

MAC Protocol for Reducing Outage Probability in DECT-2020 New Radio

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Abstract—DECT-2020 New Radio (NR) is a Radio Interface Technology (RIT) recognized for fulfilling the requirements of IMT-2020 Ultra Reliable Low Latency Communications (URLLC) and massive Machine Type Communications (mMTC) application scenarios. A single DECT-2020 NR Radio Device (RD) in Fixed Termination (FT) mode announces the radio resources, while other RDs in Portable Termination (PT) mode directly connect to it. A single RD can also operate in both modes simultaneously as an FT/PT. In this research work, we consider the requirement of an ultra-reliable DECT-2020 NR private network with a limited number of RDs in a given Region Of Interest (ROI) and propose a Medium Access Control (MAC) protocol to reduce the outage probability by exploiting the FT/PT mode functionality of an RD. We utilize the Cluster and Network Beacon Messages periodically transmitted by the FT to prompt connected PTs to change to FT/PT mode and route the data for a specific RD positioned in an outage location, ensuring an outage rate of less than 1% in the ROI. Furthermore, we demonstrate the effectiveness of our proposed technique through event-based simulations.

Index Terms—URLLC, TDMA, DECT-2020, MAC, 5G, New Radio, coverage, outage rate.

I. INTRODUCTION

The mobile communication industry undergoes a generation evolution almost every decade due to the escalating number of new applications day by day and their strict requirements. To facilitate this transition seamlessly, novel standards, technical specifications, and regulations are established by different organizations in a collaborative fashion [1]. To address Fifth Generation (5G) use cases encompassing URLLC, mMTC, and enhanced Mobile Broadband (eMBB), the International Telecommunication Union, Radio Communication Sector (ITU-R) Working Party 5D (WP5D) has devised requirements for IMT-2020 [15]. By addressing one or more of these 5G use cases, Third Generation Partnership Project (3GPP) has developed technologies like 5G New Radio (NR), Narrowband Internet of Things (NB-IoT), and Long Term Evolution for Machines (LTE-M) that complement the requirements set by ITU-R [17], [18].

DECT-2020 NR is an RIT developed and maintained by the European Telecommunications Standards Institute (ETSI). DECT-2020 NR mainly focuses on applications that fall between the URLLC and mMTC extremes, e.g., presence monitoring, audio streaming applications, consumer and industrial applications of Internet of Things (IoT), and smart city applications [19]. DECT-2020 NR provides local deployment options without necessitating a distinct network infrastructure or network

planning. Seamless and ubiquitous coverage are key features for wireless networks. Therefore, addressing coverage-related challenges and finding solutions is paramount.

Coverage improvement concepts are discussed in [14], suggesting solutions such as Heterogeneous Networks (HetNets), relaying, or cloud-based mechanisms for future wireless technologies. Network coverage and the network capacity trade-off are investigated in [7] along with the deployment costs. In [8], coverage analysis based on field measurements is provided. Nevertheless, full dedication to the study of coverage alone is missing in this work as other parameters, such as network throughput, and specific coverage techniques for technologies such as mm-Waves and Coordinated Multi-Point (CoMP) are evaluated. In [9], relaying and network coverage extension capabilities of device-to-device communications and Unmanned Aerial Vehicles (UAVs) are put forward. Solutions to particular issues of network coverage, such as cell radius expansion, are mentioned in [10].

Most of the literature cited in this work addresses the concept of coverage area in the framework of cellular communications or its associated domains. DECT-2020 NR enables autonomous and automatic operations once it is deployed, which minimizes maintenance efforts. This feature makes it an appealing technology for private networks. However, without prior planning, achieving seamless coverage is crucial. Therefore, in this research work, we propose a novel MAC protocol to ensure seamless coverage in a given ROI for a private network, e.g., in an industrial environment with logistics robots equipped with DECT-2020 NR RDs. Our proposed MAC protocol exploits the path diversity between the RDs to route the data for an RD positioned in an outage location to achieve an outage rate of less than 1%, i.e., more than 99% coverage in the ROI. The proposed protocol leverages the inherent capability of each RD to operate both in FT and PT modes simultaneously, i.e., FT/PT mode. The remainder of the paper is structured as follows:

In section II, we briefly explain the Physical and MAC layer of DECT-2020 NR. The system model and the factors degrading the system performance, e.g., large-scale fading models, are presented in section III. Additionally, in the same section, the coverage area and the outage probability are defined. The proposed MAC protocol is elaborated in section IV, simulation results are explained in section V, and section VI concludes the paper.

