

Minimizing Energy Consumption for 5G NR Beam Management for RedCap Devices

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Abstract—In 5G New Radio (NR), beam management entails periodic and continuous transmission and reception of control signals in the form of synchronization signal blocks (SSBs), used to perform initial access and/or channel estimation. However, this procedure demands continuous energy consumption, which is particularly challenging to handle for low-cost, low-complexity, and battery-constrained devices, such as RedCap devices to support mid-market Internet of Things (IoT) use cases. In this context, this work aims at reducing the energy consumption during beam management for RedCap devices, while ensuring that the desired Quality of Service (QoS) requirements are met. To do so, we formalize an optimization problem in an Indoor Factory (InF) scenario to select the best beam management parameters, including the beam update periodicity and the beamwidth, to minimize energy consumption based on users' distribution and their speed. The analysis yields the regions of feasibility, i.e., the upper limit(s) on the beam management parameters for RedCap devices, that we use to provide design guidelines accordingly.

Index Terms—5G NR, 3GPP, beam management, RedCap devices, energy consumption, Indoor Factory.

I. INTRODUCTION

In the last few years, standardization bodies and industry players have developed several Low-Power Wide Area Network (LPWAN) technologies, such as Long Range (LoRa), Narrowband-IoT (NB-IoT), and SigFox to support IoT applications in many fields, ranging from agriculture, transportation, logistics, and healthcare, as well as for smart cities [1], [2]. Along these lines, the 3rd Generation Partnership Project (3GPP) is also promoting new specifications [3] to simplify 5G NR standard operations to support high-end IoT devices, referred to as RedCap devices [4].

Among other features, RedCap devices may be operating in the lower part of the millimeter wave (mmWave) spectrum to improve the network performance in more demanding scenarios, such as in an indoor factory scenario [5]. Communication at mmWaves, however, requires directionality between the transmitter and the receiver to compensate for the additional path loss experienced at those frequencies, typically realized via Multiple Input Multiple Output (MIMO) antenna arrays. In 5G NR, beam management was designed to allow the endpoints to identify and continuously maintain the optimal direction of transmission, e.g., during initial access and/or channel estimation [6]. Specifically, beam management implies exhaustive search based on Synchronization Signal Blocks (SSBs), collected into bursts and transmitted by a Next Generation Node Base (gNB) according to pre-specified

intervals and directions. However, beam management involves severe energy consumption for sending and receiving control signals, which is a function of the beamwidth and periodicity of SSBs [7]. Even though this is generally not an issue for 5G NR systems, it may be challenging to handle for low-complexity, battery-powered RedCap devices, and may degrade the network performance.

Recently, the scientific community has explored possible simplifications of the 5G NR standard to optimize power consumption for RedCap devices [5], for example via simplified air interface procedures [8], protocol stack, antenna configurations [9], and enhanced power-saving functionalities such as Discontinuous Reception (eDRX) or wake-up signals [10]. The 3GPP has also launched some Study and Work Items in this domain, for example in TR 38.869 [11] to study low-power wake-up signal and receiver for RedCap devices. However, to the best of our knowledge, there is no prior work focusing on beam management for RedCap devices, which stimulates further research in this domain.

To fill these gaps, in this work we formalize an optimization problem to determine the optimal beam management design for RedCap devices to minimize the energy consumption. Notably, we focus on an Indoor Factory (InF) scenario, and derive the so-called regions of feasibility, i.e., the upper limit(s) on the beam management parameters, including the number of SSBs per burst and the burst periodicity, to guarantee that the Quality of Service (QoS) constraints are met, for example that User Equipments (UEs) never go undetected and/or maintain alignment as they move. Simulation results demonstrate that there exists an optimal configuration for beam management to promote energy efficiency, which depends on the speed of the UEs, the beamwidth, and other network parameters.

The rest of the paper is organized as follows. In Sec. II we present our system model (deployment, energy, mobility, and beam management). In Sec. III we describe our optimization problem. Also, we describe the impact of the number of antennas at the gNB on the QoS constraints. In Sec. IV we present the simulation results and provide design guidelines towards the optimal set of parameters for beam management. Finally, conclusions are given in Sec. V.

II. SYSTEM MODEL

In this section we present our deployment model (Sec. II-A), beam management model (Sec. II-B), energy consumption model (Sec. II-C), and mobility model (Sec. II-D).

