

Performance Evaluation of Preamble-free Packet Transmissions in DECT NR+

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Abstract—DECT NR+ is an approved 5G technology targeting the uRLLC and mMTC use cases. The standard specifies both random access and scheduled data transmissions, where each packet includes a preamble for detection and synchronization. However, in scheduled transmissions the start of subsequent packets can be anticipated by the receiver, making per-packet synchronization an unnecessary overhead. In this paper, preamble-free packet transmission in DECT NR+ is evaluated for all subcarrier spacings, drawing on periodic synchronization signal transmission as established in 5G NR and LTE. The approach is first assessed in simulation under realistic channel conditions incorporating large-scale fading and hardware impairments including carrier and sampling rate offsets assuming the maximum specified clock drift, showing that a packet error rate of 10^{-5} can be achieved under favorable operating conditions when a preamble is scheduled once per radio frame. Results are validated through over-the-air measurements using software defined radio front-ends in an office scenario, confirming no significant error rate degradation for intervals up to 100 ms with a receiver moving at walking speed.

Index Terms—DECT NR+, 5G, link-level simulation, synchronization and timing offset, over-the-air measurements

I. INTRODUCTION

Digital Enhanced Cordless Telecommunications (DECT) New Radio+ (NR+) is a novel radio interface technology and an approved International Mobile Telecommunications-2020 (IMT-2020) 5G technology focusing on the Massive Machine Type Communications (mMTC) and Ultra-Reliable Low-Latency Communications (uRLLC) use cases [1]. Maintained by ETSI, it specifies a non-cellular, self-organizing and mesh-capable ad hoc technology, in which the Portable Termination Point (PT), the ‘user equipment’, and the Fixed Termination Point (FT), the ‘base station’, form a network autonomously [2, Part 1]. It operates in the technology-exclusive DECT band at 1.9 GHz as well as in IMT bands below 6 GHz.

The Physical Layer (PHY) [2, Part 3] employs Cyclic Prefix Orthogonal Frequency-Division Multiplexing (CP-OFDM) with FDMA/TDMA in a TDD configuration, alongside turbo coding, HARQ and MIMO. A packet comprises the Synchronization Training Field (STF), which serves as the preamble for detection and synchronization; the data field, carrying the Physical Control Channel (PCC), the Physical Data Channel (PDC) with the user data and the Demodulation Reference Symbols (DRS) used for channel estimation; and a Guard Interval (GI). The PCC signals the parameters required to decode the PDC, such as the MCS. Packets are transmitted in a scheduled manner

or via random access, and the standard mandates a preamble in every packet. While this is essential for random access, it introduces overhead in scheduled transmission, particularly for short packet bursts serving multiple devices within a radio frame.

The main idea of this paper is to omit the preamble for subsequent packets during scheduled transmissions, leveraging the PT’s prior knowledge of slot timings acquired from an initial packet containing an STF. This builds on the well-established principle of synchronizing once every one or a few radio frames, as already employed in 5G NR and LTE. The admissible interval between preamble-bearing packets in DECT NR+ depends on the oscillator stability of the devices, which the specification limits to 15 ppm [2, Part 2], and quantifying this interval is the contribution of this work. While the proposed approach would also require Medium Access Control (MAC) and Harmonised Standard (ETSI EN 301 406-2) modifications, this paper focuses exclusively on the PHY.

II. RELATED WORK

Reducing preamble overhead has been studied extensively for OFDM systems carrying short payloads, where the training fields carry no user data and their relative cost grows as packets shrink [3]. Proposed approaches recover the required synchronization from other parts of the same packet: superimposing the training sequence onto the data field [3], replacing the guard interval with a pseudo-noise sequence for timing estimation [4], reducing the preamble to a single OFDM symbol for industrial uRLLC traffic [5], or eliminating the short training field entirely and deriving coarse timing and frequency estimates from the subsequent long training field [6]. In scheduled transmission, however, the receiver already knows when the next packet begins, so the synchronization state of a previously received packet can be reused and the preamble can be omitted altogether. The admissible interval between such synchronization points is then governed by the oscillator drift relative to the CP, which for DECT NR+ has not been quantified.