II. DECT-2020 NEW RADIO

An RD in the DECT-2020 NR network with transmission and reception capabilities can be operated in either Fixed Termination (FT) mode, Portable Termination (PT) mode, or in both modes simultaneously as an FT/PT [19]. The particular RD mode depends on the local requirements. According to the DECT-2020 NR technical specifications [19], local time resources (i.e., time slots or subslots) are coordinated by the RD in the FT mode, and it announces the information regarding the connection initiation and communication with it. The RDs in PT mode, however, follow the FT's instructions and connect to it.

The DECT-2020 NR Physical layer operates in frequency bands below 6 GHz and uses Cyclic Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM) combined with Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) in a Time Division Duplex (TDD) communication manner. It supports different channel bandwidths in different frequency bands and employs turbo coding for both control and data channels with Hybrid Automatic Repeat Request (HARQ). Moreover, the Physical layer supports Multiple Input Multiple Output (MIMO) operations with up to eight antenna streams.

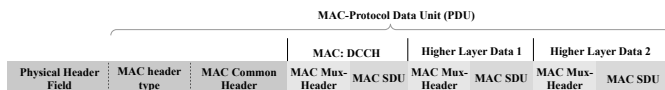


Fig. 1: Physical Header Field and Protocol Data Unit (PDU) of MAC layer.

The main purpose of the MAC layer in DECT-2020 NR is to allow the RDs to access the wireless shared medium in a random access fashion or on scheduled time resources. Additionally, it offers logical channels to the higher layers for data transfer. MAC layer has two separate parts in the Physical layer packet for transmitting and receiving information. The first part is the Physical Header Field and the second part is the MAC Protocol Data Unit (PDU). The Physical Header Field is used by the MAC layer to set the Physical layer parameters, e.g., Modulation and Coding Schemes (MCS), number of antennas, transmit power, packet length type, and transmitter/receiver identity. The MAC PDU carries the MAC messages, MAC Information Elements (IEs), and higher layer data multiplexed in a MAC PDU as shown in Fig. 1. The MAC header type informs about the type of MAC Common Header, which further tells about the type of communication, e.g., unicast, broadcast or beacon transmissions, etc. Additionally, the MAC messages and IEs along with higher layer data are multiplexed using the multiplexing headers (i.e., MAC Mux-Header(s) in Fig. 1) provided by the MAC layer [21].

III. SYSTEM MODEL

Bearing in mind that DECT-2020 NR is a non-cellular IMT-2020 RIT for 5G URLLC use cases, we focus on achieving ultra-reliable communication via DECT-2020 NR for a private 5G network. Within the ROI, we consider communication using scheduled time resources in a TDMA/FDMA fashion. Furthermore, we consider downlink (DL) data transmission

from the FT with a direct connection to the internet or a private server, whereas in the uplink (UL), only link quality feedback is transmitted. The ROI of the private network in Fig. 2 consists of one RD in FT mode which is connected to the internet (represented by $RD_{FT,G}$) and N RDs which are by default operating in PT mode. The RDs operating in PT mode are represented as $RD_{total} = \{RD_{PT,1}, RD_{PT,2}, RD_{PT,3}, \dots, RD_{PT,N}\}$. All RDs in RD_{total} fundamentally follow the instructions from $RD_{FT,G}$ for association, data transmission, and data reception. $RD_{FT,G}$ announces the radio and time resources, schedules the RDs in RD_{total} , and starts the communication. The operating band is chosen to be the DECT band, i.e., 1880-1900 MHz, with three different bandwidths, i.e., 1.728 MHz, 3.456 MHz, and 6.912 MHz are considered [20]. Furthermore, we consider that the $RD_{FT,G}$ is static, whereas the RDs in PT mode are mobile and face varying channel conditions which increase the outage risk of the system. This outage risk needs to be mitigated in a system deployment.

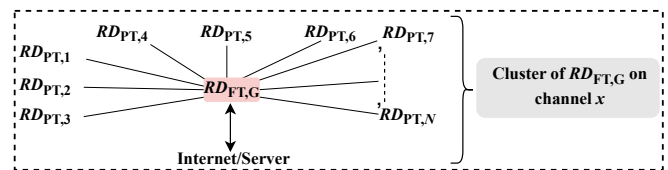


Fig. 2: DECT-2020 NR system model.