A. Deployment Model

We consider a 3GPP InF-Sparse High (InF) scenario [12] with an area of size $L \times W \times H$, a single gNB placed at the center of the ceiling at height h_{gNB} , and obstacles in the form of clutters of size d_c , height h_c , and density r . Then, K UEs are uniformly deployed at height h_{UE} around the clutters. The location of UE_k , for $k \in \{1, 2, \dots, K\}$, is given by (d_k, ϕ_k) , where d_k is the distance between UE_k and the gNB, and ϕ_k is the phase of UE_k measured counterclockwise. The UEs are assumed to be moving on a circle at constant velocity v in a counterclockwise direction.

The Signal-to-Noise Ratio (SNR) γ_k at UE_k is given by [13]

$$\gamma_k(d_{3\text{D}}) = \frac{\mathcal{H}_L P_r(d_{3\text{D}}) + \mathcal{H}_N(1 - P_r(d_{3\text{D}}))}{N_0 \cdot B \cdot \text{NF} / G_{\text{gNB},k} G_{\text{UE}}}, \quad (1)$$

where $d_{3\text{D}} = \sqrt{(h_{\text{gNB}} - h_{\text{UE}})^2 + d_k^2}$ is the distance between the gNB and UE_k , N_0 is the noise Power Spectral Density, B is the channel bandwidth, and NF is the noise figure. \mathcal{H}_L and \mathcal{H}_N include the effect of path loss, shadowing and fading parameter for the Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) channels, respectively and $P_r(d_{3\text{D}})$ is the LoS probability, as described in [12]. Specifically, we have

$$\mathcal{H}_j = |\mathfrak{h}_j^k|^2 \text{PL}_j^k, \quad j \in \{\text{L}, \text{N}\}, \quad (2)$$

where \mathfrak{h}_j^k and PL_j^k are the channel fading gain and path loss for the LoS (L) and NLoS (N) links, respectively.

In Eq. (1), $G_{\text{gNB},k}$ (G_{UE}) is the beamforming gain at the gNB (UE). We assume analog beamforming (a realistic assumption for RedCap devices to minimize the energy consumption [14]), such that the gNB (UEs) can probe only one direction at a time. Specifically, the gNB is equipped with N_{gNB} antennas, and the beamforming gain is expressed as [15]

$$G_{\text{gNB},k} = \sin\left(\frac{N_{\text{gNB}}\pi}{2} \sin \theta_k\right) / \sin\left(\frac{\pi}{2} \sin \theta_k\right), \quad (3)$$

where θ_k is the angular offset with respect to UE_k , as described in Sec. II-D.

B. Beam Management Model

According to the 5G NR specifications [16], beam management operations rely on a directional version of the 3GPP LTE synchronization signal called SSB. Specifically, each SSB consists of 4 OFDM symbols in time and 240 subcarriers in frequency, where the subcarrier spacing depends on the 5G NR numerology [6]. Each SS block is mapped into a certain angular direction so that directional measurements can be made based on the quality of the received signal, e.g., in terms of the SNR. To reduce the overhead, SSBs can be gathered together into SS bursts. An SS burst consists of $N_{\text{SS}} \in \{8, 16, 32, 64\}$ SSBs, and the periodicity between consecutive SS bursts is $T_{\text{SS}} \in \{5, 10, 20, 40, 80, 160\}$ ms.

C. Energy Consumption Model

In 5G NR beam management, the gNB transmits the SSBs by sequentially sweeping different angular directions to cover

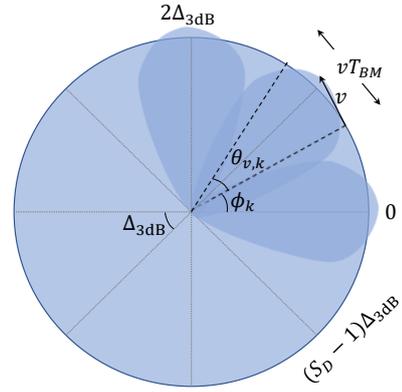


Fig. 1. UE mobility model. During beam management, UE_k accumulates an angular offset θ_k due to both initial misalignment ($\theta_{i,k}$) and mobility ($\theta_{v,k}$). The latter depends on the UE speed v , and the beam management time T_{BM} . the whole beam space (or cell sector). At the UE, the energy consumption (EC) required to receive those SSBs is equal to

$$\text{EC} = S_D P_{\text{UE}} T_{\text{SSB}}, \quad (4)$$

where S_D is the number of SSBs required to completely sweep the beam space (which is a function of the beamwidth at the gNB), P_{UE} is the power consumed for receiving each SSB at the UE, and T_{SSB} is the time required to send each SSB.

