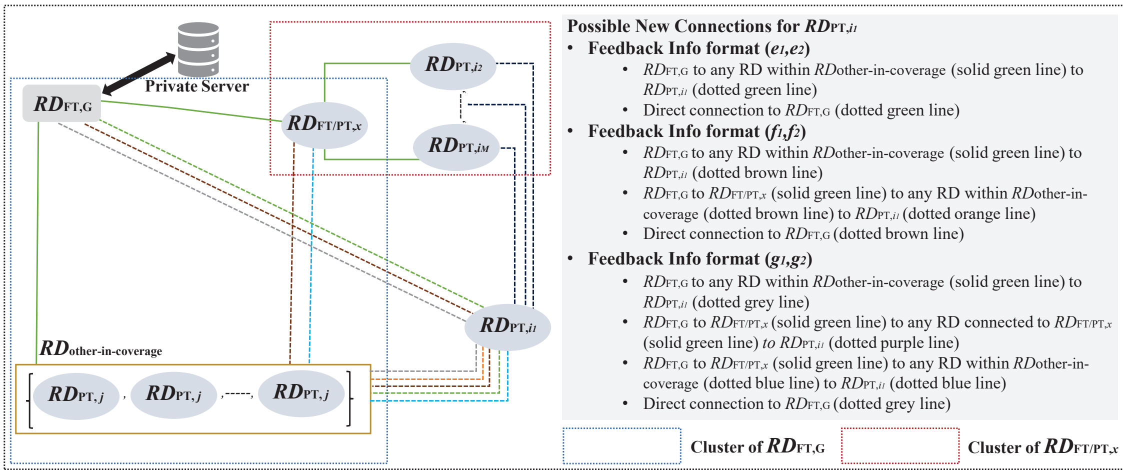


Fig. 11: Multi-hop communication options following the proposed protocol.

format with mode bits (e_1, e_2), it initiates the procedure as mentioned in Fig. 5 (a). Similarly, if (f_1, f_2) is received, it follows the procedure mentioned in Fig. 5 (a); however, in this case, the reserved field of the Cluster Beacon Message is set to (x_1, x_2, x_3), and $RD_{\text{FT/PT},x}$ initiates the Procedure in Fig. 4 to enable multi-hop communication with Network Beacon Message reserved field (x_1, x_2, x_3). The format of DCCH of MAC PDU in this case, when the feedback is sent by the intermediate routing device, i.e., $RD_{\text{FT/PT},x}$ regarding an outage is shown in Fig. 9. The inclusion of the Feedback Info format is indicated by the Physical Header [1], [5].
Furthermore, if the $RD_{\text{FT,G}}$ receives the Feedback Info format with mode bits (g_1, g_2), it again follows the procedure in Fig. 5 (a), the reserved field of the Cluster Beacon Message is set to (x_1, x_2, x_3), and $RD_{\text{FT/PT},x}$ also initiates the same Procedure in Fig. 5 (a) with its directly connected RDs, the reserved field of the Cluster Beacon Message is set to (b_1, b_2, b_3). $RD_{\text{FT/PT},x}$ also follows the procedure in Fig. 4, where the Network Beacon Message reserved field is set to (x_1, x_2, x_3). Where, $(e_1, e_2) \neq (f_1, f_2) \neq (g_1, g_2)$ and $(x_1, x_2, x_3) \neq (b_1, b_2, b_3)$. We consider option (c) in Fig. 10, as an example and assume RD_{PT,i_1} faces an outage again. Following our proposed protocol different new connection options for RD_{PT,i_1} are shown in Fig. 11. As an example, if $RD_{\text{FT/PT},x}$ transmits the Feedback Info format with mode field (e_1, e_2), then RD_{PT,i_1} may establish a new connection either directly to $RD_{\text{FT,G}}$ or to any RD $\in RD_{\text{other-in-coverage}}$ as shown in Fig. 11. Where, $RD_{\text{other-in-coverage}}$ is given as

$$\begin{aligned} RD_{\text{other-in-coverage}} &= RD_{\text{coverage}} \setminus \{RD_{PT,x}\} \\ &= \{RD_{PT,j} \mid j \neq x\}, \end{aligned}$$

and $j \in \{j_1, j_2, \ldots, j_{N-M}\}$.

V. Results and Discussion

To highlight the effectiveness of our proposed technique, our results from the link-level simulations in [3] are utilized to determine the minimum required SNR, i.e., SNR_{needed}, for the receiver sensitivity calculation, as outlined in [6]. We select MCS - 3, i.e., 16 - QAM with $1/2$ coding rate [3], to set the value of SNR_{needed} to achieve a packet error rate of 10^{-5}. For an AWGN channel with perfect channel knowledge, the SNR required to achieve a Packet Error Rate (PER) of 10^{-5} for MCS - 3 is approximately 10 dB [3]. We round it to 10 dB and set it as SNR_{needed}. To account for the 20 dB small-scale fading margin, we add this to the large-scale propagation loss at all locations in the ROI as an extra loss. We assume that communication uses MCS - 1 or MCS - 2, i.e., QPSK with coding rates of $1/2$ and $3/4$. Since SNR_{needed} is selected for a higher MCS, it ensures a PER below 10^{-5} for MCS used in communication, supporting ultra-reliable communication in the ROI. As all RDs in RD_{coverage} meet the SNR_{needed}, $RD_{\text{FT,G}}$ can switch from QPSK to QAM, adjusting control information while maintaining the same required PER. This is feasible because DECT-2020 NR supports adaptive modulation and coding schemes.