In this research work, we reflect upon two large-scale propagation models for coverage area and outage probability assessment for system planning [6], [11]. First is the log-distance path-loss model and the second is log-normal shadowing. The log-distance model mentioned in [2] is given as follows:

$$PL(d) = PL(d_0) + 10\gamma \log_{10} \left(\frac{d}{d_0} \right), \quad (1)$$

where $PL(d)$ is the path-loss at distance d from the transmitter in decibels, γ is the path-loss rate, and $PL(d_0)$ is the path-loss at the reference distance d_0 in the vicinity of the transmitter. $PL(d_0)$ is set to free space path-loss at d_0 , i.e., 1 m for indoor propagation [12]. The path-loss rate γ depends on the environment, and its value is 1.6 for our selected industrial environment [12]. Additionally, the non-deterministic characteristics due to object blockage or reflecting and scattering objects in the propagation path are captured via log-normal shadowing [12]. The path-loss model with the log-normal shadowing is given as follows:

$$PL(d) = PL(d_0) + 10\gamma \log_{10} \left(\frac{d}{d_0} \right) + \psi_{dB}, \quad (2)$$

where ψ_{dB} is a zero-mean Gaussian distributed random variable with standard deviation $\sigma_{\psi_{dB}}$ (both in dB). Conventionally, $\sigma_{\psi_{dB}}$ is 12 dB for implicit indoor environment models, while for explicit models, 6 dB is assumed [5]. For a given ROI, a space-correlated shadowing map is acquired from a log-normal random distribution using a low-complexity variant of the Cholesky decomposition provided in [4], [5].

1) *Outage Probability*: The outage probability $\rho_{\text{out}}(P_{\min}, d)$ is defined as a probability that the received power $P_r(d)$ at a given distance d falls below the targeted minimum received power P_{\min} : $\rho_{\text{out}}(P_{\min}, d) = \rho(P_r(d) < P_{\min})$. For (2), following the derivation in [12], this becomes as follows:

$$\rho(P_r(d) < P_{\min}) = 1 - Q\left(\frac{P_{\min} - (P_t - PL(d_0) - 10\gamma \log_{10}(\frac{d}{d_0}))}{\sigma_{\psi_{\text{dB}}}}\right), \quad (3)$$

where P_t is the transmitted power and the $Q(\cdot)$ is the Q -function defined in [12].

2) *Coverage Area*: For a given ROI, the coverage area is defined as the area of locations in the ROI where the received power is above a given minimum, which, according to [12], is given as follows:

$$\begin{aligned} C &= \mathbf{E}\left[\frac{1}{\pi R^2} \int_{\text{ROI area}} \mathbf{1}[P_r(d) > P_{\min \text{ in } dA}] dA\right] \\ &= \frac{1}{\pi R^2} \int_{\text{ROI area}} \mathbf{E}[\mathbf{1}[P_r(d) > P_{\min \text{ in } dA}]] dA, \end{aligned} \quad (4)$$

where R is the radius of the circular ROI, $\mathbf{E}[\cdot]$ is the expected value and $\mathbf{1}[\cdot]$ denotes the indicator function. The coverage area is calculated by dividing the ROI into incremental areas dA and integrating over these areas where $\rho(P_r(d) > P_{\min}) = \rho_A(d)$. Hence, $\rho_A(d) = \mathbf{E}[\mathbf{1}[P_r(d) > P_{\min \text{ in } dA}]]$. In the ROI the outage probability is defined as the percentage of the area in the ROI that does not meet the minimum power requirement P_{\min} , i.e., $\rho_{\text{out}}^{\text{ROI}} = 1 - C$. With the log-normal distribution for the shadowing, we have

$$\begin{aligned} \rho_A(d) &= \rho(P_r(d) > P_{\min}) \\ &= Q\left(\frac{P_{\min} - (P_t - PL(d_0) - 10\gamma \log_{10}(\frac{d}{d_0}))}{\sigma_{\psi_{\text{dB}}}}\right) \\ &= 1 - \rho_{\text{out}}(P_{\min}, d), \end{aligned} \quad (5)$$

where ρ_{out} is the outage probability from (3). In the ROI the locations where the received power is below P_{\min} are considered to be the outage locations.