From [6, Eq. (3)], the number of SSBs required to completely sweep the beam space on the horizontal plane, with azimuth ranging from 0 to 2π , can be expressed as

$$S_D = \lceil 2\pi / \Delta_{3\text{dB}} \rceil \approx \lceil \pi N_{\text{gNB}} \rceil, \quad (5)$$

where $\Delta_{3\text{dB}}$ is the 3-dB beamwidth, which can be approximated as $\Delta_{3\text{dB}} \approx 2 / N_{\text{gNB}}$ according to [15]. Since each SSB consists of 4 OFDM symbols, the time required to send one SSB can be expressed as [6, Eq. (2)]

$$T_{\text{SSB}} = 4T_{\text{symp}} = 4(71.45/2^n), \quad (6)$$

where n represents the 5G NR numerology.

Finally, the power consumption at the UE, equipped with N_{UE} antennas, can be expressed as

$$P_{\text{UE}} = N_{\text{UE}}(P_{\text{LNA}} + P_{\text{PS}}) + P_{\text{RF}} + P_C + 2P_{\text{ADC}}, \quad (7)$$

where $P_{\text{RF}} = P_M + P_{\text{LO}} + P_{\text{LPF}} + P_{\text{BB}}$ is the power consumption of the RF chain [17]. A description of the power components appearing in Eq. (7), and the relative numerical values, is provided in Table I.

D. Mobility Model

At the beginning of the beam management process, UE_k , $k \in \{1, 2, \dots, K\}$, establishes a physical link connection with the gNB using a certain beam. Due to the finite pre-defined codebook of directions available at the gNB, UE_k comes with a non-zero initial angular offset $\theta_{i,k} = \min(\phi_k - \bar{\phi}_{\text{br}})$ with respect to the gNB antenna boresight directions $\bar{\phi}_{\text{br}} \doteq [0, 1, 2, \dots, S_D - 1] \Delta_{3\text{dB}}$, as represented in Fig. 1.

At the same time we assume that, during beam management, UE_k can move in a counterclockwise direction at constant velocity v . During this time, UE_k may lose beam alignment and the corresponding beamforming gain, and get disconnected if the resulting SNR is lower than a pre-defined threshold [18]. Thus, we define $\theta_{v,k}$ as the angular offset due to mobility during beam management, i.e.,

$$\theta_{v,k} = vT_{\text{BM}}/d_k. \quad (8)$$

In Eq. (8), T_{BM} is the time for beam management, and is measured as the delay from the first SSB transmission to the completion of the sweep in all possible angular directions, which can be expressed as in [6, Eq. (4)], i.e.,

$$T_{\text{BM}} = T_{\text{SS}} (\lceil S_D/N_{\text{SS}} \rceil - 1) + T_\ell, \quad (9)$$

where T_ℓ is the time required to send the remaining SSBs in the last burst and is given in [6, Eq. (6)]. Therefore, the overall angular offset for UE_k during beam management, due to both the initial offset ($\theta_{i,k}$) and the offset accumulated due to mobility ($\theta_{v,k}$), can be expressed as

$$\theta_k = |\theta_{v,k} + \theta_{i,k}|. \quad (10)$$

III. OPTIMIZATION PROBLEM

In this section we define an optimization problem to minimize the energy consumption for RedCap devices for transmitting/receiving SSBs during beam management. The optimization problem can be formalized as follows:

$$\min_{N_{\text{gNB}}} \text{EC} = S_D P_{\text{UE}} T_{\text{SSB}}, \quad (11a)$$

$$P_T \gamma_k \geq \tau, \forall k; \quad (11b)$$

$$N_{\text{gNB}} \in \{2, 3, \dots, 64\}, \quad (11c)$$

where P_T is the transmission power at the gNB, and γ_k is the SNR at UE_k as given in Eq. (1). In (11), (11b) ensures that the SNR at UE_k is greater than or equal to a minimum threshold τ , which is large enough to ensure that UE_k can be properly detected, and (11c) restricts the number of antenna elements at the gNB to 64, as expected for RedCap devices.