Within DECT NR+ itself, the concept is not without precedent. The study phase of DECT NR+ already considered “High Efficiency” packet formats intended for continuous transmission over several frames, which carry no synchronization field and therefore depend on a prior synchronization obtained from beacon bearers or other mechanisms [7]. The interval between synchronization points was not addressed,

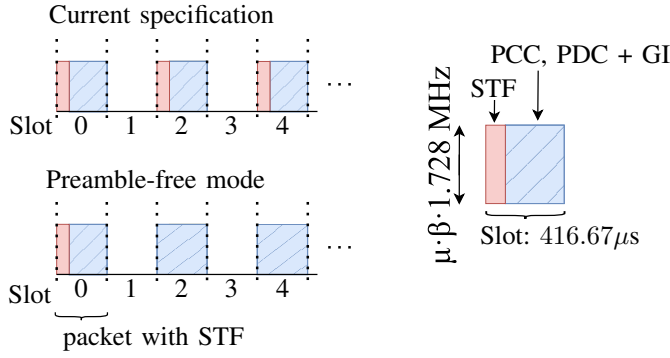


Fig. 1. Proposed preamble-free mode for scheduled transmissions. Only the first packet in slot 0 contains an STF.

and the accompanying link-level results assume perfect carrier, sampling and frame synchronization. These formats were not adopted in the released specification. The topic is currently being revisited in ETSI TC DECT, where an ongoing study on optimizing scheduled access examines the synchronization overhead of persistent allocations [8]. The argument there is that for persistent allocations from the same transmitter the received signal level changes only slowly between frames, so that the preamble may be shortened. This work specifically addresses how long the interval between synchronization points can be, accounting for the timing offset which accumulates between packets. The contribution is therefore not the concept of preamble-free transmission itself, but its quantification for DECT NR+. The proposed approach is evaluated through an impairment-aware link-level evaluation across all specified subcarrier spacings, with the goal of determining the maximum admissible synchronization interval as a function of oscillator stability, numerology and MCS, and its validation in over-the-air measurements.

III. PREAMBLE-FREE SCHEDULED TRANSMISSION MODE

In DECT NR+, the transmission configuration is based on a 10ms radio frame divided into 24 slots, each consisting of $\mu \cdot 2$ subslots of 5 OFDM symbols, which allows short packets to be scheduled at subslot level. The numerology is scaled by the subcarrier scaling factor $\mu \in \{1, 2, 4, 8\}$, giving a subcarrier spacing of $\mu \cdot 27$ kHz, and by the Fast Fourier Transform (FFT) scaling factor $\beta \in \{1, 2, 4, 8, 12, 16\}$, which scales the base FFT size of 64 and the base bandwidth of 1.728 MHz to $\beta \cdot 64$ and $\mu \cdot \beta \cdot 1.728$ MHz, respectively. The CP comprises $N_{CP} = \beta \cdot 8$ samples irrespective of μ . Consequently, its duration decreases as μ increases because the sampling rate scales with μ ; larger subcarrier spacings are therefore considerably more sensitive to residual timing offsets. In contrast to the schemes reviewed in Section II, which recover synchronization from within the same packet, the proposed mode omits the training field entirely and reuses the synchronization state of a previously received packet, so that the freed symbols can be fully utilized for user data, as represented in Fig. 1. This requires adjusting the definitions of the PCC and the DRS, which are currently specified to start

at the second OFDM symbol. Without the STF the PCC can start at the first symbol, freeing additional symbols for the PDC. Packet detection, timing and frequency offset estimation as well as Automatic Gain Control (AGC) adjustment [9] must then be obtained from the last received STF and reused for the subsequent preamble-free packets. Table I shows the resulting increase in PHY data rate as a function of PacketLengthType and μ , assuming that 6 packets are scheduled per radio frame of which only one contains a preamble. The gain is largest for very short packets (PacketLengthType 0), in which the preamble occupies a substantial portion of the packet.

The PCC may be omitted as well, since the parameters it conveys, such as the MCS, the packet length and the HARQ process, can be configured to remain constant throughout the current frame and therefore need to be signaled only once. This frees further resource elements but makes the whole burst dependent on a single control field. Only STF omission is evaluated in this work.