IV. PROPOSED MAC LAYER PROTOCOL

In section III, we considered a private DECT-2020 NR 5G network with one gateway, i.e., $RD_{\text{FT,G}}$ and N RDs in RD_{total} , operating in the PT mode. The RDs operating in the PT mode are considered mobile, which introduces outage risks to the system. In this section, we present the MAC protocol to achieve an outage rate of less than 1% according to IMT-2020 guidelines [16]. We outline the proposed protocol into distinct modules, each of which is addressed in a separate subsection.

A. Initiation of the Association Procedure by $RD_{\text{FT,G}}$

$RD_{\text{FT,G}}$ initiates the communication on free time resources after performing the channel scan as described in [21]. For the duration of *scanStatusValid* which defaults to 300 s for the 1880-1900 MHz band [21], the status of the channel is considered constant. Initially, all the channels are considered free due to the presence of only one FT in the network,

i.e., $RD_{\text{FT,G}}$. Subsequently, after the channel scan procedure, $RD_{\text{FT,G}}$ initiates the association procedure. We propose the initiation of the association procedure by utilizing the network beacons rather than the cluster beacons as traditionally used according to [21] by multiplexing the Random Access Resource Allocation IE with the Network Beacon Message. The next step is the Random Access Procedure [21], which is done on the random access time resources which are announced via Random Access Resource IE. Furthermore, the minimum periodicity of network beacon transmission is changed from 50 ms to 10 ms. The reason behind multiplexing the Random Access Resource Allocation IE with the network beacons and changing its periodicity is elaborated in subsection IV-D. However, this approach aligns with the guidelines specified in DECT-2020 NR MAC layer Technical Specification (TS) [21], which allows the inclusion of different IEs with both Cluster and Network Beacon Messages and provides different values for periodic beacon transmissions. The response to the beacons is explained in the subsequent subsection IV-B.

B. Association with the $RD_{\text{FT,G}}$

The RDs in RD_{total} only request association if the detected network beacon is above a certain Received Signal Strength Indicator-2 (RSSI-2) requirement. The required RSSI-2 depends on the receiver sensitivity and the quality margin, i.e., minimum quality above receiver sensitivity. To account for the impact of small-scale fading, a 20 dB quality margin is used [13]. Initially, we consider that all the RDs in RD_{total} meet the minimum RSSI-2 requirement. Hence, the RDs request the association with the $RD_{\text{FT,G}}$ by sending the Association Request Message IE. Following the Random Access Procedure, the association request is sent on the random access time resources announced by the $RD_{\text{FT,G}}$ for the UL transmission, whereas, the RDs receive the association response from the $RD_{\text{FT,G}}$ on the announced DL time resources as mentioned in subsection IV-A. $RD_{\text{FT,G}}$ responds using the Association Response Message IE with unicast header. We consider that all the RDs complete their association with the $RD_{\text{FT,G}}$ by receiving the Association Response Message IE with the positive acknowledgment (ACK). Furthermore, in the association response along with the Association Response Message IE, we propose to multiplex the Cluster Beacon Message and Resource Allocation IE. The Cluster Beacon Message informs the associated RDs about the frame and slot timing, e.g., sets the time reference, while, the Resource Allocation IE informs the RDs in RD_{total} about their respective scheduled time resources for DL and UL transmissions. The initial association procedure is shown in Fig. 3 (a). In the next subsection IV-C, we discuss the DL and UL transmission of data on the scheduled time resources.

C. Data transmission on scheduled time resources

After $RD_{\text{FT,G}}$ allocates the scheduled time resources to the RDs in RD_{total} , it repeats the allocation in each frame until the *scanStatusValid* timer ends. If the consecutive transmissions on the repetitive time resources are deferred, then an interference scenario may occur [21] where other FTs in the network start