Modeling of the constraints. The optimization problem determines the optimal value of N_{gNB} , referred to as N^* , based on the SNR $\gamma_k, \forall k$, which depends on G_{gNB} , so on the angular offset θ_k introduced by the moving UEs. Indeed, as the UE moves at constant velocity v during the beam management process, it may lose alignment with respect to the associated beam, potentially deteriorating the beamforming gain. This may cause the SNR of UE_k to drop below the sensitivity threshold τ , preventing it from being detected. The factors that may lead to misalignment include: (i) the UE velocity v (the faster the UE, the sooner it may lose alignment); (ii) the beam management time T_{BM} and, consequently T_{SS} and N_{SS} (the slower the beam management procedure, the higher the probability that the UE would lose alignment); and (iii) the number of antennas N_{gNB} , which defines the beamwidth (the narrower the beam, the higher the probability that the UE would lose alignment). In the following, we investigate the impact of those terms on the optimization problem.

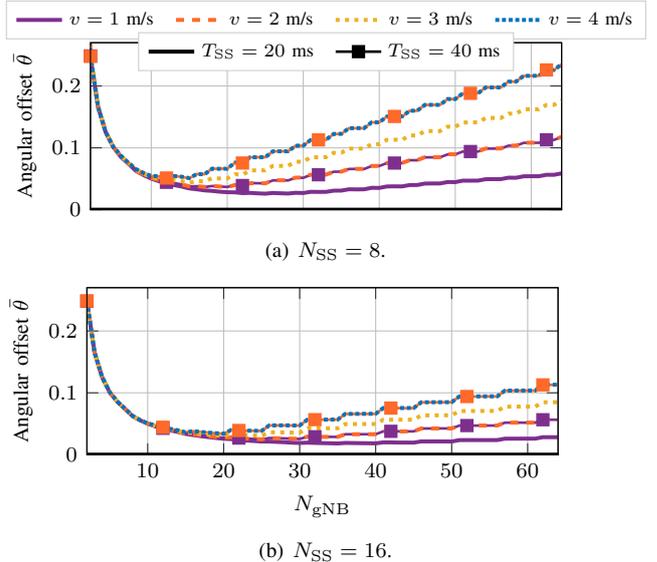


Fig. 2. Average angular offset $\bar{\theta}$, as a function of N_{gNB} , the UE speed v , and the SS burst periodicity T_{SS} .

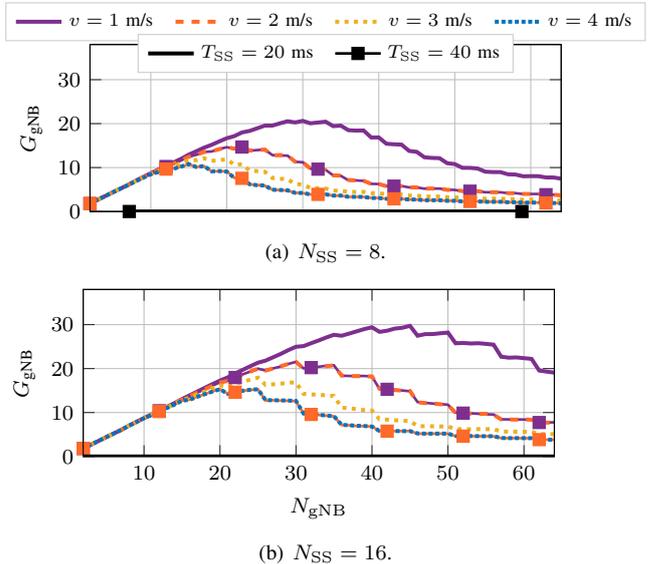


Fig. 3. Average gain at the gNB G_{gNB} as a function of N , the UE speed v , and the SS burst periodicity T_{SS} .