The preamble-free packets depend on the synchronization state acquired from the STF-bearing packet, so a distinction has to be made between two failure events. If the STF is detected and timing, frequency and gain estimates are obtained, but the payload of this STF-bearing packet is not successfully decoded, the synchronization state remains valid and the following preamble-free packets are decoded independently. This case is included in the reported results. Only a failure of packet detection and synchronization acquisition invalidates the state for the whole preamble-free burst. The error rate of the burst is therefore bounded by the detection and acquisition failure rate of the STF-bearing packet, not by its packet error rate. Since acquisition performance is governed by the correlation properties of the STF and the estimator variance, the robustness is instead improved by shortening the synchronization interval, or by falling back to conventional STF-bearing transmission whenever no valid synchronization state is available.

TABLE I
DATA RATE INCREASE IN % FOR THE PREAMBLE-FREE SCHEDULED TRANSMISSION MODE

PacketLengthType PacketLength	0	0	1	1
	1	2	1	2
μ	1	43 %	16 %	16 %
	2	83 %	24 %	9 %
	4	83 %	24 %	4 %
	8	167 %	28 %	2 %

PacketLengthType 0 and 1 denote a packet length given in subslots and in slots, respectively. The STF spans 14/9 OFDM symbols for $\mu=1$ and 2 symbols for $\mu=2, 4, 8$, the GI 4/9, 1, 1 and 2 symbols, respectively.

IV. EXTENDED LINK LEVEL SIMULATION

A. PHY and Hardware Simulation Model

The link-level simulation framework used for the 5G assessment in [1] was extended to support omitting the STF and reallocating the freed symbols to user data in the PDC, which required modifying the definitions of the PCC and DRS as discussed in Section III. To also take hardware effects into

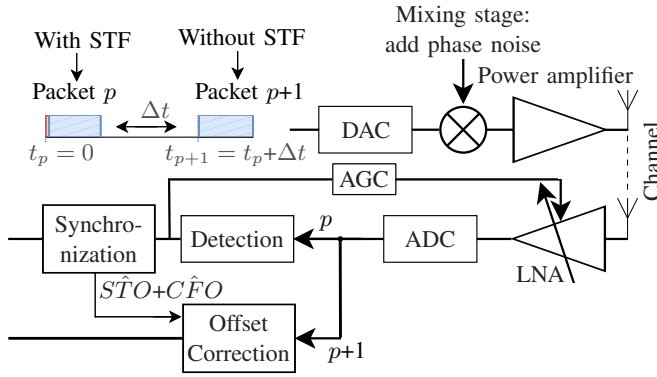


Fig. 2. Simulation model used, incorporating transmitter and receiver hardware effects.

account, transmitter and receiver models were incorporated, as shown in Fig. 2. The transmitter model includes a 14-bit Digital-to-analog Converter (DAC), an ideal power amplifier with 23 dBm output power, and phase noise generation, while the receiver model includes a multi-stage synchronization algorithm [10], an ideal Low Noise Amplifier (LNA) with a maximum gain of 60 dB, a 12-bit Analog-to-digital Converter (ADC) and a basic AGC. The AGC operates in two stages: an initial gain is used to detect the STF and measure the signal power, after which an appropriate gain is selected, applied to the detected packet and stored for reuse with subsequent packets without a preamble. A large-scale fading model [11] accounting for path loss, shadowing and amplitude variations due to receiver motion is incorporated, enabling assessment of AGC over- or under-amplification in the absence of an STF. For each simulation step, two packets are generated. The first is transmitted at the start of a radio frame and includes an STF, while the second is transmitted after a variable interval and omits it. During reception of the first packet, the Symbol Timing Offset (STO) and Carrier Frequency Offset (CFO) are estimated (denoted by $\hat{S}TO$ and $\hat{C}FO$) and reused for decoding the subsequent packet. The oscillator mismatch between transmitter and receiver, characterized by the stability ($\Delta f/f_0$) of both ends, is incorporated into the channel model.