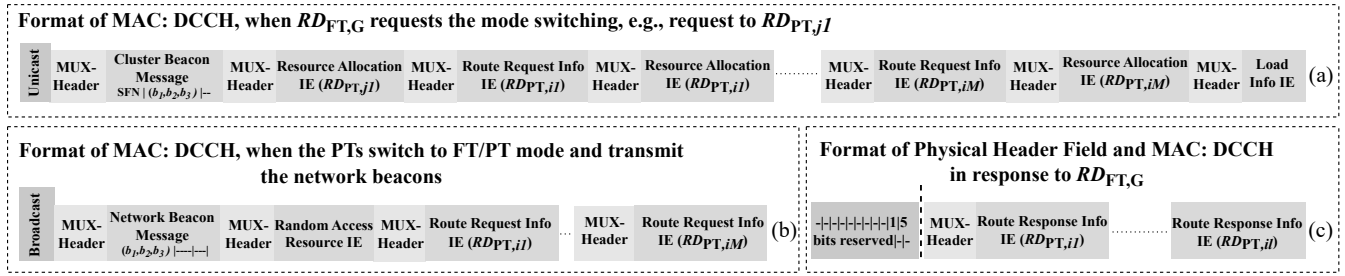


Fig. 4: Multiplexing of control messages and IEs following the proposed MAC protocol for outage reduction.

and the Load Info IE. The Route Request Info IEs for all the RDs in RD_{outage} , along with their respective Resource Allocation IEs are multiplexed within the PDU of each RD in RD_{FPmin} on its DL time resources. Fig. 4(a) illustrates the multiplexing process for $RD_{PT,i1}$.

- In the Resource Allocation IE for a particular RD (e.g., $RD_{PT,iq}$, where $q = 1, 2, 3, \dots, M$) in outage, we use its previous allocated time resources, i.e., $X_{tr,iq} = DL_{tr,iq} + UL_{tr,iq}$ for announcing them to the RDs in RD_{FPmin} for the reception of route data in the DL and feedback in the UL.
- The Load Info IE informs about the load on the operating channel [21]. This helps the RDs in RD_{FPmin} to quickly scan the channels, and find the possibility of scheduling the RDs in an outage on the same operating channel being used by the $RD_{FT,G}$ to save the time resources. The FT/PT mode switching request is shown in Fig. 3 (b).

After receiving the MAC PDU with (b_1, b_2, b_3) bits in the Cluster Beacon Message, the RDs in RD_{FPmin} recognize the need to switch to FT/PT mode. Additionally, they know about the scheduled time resources allocated for the reception of the route data and transmission of feedback for a particular RD in RD_{outage} if it becomes associated with any of them. Afterwards, the RDs in RD_{FPmin} proceed with the following procedures:

- Initiate the association procedure as mentioned in subsection IV-A and IV-B. All RDs in RD_{FPmin} use the Network Beacon Message for initiating the association as discussed in IV-A.
- We employ the first reserved field of the Network Beacon Message which is three bits long, to announce that the association initiation is for the RDs in outage and avoid the association with any irrelevant RD. For the sake of consistency, the bit combination is the same as used by the $RD_{FT,G}$ in the cluster beacon, i.e., (b_1, b_2, b_3) .
- Each RD in RD_{FPmin} for the initiation of the association procedure multiplexes the Network Beacon Message, followed by the Random Access Resource IE and Route Request Info IEs it received from the $RD_{FT,G}$ as shown in Fig. 4 (b). The general association procedure of RDs in RD_{outage} with the RDs in RD_{FPmin} is shown in Fig. 3 (c).
- When the RDs in RD_{outage} associate with any RD in RD_{FPmin} , that particular RD in RD_{FPmin} informs the $RD_{FT,G}$ about the association as a response. For this purpose, we propose a 32-bit (i.e., four octets) long Route Response Info IE. The structure consists of 32 bits allocated for the address of an RD in the outage.

- The Response is sent on the UL time resources specified by $RD_{FT,G}$ in the mode switching request message. The MAC layer uses Physical Layer Control Field Type 2 for scheduled transmission and reception [21]. For the response transmission, we utilize Type 2 with header format 001, allocating one reserved bit to be set to 1 out of the total 6 available as shown in Fig.4 (c), i.e., left to the dotted line, followed by the Route Response Info IE(s) containing the address(es) of the associated RD(s) previously in outage.