In Fig. 2 we plot $\bar{\theta}$ (the angular offset averaged over all K UEs in the scenario) vs. N_{gNB} for different values of v and T_{SS} , and for $N_{\text{SS}} = \{8, 16\}$. We observe that $\bar{\theta}$ initially decreases with N_{gNB} . In fact, when the number of antennas is small, the beam is large enough to ensure continuous alignment despite mobility. In this region, $\bar{\theta}$ is thus dominated by the initial offset $\theta_{i,k}$ with respect to the antenna boresight direction. Then, as N_{gNB} increases, the beams become progressively narrower, and the number of SSBs that are required to be sent to completely sweep the beam space also increases, which increases the beam management time. In these conditions, the angular offset due to mobility $\theta_{v,k}$ increases accordingly as per Eq. (8). In addition, we observe that in both Fig. 2(a) and 2(b) the angular offset for $v = 2$ m/s and $T_{\text{SS}} = 20$ ms overlaps with the offset for

$v = 1$ m/s and $T_{SS} = 40$ ms. Similarly, the offset for $v = 2$ m/s and $T_{SS} = 40$ overlaps over the offset for $v = 4$ m/s and $T_{SS} = 20$ ms. Therefore, we conclude that the angular offset depends on v and T_{SS} only through their product. This observation becomes significant while analyzing the feasibility regions in Sec. IV.

Notice that the zigzag effect in Fig. 2 is due to the fact that $\theta_{v,k}$ and hence $\bar{\theta}$ is a function of T_{BM} which, as reported in Eq. (9), is a ceiling function. This effect increases as N_{gNB} increases, i.e., as $\theta_{v,k}$ dominates the average angular offset $\bar{\theta}$.

Additionally, in Fig. 3 we plot the average antenna gain at the gNB (G_{gNB} , averaged over all K UEs in the scenario) vs. N_{gNB} for different values of v and T_{SS} , and for $N_{SS} = \{8, 16\}$. We notice that G_{gNB} initially increases with N_{gNB} , and then drops after a threshold due to mobility. If N_M is the number of antennas corresponding to the point where G_{gNB} is maximum, we conclude that the optimization problem in (11) is restricted to the values of $N_{gNB} \leq N_M$ because the energy consumption increases with N_{gNB} . We further observe that N_M decreases with v and T_{SS} , and increases with N_{SS} . In other words, the product vT_{SS} for a given value of N_{SS} establishes an upper limit to determine the regions of feasibility, as further discussed in Sec. IV: if the SNR constraints are not satisfied for $N_{gNB} \leq N_M$, the optimization problem will be infeasible.

Optimization algorithm. Based on the optimization problem in (11), and the considerations above, we conclude that the energy consumption at the UE increases monotonically with the number of antennas at the gNB. This suggests that the minimum value of N_{gNB} at which the SNR constraints are satisfied should be the optimal N_{gNB} , or N^* . For a given transmit power (P_T) and SNR threshold (τ), if the constraints are not met, the problem is infeasible.

IV. NUMERICAL RESULTS

In this section, we evaluate the energy consumption for beam management as a function of N_{SS} , T_{SS} , N_{gNB} , v , P_T , and τ . Specifically, we perform 10^5 Monte Carlo simulations in MATLAB for each combination of parameters, and in each simulation we find N^* using the algorithm presented in Sec. III. The simulation parameters are reported in Tab. I, taken from [12, Table 7.2-4] for the InF-SH scenario, [5] for the RedCap devices, and [17] for the power consumption.

The goal of our analysis is to determine the regions of feasibility, and the corresponding set of 5G NR beam management parameters which minimize the energy consumption while satisfying SNR constraints. Notice that we assume zero misdetection probability in the analysis, i.e., no user goes undetected during the beam management process.

A. Impact of T_{SS} and N_{SS}

Figs. 4(a) and 4(b) depict the UE misdetection probability and N^* , respectively, as a function of T_{SS} and v , for $N_{SS} = 8$. While N^* depends on P_T and τ , it does not change with v , T_{SS} , and N_{SS} . This is because the objective function always drives the optimization problem towards the minimum value of N_{gNB} that meets the SNR constraints for each UE, so as

TABLE I
SIMULATION PARAMETERS.

