

Impact of SSB periodicity on EMF and user mobility in 5G systems

KEZE LI

23577611@student.gla.ac.uk

University of Glasgow

Olaoluwa Popoola

University of Glasgow

Muhammad Ali Imran

University of Glasgow

Yusuf Sambo

University of Glasgow

Research Article

Keywords:

Posted Date: October 27th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11196279/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Impact of SSB periodicity on EMF and user mobility in 5G systems

Keze Li*, Olaoluwa Popoola*, Muhammad Ali Imran* and Yusuf Sambo*

*James Watt School of Engineering, University of Glasgow

23577611@student.gla.ac.uk

{olaoluwa.popoola,muhammad.imran,yusuf.sambo}@glasgow.ac.uk

Abstract—Synchronization signal block (SSB) periodicity influences both the availability of mobility measurements and the SSB contribution to electromagnetic field (EMF) power density. This paper evaluates this trade-off in a two cell 5G NR mobility scenario using six SSB periodicities from 5 to 160 ms. SS-RSRP measurements determine A3 based handover timing, while independently configured CSI-RS measurements characterize connected link quality and effective data delivery. Matched channel realizations and a common evaluation window provide a consistent basis for comparison. Relative to the 5 ms baseline, periodicities of 20 and 40 ms reduce mean SSB power density by 75% and 87.5%, respectively, with mean additional handover delays of 13.69 and 19.01 ms and mean effective data reductions of 1.31% and 1.99%. At 160 ms, the power-density reduction reaches 96.875%, but the additional handover delay increases to 252.84 ms and effective data delivery decreases by 25.95%. These results identify 20–40 ms as a favorable operating range for the evaluated scenario and demonstrate the importance of selecting SSB periodicity jointly with mobility and data delivery requirements.

Index Terms—5G NR, synchronization signal block, SSB periodicity, handover, event A3, CSI-RS, SINR, CQI, mobility robustness, green communications, EMF power density.

I. INTRODUCTION

Fifth generation New Radio (5G NR) employs configurable synchronization and reference signal resources to support cell discovery and mobility management [1]–[3]. Among these resources, the synchronization signal block (SSB) supports cell search, synchronization, and beam discovery, and enables synchronization signal reference signal received power (SS-RSRP) measurements [4], [5]. During connected mode mobility, these measurements provide a basis for comparing serving and neighboring cells and reporting conditions that support handover decisions [6], [7]. The SSB transmission periodicity consequently influences the availability of measurement opportunities and the timeliness of SSB based handover procedures. At the same time, repeated SSB transmissions contribute to electromagnetic field (EMF) power density at the receiver location [8]. For fixed burst content and transmit power per burst, increasing the SSB periodicity reduces this time averaged contribution, but also makes mobility measurement opportunities less frequent and can delay handover. SSB periodicity therefore couples mobility performance with the SSB contribution to EMF power density, motivating a joint assessment of these two effects.

The trade off between handover performance and EMF power density extends beyond the timing of the handover trigger.

With longer SSB periods, a neighboring cell may become preferable between successive measurement occasions, delaying the observation of the condition used to initiate a measurement report [6], [7], [9]. The UE may consequently remain connected to a weaker serving cell for longer, potentially degrading link quality and reducing data delivery during the mobility transition [10], [11]. These performance penalties can arise even without an outage or radio link failure (RLF) [11]. Assessing this trade off therefore requires evaluating both mobility timing and its consequences for communication performance. In this study, SSB derived SS-RSRP measurements determine event A3 timing under the configured time to trigger (TTT) rule, while independently configured channel state information reference signals (CSI-RS) provide the measurements used to estimate the connected link signal to interference plus noise ratio (SINR) and derive the channel quality indicator (CQI) and effective data rate. The CSI-RS measurement interval remains fixed across SSB configurations, allowing changes in connected link performance to be evaluated under a consistent measurement schedule. These performance metrics are assessed jointly with the SSB contribution to EMF power density to quantify the trade off between less frequent SSB transmission and the associated handover and data delivery penalties.

The relationship between SSB periodicity, handover performance, and EMF power density connects several areas of research, including NR beam based mobility [9], [12], [13], mobility robustness optimization [10], [14], and SSB related EMF assessment [8]. These research areas provide the foundations for examining mobility procedures and reference signal exposure, but an assessment of SSB periodicity must also establish how changes in measurement availability translate into communication performance penalties alongside reductions in SSB related EMF power density. In particular, handover timing alone does not capture the link quality degradation and reduced data delivery that may result from prolonged attachment to the serving cell. This paper therefore jointly evaluates SSB driven event A3 timing, connected link quality obtained from independently configured CSI-RS measurements, effective data delivery, and SSB related EMF power density. Matched channel realizations and a common evaluation interval provide a consistent basis for comparing these outcomes across SSB periodicities.

The study considers a controlled two cell mobility scenario with 300 matched channel realizations, each evaluated at SSB periodicities of 5, 10, 20, 40, 80, and 160 ms. For

each realization, a common high resolution SS-RSRP trace is sampled at the measurement occasions associated with each SSB configuration, allowing mobility timing to be compared under the same underlying channel conditions. A 3dB event A3 offset is applied with the study specific rule 40 ms TTT, whereas the 80 and 160 ms configurations combine less frequent observations with a longer TTT. Their performance differences therefore reflect both effects. Handover preparation and execution delays are set to zero to isolate measurement and TTT contributions to the modeled handover timing. Connected link performance and SSB related EMF power density are evaluated over a common 600 ms interval anchored to the 5 ms baseline handover time for each realization. The data metric represents an effective physical layer data opportunity, while the EMF metric includes only the modeled SSB contribution.

The main contributions of this paper are as follows:

- The effects of SSB periodicity on handover performance and SSB related EMF power density are evaluated jointly, quantifying the trade off between less frequent SSB transmission and delayed handover.
- The consequences of delayed handover are quantified in terms of connected link SINR, CQI, effective data delivery, and the time spent connected to a weaker serving cell. These metrics reveal performance degradation that may not be captured by outage and RLF indicators alone.
- Six SSB periodicities are compared using 300 matched channel realizations and a common evaluation interval for each realization. Independent CSI-RS measurements and paired statistical analysis provide a consistent basis for assessing performance differences and their variability.

The remainder of this paper is organized as follow: Section II reviews related work on NR mobility, reference signal configuration, and EMF assessment. Section III presents the system model and simulation configuration. Section IV describes the methodology for evaluating handover timing, connected-link quality, effective data delivery, and the SSB contribution to EMF power density, together with the statistical analysis procedure. Section V presents and discusses the results. Section VI concludes the paper and outlines directions for future research.

II. RELATED WORK

A. SSB Based Mobility Measurements

An SSB comprises the primary synchronization signal (PSS), secondary synchronization signal (SSS), and physical broadcast channel (PBCH), together with its demodulation reference signals [4]. The RRC configuration supports serving cell SSB periodicities of 5, 10, 20, 40, 80, and 160 ms [6]. For mobility measurements, SS-RSRP is defined using the average received power over resource elements carrying the SSS, with additional reference signals permitted under the conditions specified in TS 38.215 [5]. These measurements can support event triggered reporting according to the configured RRC measurement procedure. In particular, event A3 compares the neighboring cell measurement with that of the serving SpCell, accounting for measurement object offsets, cell specific offsets, the A3 offset, and hysteresis. Reporting is initiated when the entering

condition satisfies the configured TTT requirements [6]. Event A3 therefore provides a measurement reporting mechanism that supports handover decisions, rather than directly specifying handover execution.