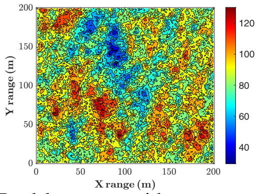


Fig. 12: Total loss map with respect to $RD_{\text{FT,G}}$.

The $Rx_{\text{sensitivity}}$ is calculated as $-88\,\text{dBm}$ using the formula in [1], with the selected bandwidth of $6.912\,\text{MHz}$ and a noise figure of $7\,\text{dB}$. It is the required P_{min}, the received power level below this threshold is considered an outage. To analyze the outage percentage in the ROI with a single FT, i.e., $RD_{\text{FT,G}}$, we consider a 200×200 meter area, e.g., factory hall, with coordinates ranging from $(0,0)$ to $(200,200)$ and a 1-meter resolution. The $RD_{\text{FT,G}}$ is placed at $(100,100)$ and considered static. Different numbers of PTs are considered in RD_{total}. We analyze the results by considering 10 PTs in RD_{total}. First, the total loss map with respect to $RD_{\text{FT,G}}$ is calculated as shown in Fig. 12, using the log-distance path-loss model in [1] with $d_0 = 1\,\text{m}$, $\gamma = 1.6$, and antenna gain of $0\,\text{dBi}$ for both transmitter and receiver, assuming equal antenna heights. The carrier center frequency is $1.885\,\text{GHz}$, and the log-normal shadowing map with $\sigma_{\psi_{\text{dB}}} = 12\,\text{dB}$ with respect to $RD_{\text{FT,G}}$ is calculated using [7] and [8]. After calculating the large-scale path loss, a $20\,\text{dB}$ small-scale fading margin is added, resulting in the total loss map in the ROI with respect to $RD_{\text{FT,G}}$ given in Fig. 12.

The received power at different locations within the ROI, with respect to RD_{total} is calculated by subtracting the total loss map from the transmit (Tx) power. The coverage percentage is determined by counting the locations on 200×200 meter grid where the received power is greater than or equal to $\text{Rx}_{\text{sensitivity}} = -88\,\text{dBm}$, dividing by the total number of locations $(40,000)$, and multiplying by 100. The outage percentage is then obtained by subtracting the coverage percentage from 100.

Tx power (dBm)	13	16	19	21	23
Outage (%)	19.87	14.01	8.99	5.89	4.68

TABLE I: Outage rate (%) analysis for different transmit power levels of $RD_{\text{FT,G}}$ within the Region of Interest (ROI), without using the proposed protocol.

TABLE I shows the outage percentages for different Tx power levels of the $RD_{\text{FT,G}}$. The first row provides the values of the different Tx power levels, while the second row presents the corresponding outage percentages at each Tx power level. As observed, the required outage rate of less than 1% is not achieved even at the maximum Tx power of $23\,\text{dBm}$, as specified in [5]. At this power level, the outage remains at 4.68%. Therefore, we employ our proposed technique to achieve the desired outage rate. To minimize the outage with respect to $RD_{\text{FT,G}}$, we use a Tx power of $23\,\text{dBm}$ and apply the protocol to meet the required outage. For mobile RDs (RD_{total}), power saving is considered. Therefore, we analyze the effectiveness of our technique with lower Tx power levels from [5].

#RDs in RD_{total}	**Tx power of RDs in FT/PT mode (dBm)**				
	0	4	7	10	13
10	2.35	1.56	1.25	0.67	0.31
20	2.05	1.07	0.35	0.19	0.12

TABLE II: Outage rate (%) analysis for different transmit power levels of RDs operating in FT/PT modes. The Tx power of $RD_{\text{FT,G}}$ is fixed at $23\,\text{dBm}$. The analysis is performed for varying numbers of RDs in RD_{total}, representing the default number of RDs in PT mode within the Region of Interest (ROI). Outage performance is evaluated under the constraint that only a single intermediate node is selected to assist communication and mitigate outage. It is observed that increasing the number of RDs in RD_{total} enables a reduction in the required Tx power of RDs in FT/PT mode, contributing to improved energy efficiency.

TABLE II presents the outage rate for the proposed protocol in a single-hop scenario, as a function of the number of RDs in RD_{total} and the Tx power of RDs in RD_{total} operating in FT/PT mode. The rows correspond to different numbers of RDs in RD_{total} used in the network, specifically 10 and 20. The columns correspond to the Tx power levels of the RDs switched to FT/PT mode, varying from $0\,\text{dBm}$ to $13\,\text{dBm}$. The numerical entries in the table are outage rates in percent.