Parameter	Description	Value
h_{gNB}	gNB height	25 m
h_{UE}	UE height	1.5 m
d_c	Clutter size	10 m
h_c	Clutter height	5 m
r	Clutter density	20%
$L \times W \times H$	Size of the InF-SH scenario	$20 \times 20 \times 25$ m
K	Number of UEs	50
f_c	Carrier frequency	28 GHz
B	Bandwidth	50 MHz
P_T	Transmission power	18 dBm
τ	SNR threshold	$\{3, 7, 10\}$ dB
h_{LoS}^k, h_{NLoS}^k	Channel fading gains	$\mathcal{CN}(0, 1)$
PL_{LoS}^k, PL_{NLoS}^k	Path loss	[12, Table 7.4.1-1]
$P_r(d_{3D})$	LoS probability	[12, Table 7.4.2-1]
N_0	Noise Power Spectral Density	-174 dBm/Hz
NF	Noise figure	9 dB
n	5G NR numerology index	4
P_{LNA}	Low noise amplifier power	20 mW
P_{PS}	Phase shifter power	30 mW
P_M	Mixer power	19 mW
P_{LO}	Local oscillator power	5 mW
P_{LPF}	Low pass filter power	14 mW
P_{BB}	Baseband amplifier power	5 mW
P_{ADC}	ADC power	200 mW

to minimize the energy consumption. In turn, this sets N^* to the minimum value corresponding to the largest angular offset beyond which the problem becomes infeasible (which determines the values of v and T_{SS} for a given N_{SS}), as described in Sec. III.

Nevertheless, given P_T and τ , there exists only a limited set of values of v , T_{SS} at N_{SS} for which the SNR constraints are met. As a consequence, some bars are missing in Fig. 4(b), which indicates that the corresponding problem is infeasible. For example, for $T_{SS} = 160$ ms and $v \geq 1$ m/s, there are no values of N_{gNB} for which $SNR_k \geq \tau, \forall k$. This is also observed in Fig. 4(a), where the misdetection probability at $T_{SS} = 160$ ms is greater than zero for $v \geq 1$ m/s. Similarly, $v \geq 2$ m/s is infeasible for $T_{SS} \geq 80$ ms, whereas for $v \leq 4$ m/s and $T_{SS} \leq 20$ ms the problem is feasible, which yields $N^* = 5.4$ on average.¹ This is because increasing v or T_{SS} increases the average angular offset as per Eq. (10), and may cause the UEs to lose beam alignment sooner, thus making the problem infeasible.

B. Impact of P_T and τ

Fig. 5 illustrates the average optimal number of antennas N^* as a function of the transmission power P_T and T_{SS} , for $\tau \in \{3, 7\}$ dB, $v = 1$ m/s and $N_{SS} = 8$. We observe that as P_T decreases and τ increases, N^* increases. Indeed, increasing the number of antennas leads to a higher (best case) beamforming gain, thus possibly improving the minimum SNR at the UEs. At the same time, decreasing P_T and/or increasing τ also reduces the set of values for which the problem is feasible, as demonstrated by the missing bars in Fig. 5. In fact, although the angular offset does not directly depend on P_T and τ , a

¹Notice that, while we constrain N^* to be an integer in each Monte Carlo simulation, here N^* represents the average of different realizations.

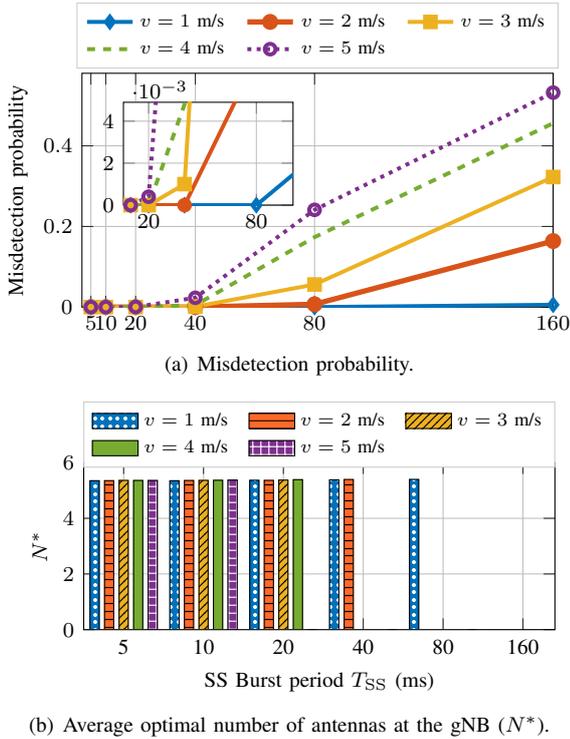


Fig. 4. Misdetection probability (top) and N^* (bottom) vs. the SS burst periodicity T_{SS} and the UE speed v , considering $P_T = 18$ dBm, sensitivity threshold $\tau = 7$, $N_{SS} = 8$.

smaller P_T or a higher τ effectively impose progressively stricter constraints on the problem, as per C1 in (11). For instance, $\{P_T = 18$ dBm, $\tau = 3$ dBm, $T_{SS} \leq 160$ ms $\}$ is a feasible configuration, whereas $\{P_T = 12$ dBm, $\tau = 3$ dBm, $T_{SS} > 40$ ms $\}$ is not.