Paper [9] review measurement techniques for beam and mobility management in NR, emphasizing the importance of measurement accuracy, responsiveness, and robustness. These considerations motivate examining how the availability of SSB measurements affects the detection of changing cell conditions. Under the periodic observation model adopted in this study, an A3 condition that becomes satisfied immediately after a measurement occasion cannot be observed until a subsequent occasion. If the condition persists and every scheduled observation is available, this waiting time can approach one SSB period before the TTT begins. This sampling delay is distinct from the configured TTT and depends on the timing of the underlying channel change relative to the observation schedule. The present study examines how these timing effects influence handover performance and effective data delivery, alongside the change in SSB related EMF power density.

B. CSI-RS, SINR, CQI, and Data Rate

CSI-RS resources support channel measurement and beam management, while the configured CSI reporting procedure specifies the resources used to characterize the desired channel and interference [15]. TS 38.215 defines CSI-SINR using the average received power on resource elements carrying CSI reference signals relative to the average noise and interference power [5]. These measurements provide information about radio conditions that can support link adaptation. In NR, CQI reporting identifies a modulation and coding combination that satisfies a specified transport block error probability under the configured reference assumptions [15]. A fixed mapping from SINR to CQI therefore represents a modeling abstraction. The present study adopts a common SINR threshold table and spectral efficiency mapping across all SSB configurations to estimate effective data delivery. This approach supports consistent comparisons of the consequences of handover timing, but does not represent application throughput because scheduling, retransmissions, and protocol overhead are not modeled.

C. Mobility Robustness

Mobility robustness optimization aims to maintain reliable connectivity during user movement through appropriate configuration of handover control parameters. Paper [10] review optimization techniques for parameters such as TTT and handover margin, highlighting their importance for connection quality in heterogeneous networks. In mobility procedures that rely on SSB measurements, the observation schedule introduces an additional factor: a suitable reporting condition must first be observed before the configured persistence requirement can be evaluated. The present study therefore examines the duration for which the UE remains connected to the serving cell after the target cell develops a sustained SS-RSRP advantage. This duration is evaluated together with connected SINR, CQI, and effective data delivery to characterize the

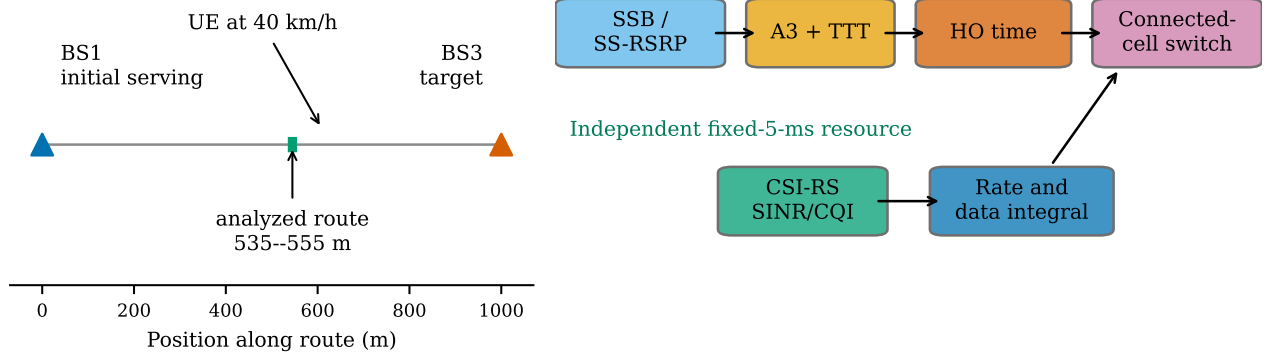


Fig. 1. Two-cell simulation geometry and measurement processing framework. SS-RSRP measurements determine the modeled handover time, while separately configured CSI-RS measurements provide the cell-specific SINR used to evaluate connected-link performance and effective data delivery.

consequences of delayed handover. Outage and RLF proxies provide complementary indicators of more severe degradation. These proxies are defined for the present experiment and are distinguished from standardized failure detection procedures. The combined evaluation allows performance losses to be identified even when no failure is recorded by the selected proxies.

D. Green Signaling and EMF Assessment

Green radio research examines methods for reducing the energy required to operate wireless networks [16], [17]. EMF assessment addresses the electromagnetic field produced by radio transmissions and its relevance to human exposure. The International Commission on Non Ionizing Radiation Protection (ICNIRP) provides guidelines for limiting human exposure to electromagnetic fields from 100 kHz to 300 GHz, covering the frequencies used by 5G systems [18]. These guidelines establish the exposure protection context within which contributions from individual signals can be examined. For SSB transmissions, our previous study [8] investigate the associated EMF power density at different distances and observation angles. Under fixed burst content and transmit power per burst, less frequent SSB transmission reduces its contribution to power density averaged over time. However, evaluating this contribution alone does not establish compliance with ICNIRP guidelines or quantify total network exposure. The present study therefore examines the SSB contribution to EMF power density alongside handover performance, quantifying the communication consequences of reduced SSB transmission frequency.

The EMF metric considered in this study is the modeled contribution of SSB transmissions from the two base stations to power density at the UE location. It excludes data channels, CSI-RS, uplink transmissions, and sources outside the simulated scenario. With burst content and transmit power per burst held constant, this contribution is scaled inversely with SSB periodicity. The resulting reduction therefore describes a change in the modeled SSB contribution, rather than an equivalent reduction in total EMF exposure. An assessment against ICNIRP guidelines would additionally require consideration of

all relevant exposure contributions and the applicable conditions for averaging over time and space [18]. Likewise, a reduction in SSB power density does not directly quantify a reduction in base station electrical energy consumption. These distinctions define the scope of the present comparison between handover performance and EMF power density.

III. SYSTEM MODEL AND SIMULATION CONFIGURATION

The evaluation considers a two-cell downlink scenario in which a moving UE transitions from an initial serving cell to a neighboring target cell. The simulation combines SSB-based mobility measurements, separately generated CSI-RS measurements, and an SSB power-density calculation. The same underlying measurement traces are reused across SSB configurations within each channel realization.

A. Network Geometry and UE Mobility

The serving base station, BS_A , and the target base station, BS_B , are separated by 1000 m along a straight route. Their horizontal coordinates are 0 and 1000 m, respectively. The UE moves toward BS_B at a constant speed of 40 km/h and is initially connected to BS_A . The analyzed route extends from 535 to 555 m and covers the region used to evaluate the serving-to-target transition.

The propagation calculations use a transmit-array height of 15 m and a receive-array height of 1.5 m. The route is sampled at spatial intervals of 0.055 m (corresponding to 40 km/h).

The simulation operates at a carrier frequency of 3.5 GHz with a nominal bandwidth of 20 MHz. The resource grid contains 51 resource blocks with a subcarrier spacing of 30 kHz. Fig. 1 illustrates the two-cell geometry and the measurement processing framework. SS-RSRP measurements determine handover timing, while separately configured CSI-RS measurements support the evaluation of connected-link quality and effective data delivery.

B. Propagation and Antenna Configuration

The propagation links from the two base stations to the UE are modeled separately, with a direct propagation path included

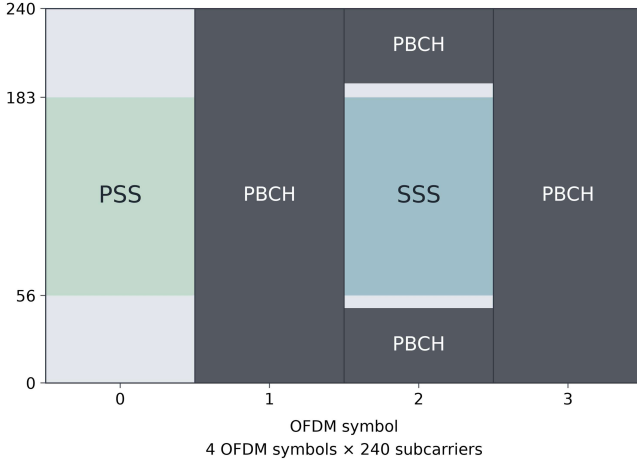


Fig. 2. Structure of a Synchronization Signal Block (SSB) in 5G NR

in each link. The channel configuration includes the carrier frequency, waveform sampling rate, transmit and receive arrays, and their positions.