B. Sampling Rate Offset and Timing Offset

A CP-OFDM signal x with N_{DFT} subcarriers, cyclic prefix length N_{CP} , and data symbols $a_{l,k}$ is assumed, following the standard baseband model in [12], where k refers to the subcarriers and l to the symbols.

The wireless channel is modeled as a frequency-selective linear time-varying system, represented by a tapped-delay line (TDL) model $h(\tau, t)$ [12]. Due to the finite stability of the device oscillators ($\Delta f/f_0$), the sampling instants of transmitter and receiver drift relative to each other, causing a timing offset Δt corresponding to $\pm \Delta n$ samples. As the associated resampling of the channel impulse response can be tracked by the channel estimator and is negligible [12], the receiver is modeled as operating at the transmitter sampling rate. The sampling mismatch also introduces a CFO $\Delta f_c = \delta f \cdot f_c$,

which is a function of the relative frequency deviation δf and manifests as a time-varying phase rotation of the received signal y . In (1) w denotes Additive White Gaussian Noise (AWGN).

$$y(nT) = e^{j2\pi\Delta f_c nT} \sum_i h_i(nT) x(nT - \tau_i - \Delta t) + w(nT) \quad (1)$$

The timing offset misaligns the FFT window at the receiver [13], so that after CP removal and demodulation the data symbols read as in (2), depicted for $\Delta n > 0$, in which Δn samples of the previous symbol $l-1$ leak into the current symbol l .

$$r_{l,k} = \frac{N_{DFT} - \Delta n}{N_{DFT}} a_{l,k} H_{l,k} e^{-j2\pi \frac{k}{N_{DFT}} \Delta n} + \text{ICI} + \text{ISI} + w_{l,k} \quad (2)$$

With $H_{l,k}$ the channel transfer function and $w_{l,k}$ the AWGN of subcarrier k , the timing offset Δn introduces a linear phase rotation across the subcarriers and causes both Inter-carrier Interference (ICI) and Inter-symbol Interference (ISI), whose power increases with Δn [12]. As shown in (3), the accumulated offset follows from the sampling rate f_s , the relative frequency deviation δf and the elapsed time since the last synchronization t_{total} , where δf is modeled as a uniform random variable $U(-\Delta f/f_0|_{\text{max}}, +\Delta f/f_0|_{\text{max}})$ with the combined oscillator stability $\Delta f/f_0|_{\text{max}} = \Delta f/f_0|_{TX} + \Delta f/f_0|_{RX}$.

$$\Delta n = f_s \cdot \delta f \cdot t_{\text{total}} \quad (3)$$

Requiring the drift to remain within the CP, i.e., $|\Delta n| \leq N_{CP}$, yields the critical interval $t_{\text{crit}} = N_{CP} / (f_s \cdot \Delta f/f_0|_{\text{max}})$, which is independent of β since the CP scales with β as well. For a combined stability of 30 ppm it amounts to 154, 77, 38 and 19 ms for $\mu = 1, 2, 4$ and 8, respectively. As this neglects the ICI and ISI already introduced by smaller offsets as well as the delay spread and the residual CFO, it represents an upper limit, whereas Section V quantifies the intervals that are actually achievable.

For STF-bearing packets, synchronization proceeds in four stages [10]: (i) coarse timing from the autocorrelation of the L repeated preamble patterns [14], [15]; (ii) fractional CFO estimation and correction; (iii) integer CFO estimation and correction; (iv) fine timing from the cross-correlation with the known preamble template. For preamble-free packets, none of these stages are available. Instead, the timing and CFO estimates of the last STF-bearing packet are applied, and only the pilot-based residual STO (4) and residual CFO (5) estimations are performed. The residual STO manifests as a linear phase slope across the subcarriers and is estimated by correlating adjacent pilot subcarriers k_s and k_{s+1} separated by Δk [16], as depicted in (4).

$$\hat{\Delta n}_{\text{res}} = \frac{N_{DFT}}{2\pi \Delta k} \angle \sum_{l,s} (r_{l,k_s} a_{l,k_s}^*) (r_{l,k_{s+1}} a_{l,k_{s+1}}^*)^* \quad (4)$$