C. Feasibility Regions

For given values of P_T and τ , there exists only a limited set of values of v , T_{SS} , and N_{SS} for which the problem in (11) is feasible, i.e., the SNR constraints are guaranteed. Table II reports these feasibility regions for $P_T = 18$ dBm and $\tau \in \{3, 7, 10\}$ dB, in terms of the highest product of v and T_{SS} supported by the system. We recall that, as observed in Sec. III, both v and T_{SS} have the same impact on the angular offset, and the feasibility regions are perfectly defined by the product vT_{SS} . For example, for $N_{SS} = 8$ and $\tau = 7$ dB, the feasibility region is upper bounded by $vT_{SS} = 0.08$ m. The results in Table II have been obtained for different values of N_{SS} and τ , and $v \leq 25$ m/s using a similar analysis as in Sec. IV-A.

Fig. 6 depicts the feasibility regions in terms of the upper bounds of parameters N_{SS} and T_{SS} for which the optimization problem in (11) is feasible, for $P_T = 18$ dBm and $\tau \in \{3, 7, 10\}$ dB. These plots were generated using the values in Table II, and are intended to provide guidelines towards the optimal 5G NR beam management configurations to minimize the energy consumption for RedCap devices. In general, we observe that as τ increases, the feasibility regions become smaller. This is because increasing the threshold τ translates into a tighter constraint on the SNR (C1 in (11)), thus the optimization problem yields larger values of N^* to increase

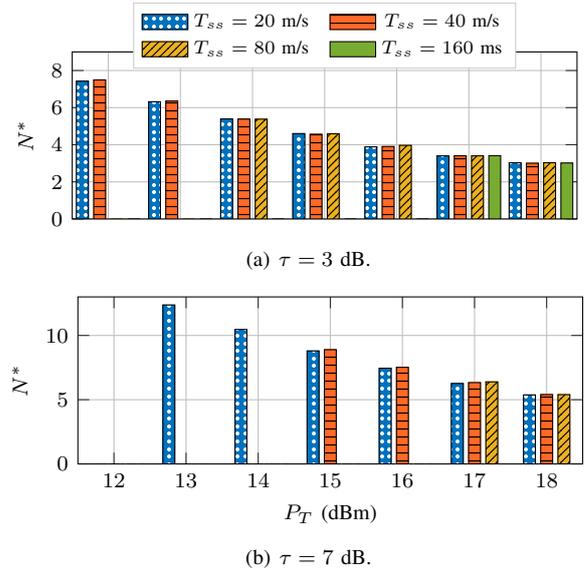


Fig. 5. Optimal number of antennas at the gNB N^* vs. P_T and SS burst periodicity T_{SS} , for sensitivity threshold $\tau \in \{3, 7\}$ dB, $N_{SS} = 8$, and UE speed $v = 1$ m/s.

TABLE II
FEASIBILITY REGIONS FOR $P_T = 18$ dBm AND $\tau \in \{3, 7, 10\}$ dB.

N_{SS}	vT_{SS}		
	3 dB	7 dB	10 dB
8	≤ 0.16 m	≤ 0.08 m	≤ 0.02 m
16	≤ 0.72 m	≤ 0.16 m	≤ 0.04 m
32	≤ 4 m	≤ 0.4 m	≤ 0.16 m
64	≤ 4 m	≤ 4 m	≤ 0.32 m

the beamforming gain. However, this also implies narrower beams, which in turn reduce the angular offset which can be tolerated by the system.

