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5G On-Demand SI Acquisition Framework and Performance Evaluation

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ABSTRACT In LTE, the system information (SI) is periodically broadcast to UEs. To improve the utilization of wireless resources and the latency of SI acquisition, SI is categorized into *minimum SI* and *other SI* in the 5G NR network. Moreover, a new approach, on-demand SI delivery, is also specified in NR. This enables gNBs to transmit *other SI* only when the UEs request it. In this paper, the MSG1-based and MSG3-based on-demand SI delivery designs are discussed. Besides, the effects of the beam sweeping and the UE behavior, ''Listen Before Request'', are also considered. Therefore, up to 10 design options are introduced. The corresponding analytical models of signaling overhead, delay and UE power consumption are also proposed. On the basis of analysis and simulation results, the SI delivery policies for the cases with different arrival rates of SI demands and the number of the base station (BS) beams are also proposed.

INDEX TERMS On-demand system information, 5G, SI acquisition.

I. INTRODUCTION

In recent years, the demand for wireless network applications, including Internet of Things (IoT), virtual reality (VR), augmented reality (AR), unmanned (aerial) vehicle, etc., has exponentially increased. The 5G wireless network targets to satisfy the various requirements, such as low latency, high data rate, high reliability and the enormous number of connections [1]. Third Generation Partnership Project (3GPP) started the standardization work for 5G systems in 2016 and the development of 5G New Radio (NR) in 3GPP Release 15 is provided in [2]. It is obvious that the utilization of the spectrum above 24 GHz, also known as millimeter-wave (mmWave) bands, is inevitable because of the lack of frequency resources. Besides, to enhance the transmission range and eliminate the interference, beamforming is applied in NR systems. This can compensate for the high propagation loss of mmWave links as well [3]. However, the directionality of beamformed mmWave links unfits most existing Medium Access Control (MAC) layer procedures, such as system information (SI) acquisition [4]–[6]. For example, before a UE in idle or inactive mode transfers to connected mode, it needs the SI to access the network. If the communication links are directional, then the difficulty to acquire the SI is significantly increased.

Moreover, the evolution of SI acquisition in 5G NR involves not only the directional transmission but the delivery procedure [7]. The System information (SI) for UEs is classified into the Master Information Block (MIB) and a set of System Information Blocks (SIBs). In LTE systems, MIB comprises fundamental information such as System Frame Number (SFN) and system bandwidth. MIB is broadcast on Physical Broadcast Channel (PBCH) periodically. On the other hand, SIBs containing scheduling and cell access information are broadcast on Physical Downlink Shared Channel (PDSCH). Different from the periodically broadcast system information in LTE, the 5G NR system introduces a new approach for SI transmission, known as on-demand SI delivery [7]. In NR, MIB and SIB1 are defined as *minimum SI* while the other SIBs (SIB2, SIB3, and so on) are defined as *other SI*. *Minimum SI* contains the basic information on acquiring *other SI* and processing initial access [8]. *Minimum SI* is broadcast periodically in the SI window [9], as shown in Fig. 1 and Fig. 2. The base station (BS) broadcasts the SI inside the SI window periodically.

Unlike minimum SI delivery, *other SI* comprises additional information and could be delivered when needed. On-demand SI acquisition is a new feature in 5G NR. In Fig. 1, the BS

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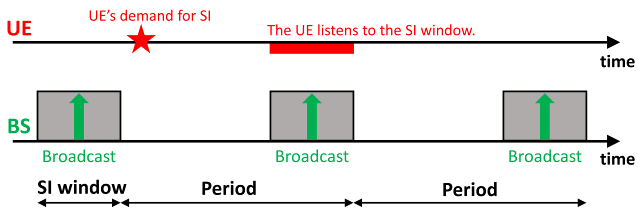


FIGURE 1. Periodically broadcasting for SI delivery in LTE. (The mechanism is the same as the delivery of *minimum SI* in 5G NR.) When the UE starts to acquire the SI, it monitors the coming SI window within the same period of broadcasting.