At each sampled UE position, the waveforms are processed through the corresponding channel objects to obtain the received signals. UE motion is represented through spatial positions, and elapsed time is assigned using the specified speed. The implementation therefore evaluates the route through a sequence of spatial channel calculations.

Each base station employs an 8×8 uniform rectangular array, while the UE employs a 2×2 uniform rectangular array. The inter-element spacing is one-half wavelength. The transmit array uses isotropic elements and a separable Chebyshev taper with a 30 dB sidelobe attenuation parameter. Beamforming weights are obtained from steering vectors for the configured directions.

The transmit-power parameter is set to 30 dBm for both base stations. Waveform amplitudes are scaled according to the resource-grid and antenna normalization used by the signal generators. The SSB and CSI-RS processing chains retain their respective waveform normalization throughout the comparison.

C. SSB and CSI-RS Configuration

Each SSB comprises the Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS), Physical Broadcast Channel (PBCH), and the associated PBCH demodulation reference signals. The SS/PBCH block occupies 240 contiguous subcarriers in the frequency domain and four OFDM symbols in the time domain [4]. In this work, we quantify the time-averaged EMF power density resulting from SSB transmissions based on physical-layer parameters, as derived from our prior measurement-based study [19].

For mobility evaluation, the strongest configured beams of BS_A and BS_B are chosen for SS-RSRP, which provide the serving cell and target cell measurements used in the handover analysis.

The CSI-RS waveforms are generated separately from the SSB waveforms. Each cell uses a non-zero-power CSI-RS resource with a configured periodicity of ten slots and a

slot offset of zero. At 30 kHz subcarrier spacing, ten slots correspond to 5 ms [4], [6].

The CSI-RS resource mapping follows row 1 of Table 7.4.1.5.3-1 in 3GPP TS 38.211, with one CSI-RS antenna port and a density of three resource elements per resource block per configured occasion [4]. In this study, the allocation spans 51 resource blocks. The two base stations use different scrambling identities to generate their CSI-RS sequences, following 3GPP [4].

Both cells occupy the same configured time-frequency resources, and the received CSI-RS power from the other cell is included in the interference term. The transmit directions correspond to the selected SSB beams, while the UE applies receive beamforming in a fixed direction.

Within each realization, the resulting cell-specific CSI-RS traces are reused for all SSB periodicities. The CSI-RS resource configuration therefore remains fixed while the connected-cell selection changes according to the handover time.

D. Handover and Data-Rate Configuration

The evaluated SSB periodicities are 5, 10, 20, 40, 80, and 160 ms. An A3 offset of 3 dB is applied, with no additional cell-specific offsets or hysteresis.

In the implementation used to generate the reported results, the required persistence duration is $\max(40 \text{ ms}, P)$. A candidate start is accepted only when the A3 condition is satisfied at every sample of the common reference trace spanning that duration. An unsuccessful candidate is discarded, and subsequent candidate measurement occasions are examined. The modeled handover time is the accepted candidate start plus the required duration.

Preparation, execution, and handover interruption are set to zero. Accordingly, the connected-cell selector changes instantaneously at the modeled handover time. This configuration isolates the effects of the adopted measurement and persistence procedure on subsequent link-quality and data-delivery metrics.

The connected CSI-RS SINR is converted to CQI using the threshold mapping in Table I. The associated spectral efficiencies determine the effective rate according to Section III. CQI 0 is assigned when SINR is below the lowest threshold and corresponds to zero effective rate. For all other values, the selected CQI is the highest index whose threshold is satisfied. A resource-utilization factor of one is applied to every configuration [20].

The SINR thresholds constitute the adopted link-quality abstraction and are applied uniformly across all realizations and SSB configurations.

E. Simulation Procedure and Statistical Configuration

The reported evaluation uses 300 matched realizations, corresponding to random seeds 51–351. Each included seed has both an SS-RSRP trace and a separately generated CSI-RS trace. All six SSB configurations are evaluated for each seed.

For each realization, the 5 ms SSB configuration provides the reference handover time. The common evaluation window extends from 100 ms before this time to 500 ms afterward. Its boundaries remain fixed across SSB configurations, while each

TABLE I
SINR-TO-CQI MAPPING AND SPECTRAL EFFICIENCY

CQI	SINR lower threshold (dB)	Spectral efficiency (bit/s/Hz)
0	Below -6.7	0
1	-6.7	0.1523
2	-4.7	0.2344
3	-2.3	0.3770
4	0.2	0.6016
5	2.4	0.8770
6	4.3	1.1758
7	5.9	1.4766
8	8.1	1.9141
9	10.3	2.4063
10	11.7	2.7305
11	14.1	3.3223
12	16.3	3.9023
13	18.7	4.5234
14	21.0	5.1152
15	22.7	5.5547

configuration selects the serving or target measurement trace according to its own handover time.

The simulation first determines the handover times and then evaluates connected-link quality, effective data delivery, and delayed serving. The delayed-serving calculation uses a common target-dominance reference identified before the baseline handover. The SSB power-density trace is evaluated over the same reference window.

Outage is identified using a connected CSI-RS SINR threshold of -6 dB. The RLF proxy requires consecutive below-threshold samples representing at least 100 ms. Delayed-serving thresholds of 100 and 200 ms provide additional descriptive indicators of prolonged attachment.

Means and standard deviations summarize the metrics across realizations. Differences and percentage changes relative to the baseline are calculated within each realization before aggregation. The reported confidence intervals for mean paired differences use 10,000 bootstrap resamples and the 2.5th and 97.5th percentiles of the resulting bootstrap distributions.

IV. METHODOLOGY

This section presents the methodology for evaluating the effects of SSB periodicity on handover performance and the SSB contribution to EMF power density. SS-RSRP measurements determine the modeled handover timing, whereas separately configured CSI-RS measurements characterize the connected link and support the estimation of effective data delivery. Each channel realization is evaluated under all considered SSB periodicities, using a common evaluation interval to ensure a consistent comparison. The following subsections define the handover model, communication performance metrics, and SSB power-density assessment.

A. SS-RSRP and SSB Power Density

SS-RSRP measurements provide the basis for both handover evaluation and the calculation of the SSB contribution to EMF power density. Let $p_{b,i}(t)$ denote the simulated SS-RSRP of beam i from base station $b \in \{A, B\}$ at the UE location, expressed in watts. These measurements capture the effects of

propagation, beam direction, and UE position on the received reference-signal power.

Following the approach in [8], the received SSB power averaged over one transmission period is estimated as

$$\bar{P}_{\text{SSB}}(t; P) = \sum_{b \in \{A, B\}} \sum_{i=1}^{L_b} p_{b,i}(t) \frac{N_{\text{RE}} t_{\text{sym}}}{P}, \quad (1)$$

where P is the SSB periodicity, L_b is the number of transmitted SSB beams at base station b , N_{RE} is the equivalent number of occupied resource elements per SSB, and t_{sym} is the OFDM symbol duration. The quantities t_{sym} and P are expressed in the same time units. The resource factor accounts for the modeled SSB content, while division by P accounts for its repetition interval.

The corresponding incident power density is obtained using the effective aperture of the receiving antenna:

$$S_P(t) = \frac{4\pi}{\lambda^2 G_r} \bar{P}_{\text{SSB}}(t; P), \quad (2)$$

where λ is the carrier wavelength and G_r is the receive-antenna gain in linear units. This conversion adopts the equivalent plane-wave approximation and yields power density in W/m².