The residual CFO manifests as a phase rotation between consecutive OFDM symbols and is estimated from the phase change of the pilot-weighted sum $W_l = \sum_k a_{l,k} r_{l,k}^*$ between pilot-bearing symbols l and $l+1$ with spacing ΔN_{symb} [17], as shown in (5).

$$\hat{\epsilon}_{\text{res}}(l) = \frac{\angle(W_{l+1} W_l^*)}{2\pi \Delta N_{\text{symb}}} \quad (5)$$

V. RESULTS

A performance evaluation is conducted by determining the Packet Error Rate (PER) for different DECT NR+ numerologies, MCS levels, packet intervals, Doppler frequencies and delay spreads, targeting the IMT-2020 reliability requirement of 10^{-5} throughout. Each point on the horizontal axis corresponds to one propagation scenario, in which the delay spread is increased jointly with the receiver velocity, so that the axis represents a monotonically more demanding operating condition. The delay spread, varied between 10 ns and 1000 ns, sets the RMS delay spread of the TDL power delay profile. The Doppler frequency is not applied as an independent parameter but follows from the receiver velocity v according to $f_D = v \cdot f_c / c$ using $f_c = 1.9$ GHz and $v \in \{0.1, 0.3, 1, 3, 10\}$ m/s. The Signal-to-Noise Ratio (SNR) is chosen per numerology such that the reference STF-bearing packet meets the reliability target. According to (3) the timing offset scales with the sampling rate and thus with μ and β ; since a larger μ additionally shortens the CP, this paper focuses on the different subcarrier spacings at a constant FFT size of 64 ($\beta = 1$).

The simulation is configured to match the Ettus Universal Software Radio Peripheral (USRP) X410 [18]. Per packet, a random deviation δf is drawn for the worst-case specified oscillator stability of 15 ppm and for an improved stability of 2 ppm, both per device. The timing offset follows from (3) and its fractional component is applied via a fractional delay filter [19], while the matching CFO is introduced according to (1) assuming a carrier frequency of 1.9 GHz. For the first packet, STO and CFO estimation is based on the STF and the DRS, whereas for the subsequent packets the stored CFO is reused in conjunction with the pilot-based residual estimation. A Wiener filter matched to the channel is utilized as the equalizer for both packet types.

A. MCS 1

The preamble-free packets are first evaluated for MCS 1 (QPSK, coding rate 1/2), transmitting packets of one-slot duration over a Rician fading channel in the ‘InH - Office’ [11] scenario, with a stationary transmitter and a receiver moving at a constant velocity corresponding to the Doppler frequency. Fig. 3 shows the smoothed PER contour lines of 10^{-4} and 10^{-5} at clock stabilities of 15 ppm and 2 ppm per device (30 ppm and 4 ppm combined, as labeled in the legends), alongside the reference PER of the packet containing the preamble. A PER of 10^{-5} is achieved within one radio frame (10 ms) for the numerologies of $\mu \in \{1, 2, 4\}$. For $\mu=1$ the interval extends to 100 ms at a clock stability of 2 ppm. For the largest subcarrier spacing of $\mu=8$, a PER of 10^{-5} is only achieved at 2 ppm