We assume that all RDs in RD_{outage} establish communication links that meet the minimum power requirement. This way, we leave it to the application requirement how long the RDs in RD_{FPmin} should keep searching for RDs in RD_{outage} before being switched back to PT mode by the $RD_{FT,G}$. Once a response for all RDs in RD_{outage} is received, $RD_{FT,G}$ requests all the other RDs to switch back to PT mode with which the RDs in RD_{outage} did not associate by sending the switch back request message on their allocated DL time resources using the same field of the Cluster Beacon Message used for the request with bits combination (a_1, a_2, a_3) such that $(a_1, a_2, a_3) \neq (b_1, b_2, b_3)$ and starts the DL transmission of route data from the next frame and maintain the feedback in the UL. The RDs in RD_{FPmin} that are now operating in FT/PT mode and associated with the particular RD(s) in RD_{outage} form their clusters and start routing the data. An illustrative example is presented in Fig. 3 (d), where we assume that the RDs depicted in the figure are associated with the RDs in RD_{outage} . In case the intermediate routing RD operating in FT/PT modes, faces an outage, it ends the association with the RDs associated with it following the procedure mentioned in [21]. The $RD_{FT,G}$ updates the RD_{outage} and follows the procedure mentioned above. Furthermore, we assume that an RD in outage once becomes associated with an RD in RD_{FPmin} does not face the outage again.

The use of Random Access Resource IE in conjunction with the Network Beacon Message to initiate the association and setting the minimum periodicity to 10 ms offers several advantages, as mentioned below:

- This avoids polluting the operating channels with the Cluster Beacon Messages of newly switched RDs to FT/PT mode because each RD will first scan one dedicated channel and transmit its network beacon when it is free. The RDs in outage also scan the same channel for the new association.
- When a particular RD is transmitting its network beacons, the other RDs switched to FT/PT mode can also scan it,

therefore, know about the random access time resources (UL and DL) and avoid using the same time resources. In the UL for the association request, same time resources can be used because the Random Access Procedure uses the Listen Before Talk (LBT) Protocol with the unicast header for the association, therefore, interference can be avoided. While, for sending the association response in the DL, different time resources are preferred because if there is a delay in the generation of the association response, interference in the DL can occur.

V. RESULTS AND DISCUSSION

To demonstrate the effectiveness of our proposed technique, we use our link-level simulation results in [1] to acquire the minimum required Signal-to-Noise Ratio (SNR_{needed}) for calculating the receiver (Rx) sensitivity which, according to [22], is given as

$$R_{x\text{sensitivity}} = R_{x\text{Noise-Floor}} + SNR_{\text{needed}}, \quad (8)$$

and $R_{x\text{Noise-Floor}}$ is calculated as

$$R_{x\text{Noise-Floor}} = -174_{\text{dBm/Hz}} + NF_{\text{dB}} + 10 \cdot \log_{10}(\Delta f), \quad (9)$$

where, NF_{dB} and Δf are the receiver's noise figure and operating bandwidth, respectively. In subsection IV-C, we considered low data rate requirement, therefore, we have selected Modulation and Coding Scheme (MCS)-3 (i.e., 16-QAM with 1/2 coding rate [1]) for setting the value of SNR_{needed} to achieve a packet error rate of 10^{-5} . The Signal-to-Noise Ratio (SNR) required for achieving the PER of 10^{-5} in an Additive White Gaussian Noise (AWGN) channel with perfect channel knowledge for an MCS-3 is around 9 dB [1], we ceil it to 10 dB, and use it as an SNR_{needed} . To cover the 20 dB small fading margin as mentioned in subsection IV-B, we add this to the large-scale propagation loss on all locations in the ROI described later in this section. Furthermore, we assume that the actual communication is using MCS-1 or MCS-2 (i.e., QPSK with a coding rate of 1/2 and 3/4, respectively). As SNR_{needed} is selected for a higher MCS scheme, this will achieve the packet error rate (PER) below 10^{-5} for an MCS being used for the communication. Hence, it supports ultra-reliable communication within the ROI. Since all the RDs in RD_{FPmin} meet the SNR_{needed} requirement, $RD_{\text{FT,G}}$ can switch the modulation from QPSK to QAM. This allows the control information proposed in the protocol to be easily adjusted within the allocated DL time resources while still maintaining a PER of 10^{-5} . This is possible because DECT-2020 NR supports adaptive modulation and coding schemes.