For unchanged burst content and transmit power per burst, the modeled SSB power density is inversely proportional to the transmission periodicity. Both base stations contribute to this quantity, irrespective of the cell serving the UE. The resulting metric represents the SSB contribution at the UE location and excludes other transmitted signals. Its average over the common evaluation window is defined subsequently.

B. SSB-Based Handover Timing

For handover evaluation, the SS-RSRP of each cell is represented by its strongest measured SSB beam and expressed in dBm. In contrast, the power-density calculation in Section III-A includes the contributions from all modeled SSB beams. Let P denote the SSB periodicity, and let $M_A(t)$ and $M_B(t)$ denote the SS-RSRP measurements of the serving cell BS_A and target cell BS_B , respectively, expressed in dBm. With additional cell-specific offsets and hysteresis set to zero, the modeled event-A3 entering condition is

$$M_B(t) - M_A(t) > H, \quad (3)$$

where H is the configured A3 offset in dB. This condition requires the target-cell measurement to exceed the serving-cell measurement by the specified margin [6].

The condition is evaluated at the available SSB measurement occasions. A qualifying observation initiates a candidate interval. If a subsequent observation fails to satisfy A3 condition before confirmation, the candidate interval is discarded. Confirmation occurs at the first measurement occasion at which the elapsed time since the candidate start is at least the configured time-to-trigger, T_{TT} , provided that all observations within the interval satisfy the A3 condition. This procedure evaluates persistence at the available measurement occasions and does not establish whether the condition holds between observations.

For regularly spaced measurement occasions, the elapsed time from the start of a successful candidate interval to confirmation is

$$T_{\text{obs}}(P) = P \left\lceil \frac{T_{\text{TTT}}}{P} \right\rceil, \quad (4)$$

where $\lceil \cdot \rceil$ denotes the ceiling operator. The configured TTT remains fixed across SSB periodicities. However, confirmation may occur after its expiry because a further measurement is required. Consequently, $T_{\text{obs}}(P)$ represents the elapsed confirmation duration, rather than a change in the configured TTT.

Let $t_{A3}(P)$ denote the start of the first candidate interval that reaches confirmation. The modeled handover time is

$$t_{\text{HO}}(P) = t_{A3}(P) + T_{\text{obs}}(P) + T_{\text{prep}} + T_{\text{exec}}, \quad (5)$$

where T_{prep} and T_{exec} represent handover preparation and execution delays, respectively. Both terms are set to zero in this study to isolate the contributions of measurement availability and confirmation. Successful execution is assumed following confirmation. Accordingly, $t_{\text{HO}}(P)$ represents a modeled connection change rather than a complete implementation of the handover signaling procedure.

Relative to the reference SSB periodicity P_0 , the handover timing difference is

$$\Delta t_{\text{HO}}(P) = t_{\text{HO}}(P) - t_{\text{HO}}(P_0). \quad (6)$$

A positive value indicates a later handover than in the reference configuration. This difference reflects both the start time of the successful candidate interval and the duration required for its confirmation. If no candidate reaches confirmation during the simulated interval, the UE remains connected to the serving cell.

C. Position Mapping

The UE moves along a straight trajectory at a constant speed v . Consequently, differences in handover timing translate directly into differences in handover position. Relative to the reference SSB periodicity P_0 , the handover displacement is

$$\Delta x_{\text{HO}}(P) = v [t_{\text{HO}}(P) - t_{\text{HO}}(P_0)] = v \Delta t_{\text{HO}}(P), \quad (7)$$

where $\Delta x_{\text{HO}}(P)$ denotes the displacement along the UE trajectory relative to the reference configuration. Time differences are expressed in seconds and speed in meters per second, yielding displacement in meters. A positive value indicates that the UE travels farther before handover. This metric expresses the spatial consequence of the relative handover delay and is distinct from the distance traveled while remaining connected to a weaker serving cell.

D. Independent CSI-RS Measurement

CSI-RS measurements characterize the link quality of the serving and target cells using a measurement schedule configured separately from the SSB schedule. The CSI-RS periodicity is configured as ten slots, corresponding to 5 ms at a subcarrier spacing of 30 kHz [4], [6]. This configuration

remains unchanged across all SSB periodicities, providing a consistent basis for evaluating the effects of different handover times.

For cell $b \in \{A, B\}$, the modeled CSI-RS SINR is

$$\gamma_b(t) = \frac{P_{b,\text{CSI}}(t)}{I_{b,\text{CSI}}(t) + P_N}, \quad (8)$$

where $P_{b,\text{CSI}}(t)$ is the desired received CSI-RS power, $I_{b,\text{CSI}}(t)$ is the corresponding interference power, and P_N is the receiver noise power. All power terms are expressed in linear units over a consistent measurement bandwidth.

The connected-link SINR depends on the cell serving the UE at each instant. For SSB periodicity P , it is expressed as

$$\gamma_P(t) = \begin{cases} \gamma_A(t), & t < t_{\text{HO}}(P), \\ \gamma_B(t), & t \geq t_{\text{HO}}(P), \end{cases} \quad (9)$$

where $\gamma_A(t)$ and $\gamma_B(t)$ denote the serving- and target-cell SINR traces, respectively. The connection changes instantaneously at the modeled handover time, consistent with the omission of handover interruption. If no handover occurs, the serving-cell trace remains selected throughout the evaluation interval.

Within each channel realization, the same cell-specific CSI-RS traces are used for all SSB periodicities. Consequently, SSB periodicity affects the connected-link SINR through the handover time, while the underlying link-quality measurements remain unchanged. These connected-link measurements subsequently determine the CQI and effective data rate.

E. Common Evaluation Window

A common evaluation window is defined for each channel realization to compare all SSB configurations over the same portion of the UE trajectory. The window is anchored to the handover time of the reference SSB periodicity P_0 :

$$\mathcal{W} = [t_{\text{HO}}(P_0) - T_{\text{pre}}, t_{\text{HO}}(P_0) + T_{\text{post}}], \quad (10)$$

where T_{pre} and T_{post} denote the evaluation durations before and after the reference handover, respectively. The total duration is $T_W = T_{\text{pre}} + T_{\text{post}}$. The reference periodicity and window durations are specified in Section IV.

Within each realization, the window boundaries remain unchanged across SSB configurations. Consequently, all configurations are evaluated at the same UE positions and under the same underlying channel conditions. The connected cell nevertheless follows the handover time of each configuration: serving-cell measurements are selected before handover, and target-cell measurements are selected afterward. If handover occurs after the window or does not occur during the simulation, the serving-cell measurements are used throughout the window. If handover occurs before the window, the target-cell measurements are used throughout.

This common-window approach ensures that differences in connected-link performance reflect the effects of handover timing rather than changes in the evaluation interval.

F. Effective Data Delivery

The connected-link SINR is mapped to CQI using a common threshold table across all SSB configurations. At measurement time t_k , the CQI and corresponding effective data rate are

$$q_{P,k} = Q(10 \log_{10} \gamma_P(t_k)), \quad R_{P,k} = B\eta(q_{P,k}), \quad (11)$$

where $Q(\cdot)$ denotes the adopted SINR-to-CQI mapping, B is the bandwidth in Hz, and $\eta(q_{P,k})$ is the spectral efficiency associated with the selected CQI, expressed in bit/s/Hz. The same mapping and bandwidth are used for every SSB periodicity.