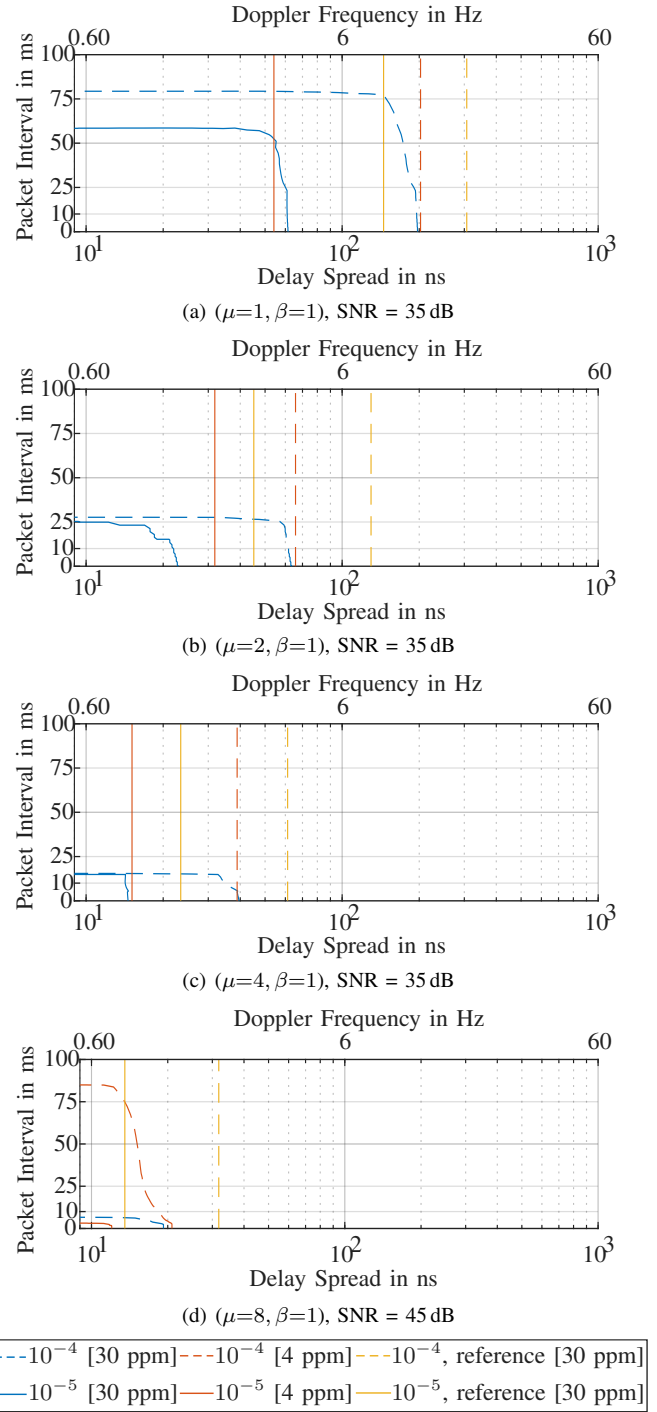


Fig. 3. PER for different subcarrier spacings μ as a function of packet interval, delay spread and Doppler frequency in the ‘InH - Office’ scenario for MCS 1. Delay spread and Doppler frequency are jointly swept. The legend values denote the combined TX and RX oscillator stability.

clock stability, requiring synchronization approximately every 4 ms.

B. MCS 6

In Fig. 4 the PER of MCS 6, corresponding to 64-QAM and a coding rate of 3/4, is evaluated using two receive antennas