TABLE I: DECT 2020-NR Receiver Configuration Parameters

Bandwidth Δf (MHz)	Noise Figure NF (dB)	Noise Floor (dBm)	$R_{x\text{sensitivity}}$ (dBm)
1.728	7	-104.6246	-94
3.456	7	-101.6143	-91
6.912	7	-98.6040	-88

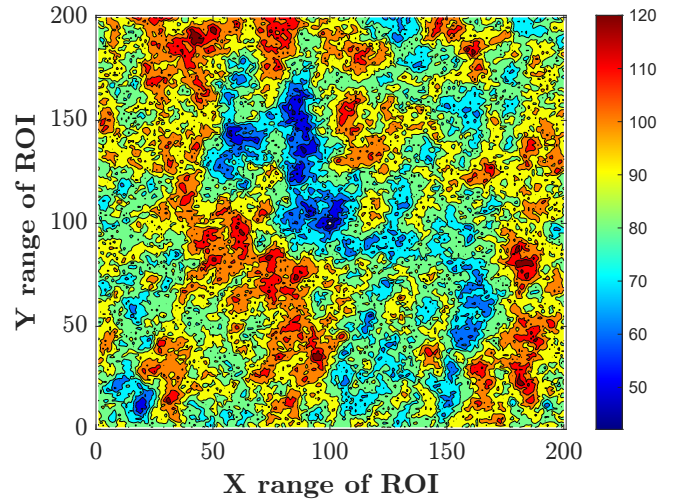


Fig. 5: Total loss map w.r.t to $RD_{\text{FT,G}}$ with coordinates (100,100) in the ROI.

We first calculate the $R_{x\text{Noise-Floor}}$ as shown in the third column of Table I with $NF_{\text{dB}} = 7$ dB [16]. The ceil $R_{x\text{sensitivity}}$ for different available bandwidths in 1880-1900 MHz band is shown in Table I. It is the required P_{min} , the received power level below this level is considered as an outage. To analyze the coverage and outage percentage in the ROI with a single FT, i.e., $RD_{\text{FT,G}}$, we consider an area of 200×200 meters. The range of the ROI starts from coordinates (0,0) to (200,200) with a resolution of 1 meter (m). 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, 20, and 30 PTs in RD_{total} . For analysis, first the total loss map w.r.t $RD_{\text{FT,G}}$ is calculated as shown in Fig. 5 using (2), where, d_0 is 1 m, $\gamma = 1.6$, transmitter, and receiver antenna gain is 0 dBi, and the same antenna height is assumed. Whereas, for the path-loss calculation, the carrier center frequency of 1.885 GHz is considered, and the correlated log-normal shadowing map with $\sigma_{\psi_{\text{dB}}} = 12$ dB w.r.t $RD_{\text{FT,G}}$ is calculated using the technique proposed in [4] and [5]. After acquiring the large-scale path-loss map, we add 20 dB small-scale margin on each location as an extra loss. This gives us the total loss map in the ROI w.r.t $RD_{\text{FT,G}}$ as shown in Fig. 5.

The received power at different locations within the ROI w.r.t to RD_{total} is calculated by subtracting the total loss map from the transmit (Tx) power. Whereas, the percentage of coverage is calculated by counting the number of locations on 200×200 meters grid where the received power is equal to or greater than $R_{x\text{sensitivity}} = -88$ dBm, divided by the total number of locations (40000) and finally multiplying the result by 100. The outage percentage is calculated by subtracting the coverage percentage from 100. We choose $R_{x\text{sensitivity}} = -88$ dBm because this is the upper limit of the required minimum in Table I. In Fig. 6 (a), coverage and outage percentages for different Tx -power levels of the $RD_{\text{FT,G}}$ are provided. It can be seen in Fig. 6 (a), that within the ROI, the required outage rate of less than 1% is not achieved using a single FT even when we used the maximum allowed Tx -power of 23 dBm according to [21]. Therefore, we further use our proposed technique to achieve