Effective data delivery is calculated by accumulating the data rate over the common evaluation window:

$$D_P = \sum_{k=1}^{N_W} R_{P,k} \Delta t_k, \quad (12)$$

where N_W is the number of samples representing the window and Δt_k is the duration represented by sample k within that window. With rate expressed in bit/s and duration in seconds, D_P is expressed in bits. Each configuration uses its own connected-cell rate while retaining the same evaluation interval.

An ideal reference is obtained by selecting the higher of the serving- and target-cell rates at each sample and applying the same accumulation procedure. This reference assumes instantaneous cell selection without switching costs and provides an upper bound within the adopted rate model. The ratio D_P/D_{ideal} measures data delivery relative to this reference.

The percentage change relative to the reference SSB periodicity P_0 is

$$\delta_D(P) = \frac{D_P - D_{P_0}}{D_{P_0}} \times 100\%, \quad (13)$$

where a negative value indicates reduced effective data delivery. Relative metrics are calculated for each realization with a positive reference denominator before aggregation.

The same SINR-to-CQI mapping is applied to all SSB configurations, providing a consistent basis for comparing the effects of handover timing on estimated data delivery. The estimate is derived from the connected-link quality and available bandwidth, without explicitly modeling scheduling, retransmissions, or protocol overhead.

G. Delayed Serving and Reliability

Delayed serving describes the interval during which the UE remains connected to the serving cell after the target cell develops a sustained SS-RSRP advantage. Let t_{cross} denote the onset of the final target-dominance interval preceding the reference handover at periodicity P_0 . This reference time is held fixed across SSB configurations within each channel realization. The delayed serving duration and corresponding travel distance are

$$T_{\text{late}}(P) = t_{\text{HO}}(P) - t_{\text{cross}}, \quad L_{\text{late}}(P) = vT_{\text{late}}(P), \quad (14)$$

where v is the UE speed and the duration is expressed in seconds when calculating distance in meters. The crossing corresponds to the target SS-RSRP exceeding the serving SS-RSRP, without requiring the additional A3 offset. These metrics

quantify the duration and distance associated with delayed attachment relative to a common target-dominance reference.

The proportions of realizations with delayed serving durations exceeding 100 ms and 200 ms are reported as descriptive indicators of prolonged attachment. These thresholds characterize the evaluated scenario and do not represent standardized handover-failure classifications. Realizations without a qualifying reference crossing or a completed handover are excluded from the corresponding duration statistics.

Reliability is additionally evaluated using the connected-link SINR within the common evaluation window. The outage fraction is

$$p_{\text{out}}(P) = \frac{N_{\text{out}}(P)}{N_W}, \quad (15)$$

where $N_{\text{out}}(P)$ is the number of connected CSI-RS samples below the selected SINR threshold and N_W is the total number of samples in the window. For equally spaced samples, this fraction approximates the proportion of time spent below the threshold.

An RLF proxy identifies realizations containing consecutive below-threshold samples representing a duration of at least 100 ms. The SINR threshold is set to -6 dB, and the occurrence probability is calculated as the fraction of valid realizations satisfying this criterion. This indicator provides a measure of sustained link degradation without implementing the complete NR radio-link failure procedure. Together, the delayed serving and reliability metrics characterize performance degradation that may arise before a failure is recorded.

H. Mean SSB Power Density

Using the SSB power-density trace derived in Section III-A, the mean contribution over the common evaluation window is

$$\bar{S}_P = \frac{1}{T_W} \int_{\mathcal{W}} S_P(t) dt, \quad (16)$$

where $\mathcal{W}$ is the evaluation window and T_W is its duration. Both base stations contribute throughout the window, irrespective of the cell serving the UE. Consequently, the connection change does not alter which SSB contributions are included in the power-density calculation.

Using the same evaluation window for communication and power-density metrics provides a consistent basis for assessing the trade-off between handover performance and reduced SSB transmission activity.

I. Paired Statistical Analysis

All SSB configurations are evaluated using the same set of channel realizations. For each performance metric, the difference between a given configuration and the reference periodicity P_0 is calculated within each realization before aggregation. This paired comparison accounts for variation between realizations and provides a consistent basis for assessing the effects of SSB periodicity.

Results are summarized using the mean and standard deviation across valid realizations. Confidence intervals for the mean paired differences are estimated using bootstrap

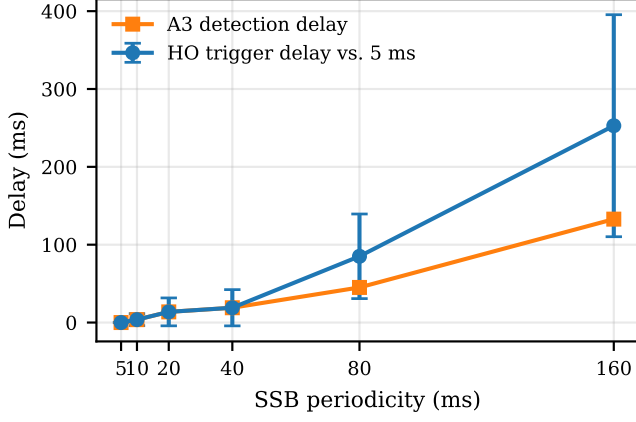


Fig. 3. Mean additional handover delay and A3 observation delay relative to the 5 ms SSB configuration. Error bars indicate standard deviations across channel realizations.

TABLE II
EXPERIMENT CONFIGURATION

Parameter	Value
Carrier frequency	3.5 GHz
Bandwidth	20 MHz
Subcarrier spacing	30 kHz
BS _A / BS _B position	0 m / 1000 m
Analyzed UE route	535 to 555 m
UE speed	40 km/h (11.111 m/s)
Base station antenna array	8 × 8
UE antenna array	2 × 2
SSB beams per base station	8
SSB periodicities	5, 10, 20, 40, 80, 160 ms
Matched channel realizations	300
A3 offset	3 dB
Additional offsets and hysteresis	0 dB
Configured TTT	Fixed 40 ms
Trigger evaluation	At SSB measurement occasions
CSI-RS measurement interval	Fixed 5 ms
Preparation and execution delays	0 ms
Handover interruption	0 ms
Common evaluation window	100 ms before to 500 ms after $t_{HO}^{(5)}$
Outage threshold	SINR below −6 dB
RLF proxy duration	At least 100 ms of consecutive outage

resampling. Each bootstrap sample resamples channel realizations with replacement while retaining the corresponding SSB configurations together, thereby preserving the paired structure of the comparison. The 2.5th and 97.5th percentiles of the bootstrap distribution define the 95% confidence interval.

Percentage changes are calculated within each realization before averaging. Realizations with undefined metrics or nonpositive reference denominators are excluded from the corresponding comparisons. The number of valid realizations is reported for each metric, and the number of bootstrap resamples is specified in Section IV.

Fig. 1 summarizes the geometry and signal roles. The mobility branch ends at a configuration-specific handover time. The lower branch produces cell-specific CSI-RS SINR and CQI before connection selection. SSB samples never substitute for CSI-RS SINR.

TABLE III
HANDOVER TIMING RELATIVE TO THE 5 MS SSB CONFIGURATION

SSB period (ms)	Configured TTT (ms)	Mean A3 delay (ms)	Mean HO delay (ms)
5	40	0.00	0.00
10	40	3.73	3.73
20	40	13.69	13.69
40	40	19.01	19.01
80	40	45.08	85.08
160	40	132.84	252.84

V. RESULTS AND EVALUATION

A. Handover Timing

Fig. 3 and Table III summarize the mean paired difference in handover time relative to the 5 ms SSB configuration. The mean additional delay is 3.73, 13.69, and 19.01 ms at SSB periodicities of 10, 20, and 40 ms, respectively. At 80 and 160 ms, the corresponding delays increase to 85.08 and 252.84 ms. The timing penalty therefore increases with SSB periodicity, with substantially larger increases at the two longest periods.