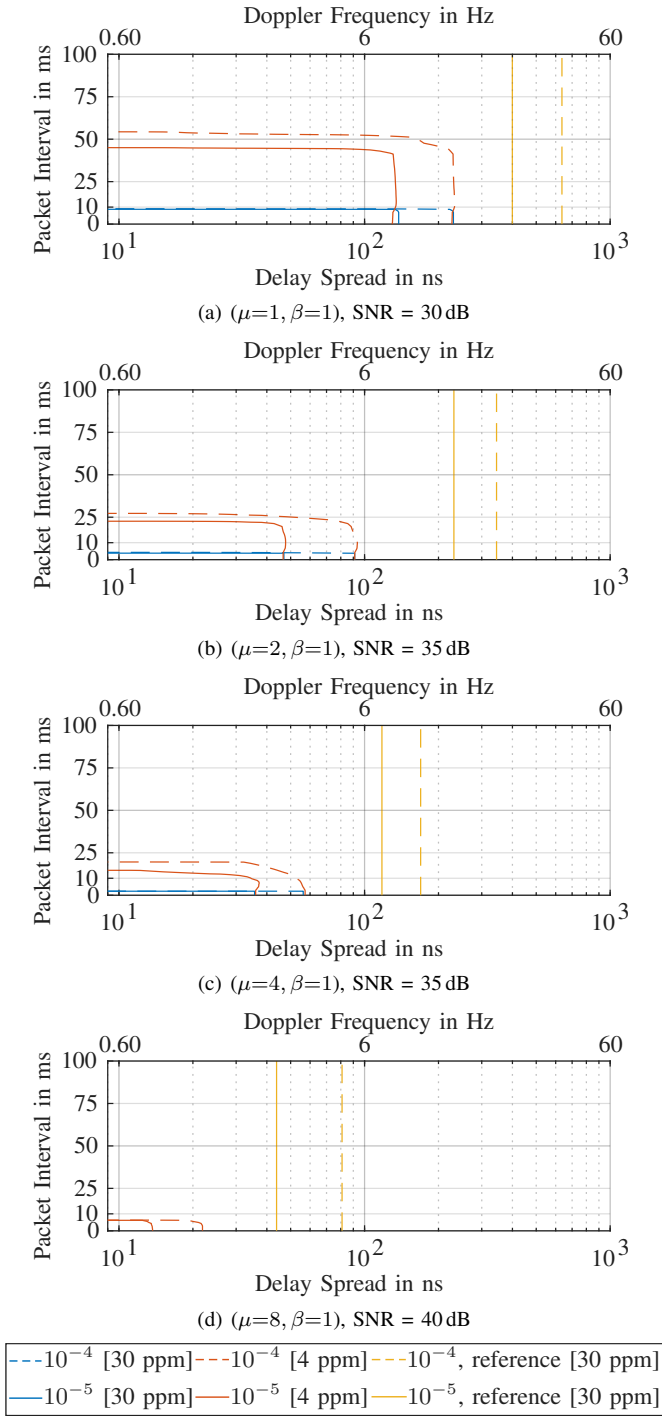


Fig. 4. PER for different subcarrier spacings μ as a function of packet interval, delay spread and Doppler frequency in the ‘InH - Office’ scenario for MCS 6 and two receive antennas. Delay spread and Doppler frequency are jointly swept. The legend values denote the combined TX and RX oscillator stability.

and maximum ratio combining. For a clock stability of 2 ppm, a PER of 10^{-5} is achieved with synchronization intervals of up to one radio frame (10 ms) for the numerologies of $\mu \in \{1, 2, 4\}$. In contrast, at a clock stability of 15 ppm, synchronization once per radio frame only achieves the same target PER at $\mu=1$. For

the largest subcarrier spacing $\mu=8$, a PER of 10^{-5} is achieved at 2 ppm clock stability with synchronization intervals up to 5 ms.

VI. MEASUREMENTS

The preamble-free mode is also evaluated over the air, using the link-level simulation in conjunction with Ettus USRP Software Defined Radios (SDRs) as the radio front-ends. A USRP X410 was used as a stationary transmitter, while a B210 connected to a laptop was used as a mobile receiver. The transmitter was configured to an output power of approximately 23 dBm at 1.9 GHz. Waveforms of 10 radio frames (100 ms) were generated, containing a packet every 5 ms, of which only the first includes an STF. The numerologies $\mu \in \{1, 2, 4, 8\}$ with $\beta=1$ were evaluated using MCS 4, while the receiver was moved at walking speed through an office environment. Preamble detection and AGC were implemented as an embedded Python block in GNU Radio. Every measurement was conducted over approximately 15 minutes. The results in Fig. 5 show the PER as a function of the pilot-based Signal-to-Interference-plus-Noise Ratio (SINR) with curves representing four ranges of the packet interval.

The curve corresponding to the STF-bearing packet is used as a reference. The PER does not differ between the four interval ranges. Even at $\mu=8$, the longest interval range, with intervals of up to 100 ms, shows no noticeable increase. However, these results only represent favorable channel conditions, with walking speed movement and good oscillator stability of 2.5 ppm and 2 ppm for the X410 [18] and B210 [20], respectively. Under these conditions, the results indicate that using the STF only once per radio frame (10 ms) is more than sufficient.