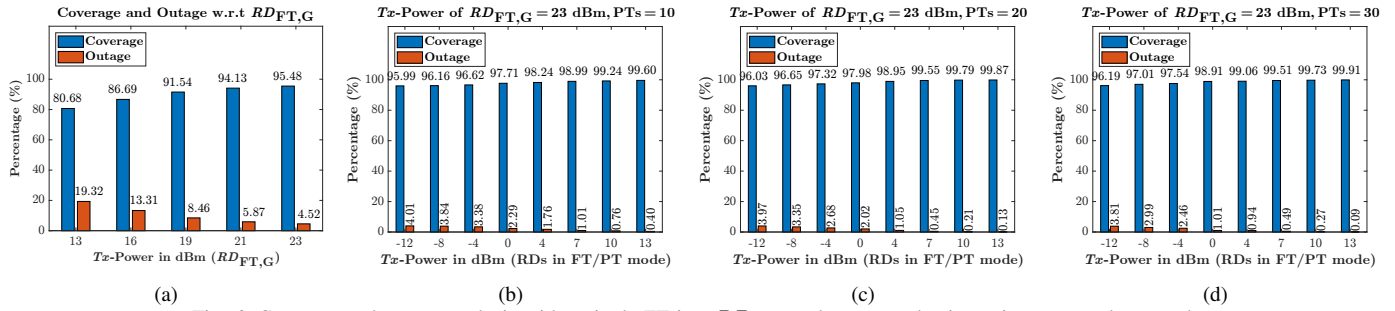


Fig. 6: Coverage and outage analysis with a single FT i.e., $RD_{FT,G}$ and outage reduction using proposed protocol.

the outage rate of less than 1%. First, to provide the maximum coverage w.r.t $RD_{FT,G}$, we use a T_x -power of the $RD_{FT,G}$ equal to 23 dBm and employ our proposed technique to achieve the required outage. For the mobile RDs (i.e., RD_{total}), power saving is considered. Hence, we analyze the effectiveness of our proposed technique using low T_x -power levels provided in [21]. The coverage and outage percentages for different T_x -power levels of mobile RDs with fixed T_x -power of $RD_{FT,G}$ are shown in Fig. 6 (b), (c), and (d) for different number of PTs in RD_{total} as mentioned above. In Fig. 6 (b), it can be seen that for all T_x -powers with values below 0 dBm, the improvement is almost negligible. DECT-2020 NR specifies these power levels for communication over very short distances. In our chosen scenario with 10 PTs, as shown in Fig. 6 (b), the T_x -power level of 7 dBm nearly achieves a 1% outage. However, at 10 dBm the required outage below 1% is achieved highlighting the effectiveness of the proposed technique. Furthermore, in Fig. 6 (c) and (d), we analyze the effect of increasing the number of PTs on the T_x -power. It can be seen that by increasing the number of PTs, low T_x -power levels can be achieved to obtain the desired outage rate. For 20 and 30 PTs, a gain of almost 3 dB and 6 dB is achieved, respectively, when comparing with the results obtained with 10 PTs. For acquiring the results in Fig. 6 (b), (c), and (d), supporting our proposed technique, an event-based simulator is used where each event corresponds to a change in the position of the RDs. For each event, the total loss map of the $RD_{FT,G}$ stays the same due to its static nature, and the received power for all the RDs at their respective position is checked. If an RD faces an outage w.r.t $RD_{FT,G}$, the total loss maps for all the remaining RDs that are not in outage are generated w.r.t their positions by following the procedure mentioned above. For the total loss map belonging to an RD, its correlated log-normal shadowing map is generated with a fixed correlation of 0.5 with the base map, i.e., shadowing map of $RD_{FT,G}$. According to [4] and [5], if all the RDs are in the same location and their antenna height is also the same, then the fixed correlation for the generation of shadowing maps could be preferred to simplify the simulation. Using their total loss maps and selected T_x -powers in Fig. 6 (b)-(d), the received power of the RD in an outage is calculated w.r.t to their location. If the minimum received power requirement is met, it is considered to be in coverage or else in an outage. The result is then accumulated for 60000 different events.

VI. CONCLUSION

In this paper, we propose a MAC protocol using MAC messages and Information Elements (IEs) to reduce the outage rate to less than 1% in a given Region of Interest (ROI) by utilizing periodic Network and Cluster Beacon Message transmissions. We demonstrate the effectiveness of our proposed technique using an event-based simulator. The simulation results show that the proposed protocol can achieve the desired outage rate while using minimal transmission power for the mobile RDs operating in FT/PT mode, thereby facilitating efficient routing. This protocol is beneficial for achieving ultra-reliable communication in a private network without initial infrastructure planning and works well with adaptive transmit powers and various received power requirements. For future work, we plan to use network coding techniques for multiplexing the control information in our proposed protocol to save time resources.

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