The timing differences reflect both the observation of a successful A3 condition and its subsequent confirmation. With a configured TTT of 40 ms, the elapsed confirmation duration is 40 ms for SSB periodicities of 5, 10, 20, and 40 ms. Consequently, the additional handover delay equals the A3 observation delay for these configurations. At 80 and 160 ms, confirmation occurs at the next available SSB measurement occasion, subject to the A3 persistence requirement. The elapsed confirmation durations therefore become 80 and 160 ms, respectively. These durations introduce an additional 40 and 120 ms relative to the baseline, accounting for the separation between the A3 and handover delay values in Table III.

The left panel of Fig. 4 shows the distribution of paired handover-time differences across channel realizations. The greater spread at 80 and 160 ms indicates that longer SSB periodicities increase both the mean timing penalty and its variability. This variability reflects the interaction between the evolution of the relative SS-RSRP and the measurement occasions at which a successful A3 condition can be observed and confirmed.

The 95% bootstrap confidence intervals for the mean additional handover delay are [16.47, 21.87] ms at 40 ms, [78.82, 91.57] ms at 80 ms, and [236.08, 269.97] ms at 160 ms. Each interval lies entirely above zero, indicating a positive mean timing penalty relative to the baseline within the evaluated scenario. These confidence intervals quantify uncertainty in the mean paired difference; the distributions in Fig. 4 describe variability across individual realizations.

With preparation and execution delays set to zero, the reported timing differences isolate the effects of measurement availability and A3 confirmation on the modeled handover time.

B. Link Quality and Data Transmission

1) *Connected SINR and SS-RSRP*: Fig. 5 presents the mean connected CSI-RS SINR and SS-RSRP over the com-

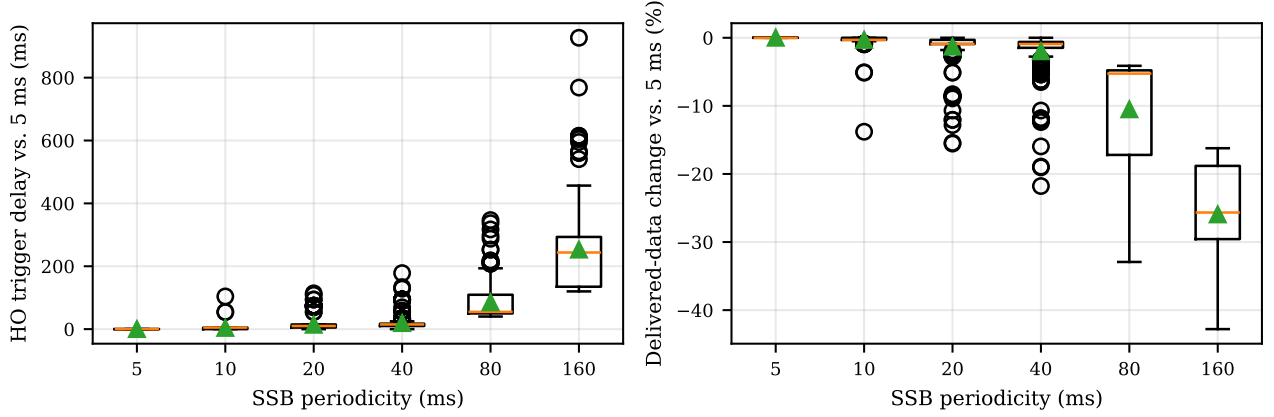


Fig. 4. Distributions of paired differences relative to the 5 ms SSB configuration: handover timing (left) and effective data delivery (right). Boxes indicate interquartile ranges, and markers indicate means.

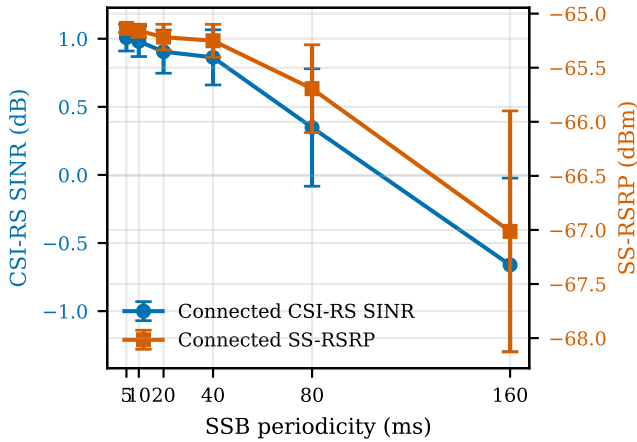


Fig. 5. Mean connected CSI-RS SINR and SS-RSRP over the common 600 ms evaluation window for each SSB periodicity.

mon 600 ms evaluation window. Table IV summarizes the corresponding link-quality and reliability metrics. The mean connected SINR decreases from 1.008 dB at an SSB periodicity of 5 ms to 0.981, 0.905, and 0.863 dB at 10, 20, and 40 ms, respectively. Larger reductions occur at 80 and 160 ms, where the mean SINR reaches 0.348 and -0.661 dB. The mean connected SS-RSRP exhibits a similar trend, decreasing from -65.137 dBm at 5 ms to -67.013 dBm at 160 ms.

These differences arise from the handover time. Within each realization, the cell-specific CSI-RS traces and evaluation window remain unchanged across SSB periodicities. A later handover therefore extends the interval over which the connected-link metrics are obtained from BS_A before switching to BS_B . The lower mean connected SINR at longer periodicities indicates that this extended attachment reduces the link quality experienced during the evaluated transition.

The corresponding CQI results follow the same trend. The mean connected CQI decreases from 3.961 at 5 ms to 3.905 at 40 ms, followed by larger reductions to 3.662 and 3.233 at 80 and 160 ms, respectively. The minimum connected SINR within

each realization, averaged across realizations, also decreases from -2.267 dB at 5 ms to -2.717 dB at 160 ms. Thus, the effect of delayed handover is evident in both the average link quality and the minimum SINR within the evaluation window.

2) *Outage and RLF Proxy*: Table IV also reports the mean fraction of the evaluation window for which the connected SINR is below -6 dB. This fraction is 0.0057% for SSB periodicities from 5 to 40 ms and increases to 0.0086% at 80 and 160 ms. No realization exhibits a consecutive below-threshold interval lasting at least 100 ms. The empirical occurrence probability of the adopted RLF proxy is therefore zero for all six configurations.

The absence of an RLF proxy event does not imply that link quality is unaffected by SSB periodicity. The reductions in connected SINR and CQI show that communication performance can deteriorate without reaching the specified outage-duration criterion. These continuous metrics therefore complement the binary RLF proxy by capturing degradation during the handover transition.

3) *Effective Data Delivery*: Fig. 6 and Table V present the effective data delivery over the common evaluation window. The ideal cell-selection reference provides a mean of 7.756 Mbit, compared with 7.258 Mbit for the 5 ms SSB configuration. The corresponding mean data efficiency relative to ideal selection is 93.57%. At SSB periodicities of 10, 20, and 40 ms, the mean effective data delivery decreases to 7.235, 7.163, and 7.114 Mbit, respectively. The mean percentage reductions, calculated within each realization relative to the 5 ms baseline, are 0.32%, 1.31%, and 1.99%.

At 80 and 160 ms, the mean effective data delivery falls to 6.495 and 5.374 Mbit, corresponding to mean reductions of 10.51% and 25.95% relative to the baseline. The mean efficiency relative to ideal cell selection decreases to 83.74% and 69.29%, respectively. These larger losses are consistent with the reductions in connected SINR and CQI: delayed handover prolongs the use of the serving-cell rate during intervals in which the target cell offers a higher effective rate.