Furthermore, the size of the feasibility regions is inversely proportional to v and T_{SS} , as expected from the analysis in Sec. III. Indeed, if the UEs move faster, or if the beam management process takes longer, the angular offset in Eq. (10) also increases, and so does the probability that the UEs would lose beam alignment. However, we can see from Eq. (9) that T_{SS} does not influence the beam management time T_{BM} if $S_D \leq N_{SS}$, i.e., if sending the SSBs requires exactly one burst [19]. Based on the expression of S_D in Eq. (5), this condition is true if $N_{gNB} \leq 3, 5, 11, 21$, for $N_{SS} = 8, 16, 32, 64$ respectively. In general, it is convenient to choose N_{gNB} accordingly, to limit the impact of T_{SS} on the shape of the feasibility regions.

D. Energy Consumption

The feasibility regions in Fig. 6 show that the smallest (highest) feasible T_{SS} (N_{SS}) (i.e., the bottom-right part of the feasibility region) would be the optimal configuration for the beam management. Indeed, this choice implies faster beam alignment and better SNR on average, but also entails the highest overhead as more time resources are used for sending control signals at the expense of data transmissions [6, Fig.

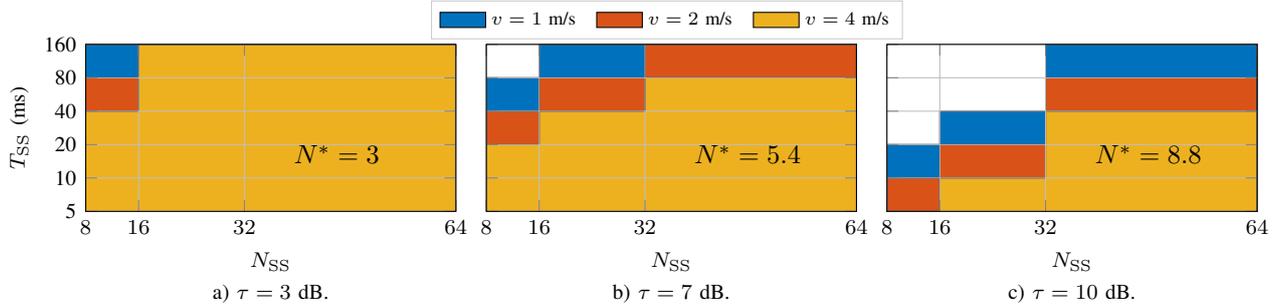


Fig. 6. Feasibility regions for different values of sensitivity threshold τ and UE speed v , and for $P_T = 18$ dBm.

17]. Furthermore, let \overline{EC}_t be the average energy consumption for sending SSBs over time, which can be expressed as [7]:

$$\overline{EC}_t = (P_{UE}T_{SSB})N_{SS}/T_{SS}, \quad (12)$$

where $P_{UE}T_{SSB}$ represents the average energy consumption for sending one SSB, as per Eq. (4).

Overall, there exists a trade-off between the beam management periodicity and the resulting overhead and \overline{EC}_t , which leads to the optimal values of T_{SS} and N_{SS} . We thus propose to operate in the top-left portion of the feasibility regions, i.e., choosing the highest possible T_{SS} at $N_{SS} = 8$. In this way, we minimize the average energy consumption per unit time, while still satisfying the SNR constraints as we are in the feasibility regions. For instance, for $P_T = 18$ dBm and $\tau \in \{3, 7, 10\}$ dB, the optimal configuration for (N_{SS}, T_{SS}) at $v = 1$ m/s is (8, 160 ms), (8, 80 ms) and (8, 20 ms), respectively.

V. CONCLUSIONS AND FUTURE WORK

In this work, we explored the 5G NR beam management design for RedCap devices in an InF-SH scenario. In this scenario, and during beam management, a moving device may lose alignment with the associated beam, potentially resulting in the UE going undetected. Therefore, we formalized an optimization problem to minimize the energy consumption during beam management, while ensuring that some desired QoS requirements, measured in terms of the misdetection probability, are met. Through simulations, we identified the feasibility regions where the problem can be solved, and proposed the optimal values of the beam management parameters for RedCap devices, such as the optimal SSB size and periodicity, to maintain a minimum energy consumption while optimizing latency and overhead. As part of our future work, we will generalize our optimization problem to other scenarios like smart agriculture, introduce additional mobility models, as well as consider more sophisticated optimization methods, e.g., based on machine learning.

ACKNOWLEDGMENT

This work was partially supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on “Telecommunications of the Future” (PE0000001 - program “RESTART”).

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