VII. CONCLUSION AND OUTLOOK

Evaluating the preamble-free scheduled transmission mode in DECT NR+, which reduces PHY overhead by omitting the STF of subsequent packets, shows a considerable data rate increase, especially for short packets. Since packets without a preamble cannot be synchronized, a timing offset accumulates depending on the sampling rate and the packet interval, and this offset must remain within the CP length to avoid ICI and ISI. Simulations in Rician fading channels assuming a worst-case oscillator stability of 15 ppm show that an error rate of 10^{-5} is achievable with synchronization once per frame for the subcarrier spacings of $\mu=1, 2, 4$, whereas $\mu=8$ requires synchronization every 4 ms even with a clock stability of 2 ppm per device, highlighting the increased sensitivity of this numerology to timing errors. Furthermore, operating a higher MCS (64-QAM) at larger subcarrier spacings requires a clock stability better than the specified 15 ppm per device to reliably achieve a PER of 10^{-5} , indicating more stringent synchronization requirements for higher-order modulation schemes. Over-the-air measurements using USRP front-ends confirm these findings, showing no significant PER degradation with increasing packet intervals up to 100 ms. The main drawback of the mode is its dependence on a single synchronization acquisition per period, whose failure

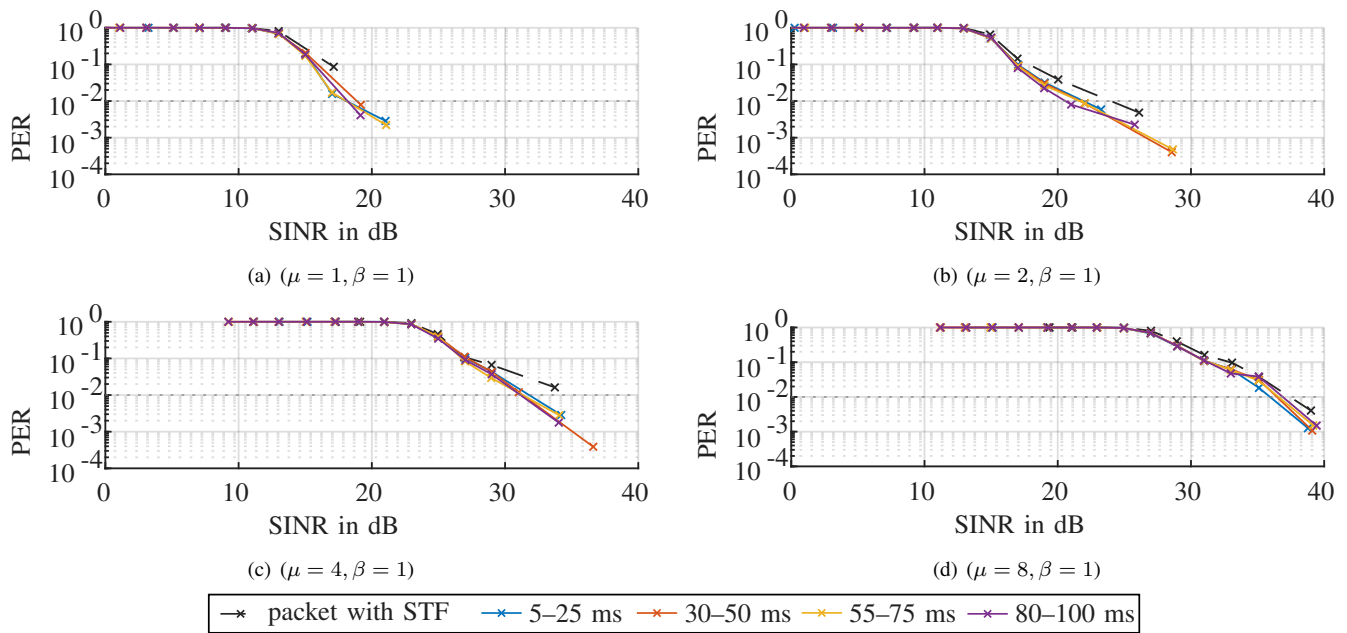


Fig. 5. Measured PER as a function of the pilot-based SINR for MCS 4 with a receiver moving at walking speed. Curves denote ranges of the elapsed time since the last STF-bearing packet.

prevents the decoding of the entire burst. These results are intended as input to the ongoing discussion in ETSI TC DECT on the synchronization overhead of scheduled access.

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