The right panel of Fig. 4 illustrates the variation in data-delivery changes across realizations. As reported in Table V, the

TABLE IV
CONNECTED LINK QUALITY AND RELIABILITY OVER THE COMMON EVALUATION WINDOW

SSB period (ms)	Mean SINR (dB)	Mean SS-RSRP (dBm)	Mean minimum SINR (dB)	Mean CQI	Mean outage fraction (%)	RLF proxy probability
5	1.008	-65.137	-2.267	3.961	0.0057	0
10	0.981	-65.158	-2.286	3.952	0.0057	0
20	0.905	-65.217	-2.339	3.925	0.0057	0
40	0.863	-65.251	-2.363	3.905	0.0057	0
80	0.348	-65.694	-2.604	3.662	0.0086	0
160	-0.661	-67.013	-2.717	3.233	0.0086	0

TABLE V
EFFECTIVE DATA DELIVERY OVER THE COMMON EVALUATION WINDOW

SSB period (ms)	Mean data (Mbit)	SD (Mbit)	Ideal data (Mbit)	Mean efficiency (%)	Mean change (%)	5th percentile (%)	95th percentile (%)
5	7.258	0.101	7.756	93.57	0.00	0.00	0.00
10	7.235	0.125	7.756	93.27	-0.32	-0.89	0.00
20	7.163	0.196	7.756	92.34	-1.31	-8.56	0.00
40	7.114	0.261	7.756	91.71	-1.99	-12.05	0.00
80	6.495	0.539	7.756	83.74	-10.51	-24.29	-4.18
160	5.374	0.579	7.756	69.29	-25.95	-41.94	-18.17

SD denotes the standard deviation across realizations. Efficiency is measured relative to ideal cell selection. The mean change and percentile values describe the percentage change in effective data delivery relative to the 5 ms configuration.

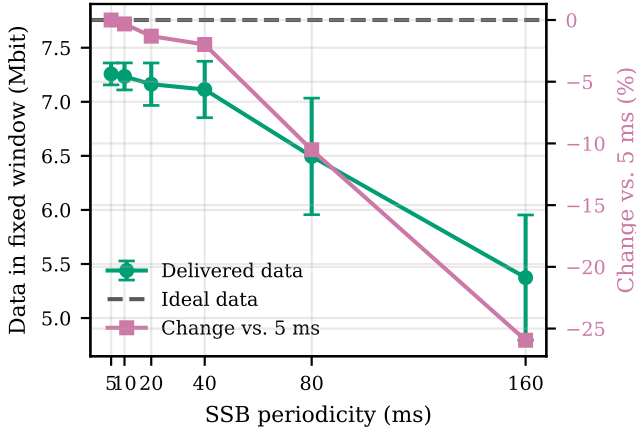


Fig. 6. Effective data delivery over the common 600 ms evaluation window and percentage change relative to the 5 ms SSB configuration. Error bars indicate standard deviations across channel realizations.

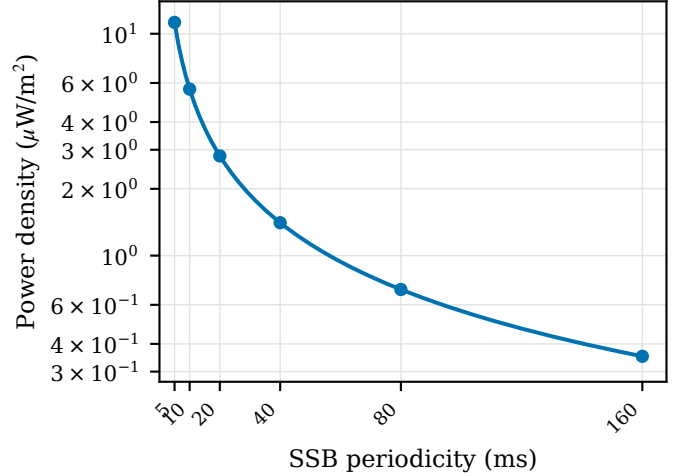


Fig. 7. Mean SSB contribution to EMF power density over the common evaluation window as a function of SSB periodicity. Both axes use logarithmic scales.

fifth percentile of the percentage change is -12.05% at 40 ms, -24.29% at 80 ms, and -41.94% at 160 ms. At 160 ms, even the 95th percentile remains negative at -18.17% , indicating that reduced data delivery occurs across most realizations.

Because the evaluation window is common to all configurations within each realization, these differences represent changes in accumulated effective data over the same observation interval. The results show that longer SSB periodicities can substantially reduce effective data delivery even when no event satisfies the adopted RLF proxy criterion.

C. SSB Power Density During Handover

Fig. 7 and Table VI present the mean SSB contribution to EMF power density over the common evaluation window. The mean density decreases from $11.254 \mu\text{W}/\text{m}^2$ at an SSB

TABLE VI
MEAN SSB POWER DENSITY ACROSS TRANSMISSION PERIODICITIES

SSB period (ms)	Mean density ($\mu\text{W}/\text{m}^2$)
5	11.254
10	5.627
20	2.813
40	1.407
80	0.703
160	0.352

periodicity of 5 ms to 5.627 , 2.813 , and $1.407 \mu\text{W}/\text{m}^2$ at 10, 20, and 40 ms, respectively. At 80 and 160 ms, the corresponding values are 0.703 and $0.352 \mu\text{W}/\text{m}^2$.

The observed decrease follows the inverse dependence on

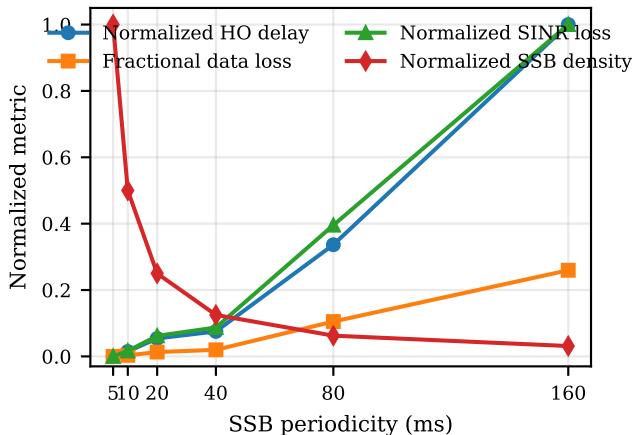


Fig. 8. Joint comparison of SSB power density and communication penalties. SSB density and data loss are expressed relative to the 5 ms baseline. The additional handover delay and SINR loss are normalized by their respective values at 160 ms.

TABLE VII
JOINT OUTCOMES RELATIVE TO THE 5 MS SSB CONFIGURATION

SSB period (ms)	SSB density (% baseline)	HO delay (ms)	SINR change (dB)	Data change (%)
5	100.0	0.00	0.000	0.00
10	50.0	3.73	-0.027	-0.32
20	25.0	13.69	-0.103	-1.31
40	12.5	19.01	-0.145	-1.99
80	6.25	85.08	-0.660	-10.51
160	3.125	252.84	-1.669	-25.95

HO delay denotes the mean additional handover delay relative to the baseline. SINR change denotes the difference in mean connected SINR. Data change is the mean percentage change calculated within each realization.

SSB periodicity in the adopted power-density model. With fixed burst content and transmit power, increasing the periodicity reduces the number of SSB transmissions per unit time. Relative to the 5 ms configuration, the reductions are 75% at 20 ms, 87.5% at 40 ms, and 96.875% at 160 ms.

Both base stations contribute to the power density calculation throughout the evaluation window, irrespective of the connected cell. The reduction therefore results from less frequent SSB transmission, rather than from the serving-cell change at handover.