The outage rates for different Tx power levels of mobile RDs, with a fixed Tx power of $RD_{\text{FT,G}}$, are shown in TABLE II for 10 PTs using a single intermediate hop communication. As shown in TABLE II, with a Tx power level of $10\,\text{dBm}$, 1% outage is achieved, demonstrating the effectiveness of our protocol. Increasing the number of RDs in RD_{total} further reduces the Tx power of the mobile RDs, as shown in TABLE II for 20 PTs, where the desired outage is achieved at $7\,\text{dBm}$. To analyze results for multi-hop communication (two intermediate nodes), we select 4 RDs in RD_{total} from the available 10 and 20 RDs. These RDs are placed at half the distance from the center location along the diagonals of the ROI, ensuring coverage with respect to $RD_{\text{FT,G}}$. The Tx power of these 4 RDs is set to $13\,\text{dBm}$, half the power of the $RD_{\text{FT,G}}$, as per [5]. With these fixed RDs and multi-hop support, the Tx power of mobile RDs can be further reduced, e.g., $3\,\text{dB}$ gain is achieved as shown in TABLE III. The placement of fixed RDs is based on the scenario where, in an industrial hall, some IoT devices, e.g., sensors, are fixed, while others, e.g., logistics robots, are mobile. These sensor devices, equipped with DECT-2020 NR RDs, can switch to FT/PT mode as needed. The gateway, having information on the location of mobile RDs, can use multi-hop extension firmware to adapt the network and reduce outages.

To obtain the results in TABLE II, an event-based simulator is used, where each event corresponds to a change in the RD position. The total loss map of $RD_{\text{FT,G}}$ remains static, and the received power of all RDs is checked at their respective locations. If an RD faces an outage with respect to $RD_{\text{FT,G}}$, new total loss maps are generated for the remaining RDs not in outage, following the procedure outlined above. Correlated log-

#RDs in RD_{total}	Tx power of RDs in FT/PT mode (dBm)				
	0	4	7	10	13
10	2.01	1.24	0.90	0.55	0.21
20	1.79	0.87	0.29	0.17	0.09

TABLE III: Outage rate (%) analysis for different transmit power levels of RDs operating in FT/PT modes. The Tx power of $RD_{\text{FT,G}}$ is fixed at 23 dBm. The analysis is performed for varying numbers of RDs in RD_{total}, representing the default number of RDs in PT mode within the Region of Interest (ROI). Outage performance is evaluated under the constraint that four RDs from the total RDs in the ROI are static with 13 dBm Tx power and within the coverage of $RD_{\text{FT,G}}$, while the remaining RDs are mobile. Multi-hop communication is allowed to mitigate the outage. It is observed that increasing the number of RDs in RD_{total} enables a further reduction in the required Tx power of RDs in FT/PT mode compared to single-hop scenario, contributing to improved energy efficiency.

normal shadowing maps are generated with a fixed correlation of 0.5 with the base map, i.e., shadowing map of $RD_{\text{FT,G}}$, for simplicity. Using the total loss maps and selected Tx powers in TABLE II, the received power of each RD is calculated. If the minimum received power is met, the RD is considered in coverage; otherwise, it is in outage. Results are then accumulated for 60,000 events. In the multi-hop scenario, e.g., TABLE III, the outage for each RD is first checked with respect to $RD_{\text{FT,G}}$. If the RD is in an outage, its coverage with respect to the remaining RDs, e.g., 4 static RDs and other mobile RDs in coverage with respect to $RD_{\text{FT,G}}$, is then evaluated. If the RD is still in outage, its coverage is checked with other RDs that are in outage with respect to $RD_{\text{FT,G}}$ but are in coverage of the remaining RD or RDs. If the RD continues to experience an outage, it is classified as an outage; otherwise, it is classified as coverage.

VI. Conclusion

In this paper, we proposed an enhanced single and multi-intermediate-hop Medium Access Control (MAC) protocol that utilizes the mesh-networking capability of DECT-2020 NR by extending the procedures and MAC messages beyond the DECT-2020 NR standard. The protocol leverages MAC messages and Information Elements (IEs) to reduce the outage rate to less than 1% in a given Region of Interest (ROI). The protocol achieves this by employing periodic Network and Cluster Beacon Message transmissions to address outage scenarios caused by the mobility of Radio Devices (RDs). Specifically, it mitigates the outages experienced by RDs directly connected to the gateway and those acting as intermediate routing nodes in FT/PT mode. To enhance network resilience, the proposed protocol enables dynamic mode switching and facilitates the identification of FT/PT-mode RDs for efficient routing. Furthermore, it ensures reliable connectivity even when the intermediate nodes or their associated RDs lose connection. Event-based simulations validate the effectiveness of the proposed approach, demonstrating its ability to achieve ultra-reliable communication while maintaining minimal transmission power for mobile RDs operating as intermediate routing nodes. The protocol operates efficiently without requiring prior infrastructure planning and adapts to varying transmit power and received power constraints, making it well-suited for private 5G/6G networks, e.g., Industrial IoT.

In future work, we plan to incorporate network coding to optimize time resource utilization, further enhancing the efficiency and reliability of the proposed protocol.

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