D. Joint Green Mobility Trade-Off

Fig. 8 and Table VII summarize the relationship between the reduction in SSB power density and the associated communication penalties. The mean SSB power density decreases inversely with periodicity, whereas the increases in handover delay, SINR loss, and effective data loss are relatively small up to 40 ms and become more pronounced at 80 and 160 ms.

At an SSB periodicity of 20 ms, the mean SSB power density is reduced by 75% relative to the baseline, while the mean additional handover delay is 13.69 ms and the mean data reduction is 1.31%. Increasing the periodicity to 40 ms raises the power-density reduction to 87.5%, with an additional handover delay of 19.01 ms and a mean data reduction of

1.99%. The corresponding decreases in mean connected SINR are 0.103 and 0.145 dB, respectively. These configurations therefore provide substantial reductions in the modeled SSB contribution with comparatively small communication penalties.

Further increases in periodicity produce larger communication penalties. Moving from 40 to 80 ms halves the remaining SSB power density, from 12.5% to 6.25% of the baseline, but increases the mean additional handover delay from 19.01 to 85.08 ms. The mean data reduction rises from 1.99% to 10.51%. At 160 ms, the SSB density falls to 3.125% of the baseline, while the mean additional handover delay reaches 252.84 ms, the mean connected SINR decreases by 1.669 dB, and the mean data reduction reaches 25.95%.

The evaluated results consequently identify 20–40 ms as a favorable operating range for this scenario. This range combines a substantial reduction in SSB power density with limited changes in handover timing and effective data delivery compared with the longer periodicities.

VI. CONCLUSION

This paper evaluated the effects of SSB periodicity on handover timing, connected-link quality, effective data delivery, and the SSB contribution to EMF power density. Under the evaluated scenario, periodicities of 20–40 ms provide a favorable trade-off: relative to the 5 ms baseline, mean SSB power density decreases by 75–87.5%, while mean additional handover delay remains below 20 ms and mean effective data loss remains below 2%. Increasing the periodicity to 80 or 160 ms further reduces SSB power density but introduces substantially larger communication penalties. These findings support selecting SSB periodicity jointly with mobility and data-delivery requirements. Future work will examine whether this trade-off persists across different mobility conditions and deployments with more detailed handover and data-transmission models.

ACKNOWLEDGMENT

This work was supported in part by the UK Engineering and Physical Sciences Research Council (EPSRC) through the CHEDDAR project under Grant EP/X040518/1 and the CHEDDAR TMF Uplift project under Grant EP/Y037421/1.

During the preparation of this manuscript, OpenAI’s ChatGPT/Codex was used to assist with drafting, language editing, and manuscript organization. The authors reviewed and edited the assisted content and take full responsibility for the final manuscript.

DATA AVAILABILITY

The simulation data supporting the findings of this study were generated using MATLAB. The supporting simulation outputs, configuration parameters, and MATLAB and Python scripts used for simulation, analysis, and figure generation are available from the corresponding author on reasonable request.

DECLARATIONS

Clinical trial registration: Not applicable. This study is based entirely on numerical simulations and does not involve a clinical trial.

Ethics, Consent to Participate, and Consent to Publish declarations: Not applicable.

REFERENCES

- [1] S. Parkvall, E. Dahlman, A. Furuskär, and M. Frenne, "NR: The New 5G Radio Access Technology," *IEEE Communications Standards Magazine*, vol. 1, no. 4, pp. 24–30, 2017.
- [2] E. Dahlman, S. Parkvall, and J. Sköld, *5G NR: The Next Generation Wireless Access Technology*, 2nd ed. Oxford, U.K.: Academic Press, 2020.
- [3] 3GPP, "NR; NR and NG-RAN Overall Description; Stage 2," 3rd Generation Partnership Project, Tech. Rep. TS 38.300, 2024, release 18.
- [4] —, "NR; Physical Channels and Modulation," 3rd Generation Partnership Project, Tech. Rep. TS 38.211, Oct. 2024, version 18.4.0, Release 18. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/138200_138299/138211/18.04.00_60/ts_138211v180400p.pdf
- [5] —, "NR; Physical Layer Measurements," 3rd Generation Partnership Project, Tech. Rep. TS 38.215, May 2024, version 18.2.0, Release 18. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/138200_138299/138215/18.02.00_60/ts_138215v180200p.pdf
- [6] —, "NR; Radio Resource Control (RRC); Protocol Specification," 3rd Generation Partnership Project, Tech. Rep. TS 38.331, Jan. 2025, version 18.4.0, Release 18. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/138300_138399/138331/18.04.00_60/ts_138331v180400p.pdf
- [7] —, "NR; Requirements for Support of Radio Resource Management," 3rd Generation Partnership Project, Tech. Rep. TS 38.133, 2024, release 18.
- [8] K. Li, M. S. Mollé, O. Popoola, Y. Sambo, and M. A. Imran, "Analysis of Electromagnetic Field Radiation From Synchronisation Signal Block (SSB) in 5G Systems," in *Proc. 5th International Conference on Computer Communication and the Internet (ICCCI)*, 2023, pp. 185–189.
- [9] M. Giordani, M. Polese, A. Roy, D. Castor, and M. Zorzi, "A Tutorial on Beam Management for 3GPP NR at mmWave Frequencies," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 173–196, 2019.
- [10] W. Tashan, I. Shaye, S. Aldirmaz-Colak, M. Ergen, M. H. Azmi, and A. Alhamadi, "Mobility Robustness Optimization in Future Mobile Heterogeneous Networks: A Survey," *IEEE Access*, vol. 10, pp. 45 522–45 541, 2022.
- [11] M. Polese, M. Giordani, M. Mezzavilla, S. Rangan, and M. Zorzi, "Improved Handover Through Dual Connectivity in 5G mmWave Mobile Networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 2069–2084, 2017.
- [12] M. Giordani, M. Mezzavilla, and M. Zorzi, "Initial Access in 5G mmWave Cellular Networks," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 40–47, 2016.
- [13] S. Barati, S. Dutta, S. Rangan, and A. Sabharwal, "Initial Access, Mobility, and User-Centric Multi-Beam Operation in 5G New Radio," *IEEE Communications Magazine*, vol. 56, no. 3, pp. 35–41, 2018.
- [14] O. G. Aliu, A. Imran, M. A. Imran, and B. Evans, "A Survey of Self Organisation in Future Cellular Networks," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 336–361, 2013.
- [15] 3GPP, "NR; Physical Layer Procedures for Data," 3rd Generation Partnership Project, Tech. Rep. TS 38.214, 2024, release 18.
- [16] C. Han, T. Harrold, S. Armour, I. Krikidis, S. Videv, P. M. Grant, H. Haas, J. S. Thompson, I. Ku, C.-X. Wang, T. A. Le, M. R. Nakhai, J. Zhang, and L. Hanzo, "Green Radio: Radio Techniques to Enable Energy-Efficient Wireless Networks," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 46–54, 2011.
- [17] S. Buzzi, I. Chih-Lin, T. E. Klein, H. V. Poor, C. Yang, and A. Zappone, "A Survey of Energy-Efficient Techniques for 5G Networks and Challenges Ahead," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 697–709, 2016.
- [18] International Commission on Non-Ionizing Radiation Protection, "Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz)," *Health Physics*, vol. 118, no. 5, pp. 483–524, 2020.
- [19] K. Li, M. S. Mollé, O. Popoola, Y. Sambo, and M. A. Imran, "Analysis of electromagnetic field radiation from synchronisation signal block (ssb) in 5g systems," in *2023 5th International Conference on Computer Communication and the Internet (ICCCI)*, 2023, pp. 185–189.
- [20] N. Yoza-Mitsuishi, Y. Ma, and J. Coder, "An SDR-based performance measurement of LTE and WLAN coexistence," in *Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2022.