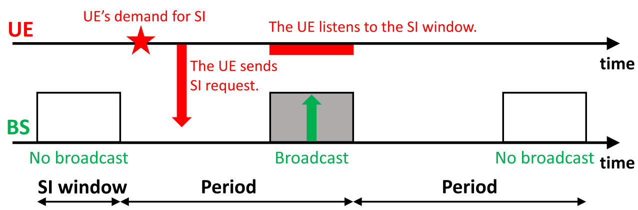


FIGURE 2. On-demand broadcasting for the delivery of *other SI* in 5G NR. When the UE starts to acquire the SI, it sends the request to the base station(BS) directly. After that, it listens to the SI window within the same period. The BS does not broadcast SI if there is no SI requests from UEs.

broadcasts SI periodically. Therefore, when a UE acquires the SI, it monitors the next SI window and receives the desire SIB. Fig. 2 is an example of on-demand broadcasting. When a UE acquires the SI, it sends the SI request directly. After that, the UE monitors the next SI window to receive the requested SIB. As for the BS, it broadcasts the requested SIB in the SI window when it receives the request. Furthermore, the on-demand transmission triggered by the UE request can apply broadcasting or unicasting.

To fit the properties of directional links, the BS can utilize the beams to sweep over the whole-cell coverage. This behavior is called beam sweeping. The BS broadcasts on one beam at a time so that the cell is entirely covered after a full sweeping. Beam sweeping solves the problem of the narrow coverage of beamformed links but costs more wireless resources. Besides, the UE request mechanism for on-demand SI can also be designed in different ways. For example, when UEs request the SI through the random access procedure, the request message can be either MSG1-based or MSG3-based.

Previous researches have evaluated the advantages of on-demand SI acquisition [10], [11], but the SI request and delivery are not explored. The complicated designs of the on-demand transmission lack a comprehensive analysis. The network system needs the analysis to decide the delivery policy of *other SI*.

Currently, there are on-demand designs in 3GPP standard documents; nevertheless, most performance evaluations are preliminary mathematical analysis or simulation comparison in 3GPP documents. To have a fundamental understanding of the on-demand design options and performance trade-offs (e.g. between overhead, delivery latency and energy consumption), a theoretic framework is needed for quantitative performance evaluation for on-demand SIB. To authors' best knowledge, this work is the first comprehensive evaluation framework for mmWave 5G on-demand SIB mechanisms.

Our contributions are summarized as follows.

1) We analyze and simulate all the delivery options of *other SI* with the detailed design. The options include all the supported designs in the 3GPP NR specification in addition to the Listen Before Request (LBR) mechanism on UE side. The details include the request and delivery mechanism and LBR. We consider all the possible options and provide the analytical models and simulation results of these options.
2) We take the UE behavior, LBR, into consideration in the on-demand SI acquisition.
3) We propose a comprehensive framework to configure the SI delivery options based on the system demand and the arrival rate of SI demands. According to the analysis and simulation results, the proposed framework suggests the best delivery option of *other SI* when considering signaling overhead, delay or UE power consumption. Besides, we discuss the effects of the number of BS beams on the system performance.

The paper is organized as follows: Section II describes the related works. On-demand SI acquisition mechanism is introduced in Section III. Section IV lists design options of SI delivery. We derive mathematical models for each design option in Section V. Comparative performance evaluation is shown in Section VI. Lastly, we conclude the paper in Section VII.

II. RELATED WORK

Ingale et al. compared on-demand SI with the all broadcasting approach [10]. Signaling overhead and UE power consumption are analyzed; nevertheless, SI delivery latency is not analyzed. 3GPP standard contributions discussed on-demand SIB design options. The periodic broadcasting, on-demand broadcasting, and on-demand unicasting for SIB delivery are compared with simulation [11]. Awada et al. improved on-demand SI broadcast with efficient broadcasting mechanism [12]. The proposed mechanism is similar to Multimedia Broadcast/Multicast Services (MBMS). Besides, the Modulation and Coding Scheme (MCS) is applied to improve SIB broadcasting efficiency. Although the previous work showed the advantages of the on-demand delivery for SI, most of the options specified in 3GPP standard are not studied in detail. In [10], only periodically broadcast SI and on-demand unicast SI are considered. In [11], [12], the on-demand broadcast SI is considered, but some protocol details (e.g. MSG1-based v.s. MSG3-based requests) and the corresponding performance evaluation are not addressed. Therefore, we study and propose the complete analytical models for all the SI delivery options in 3GPP standard.

Modified random access (RA) procedure might be applied for SIB requests. Physical layer RA preambles could be used for both initial access and SI request. Signaling messages (e.g. information in MSG3) in the RA procedure might differ between the RA of initial access and the RA of SI request. Nevertheless, mathematical analysis techniques might be similar in performance evaluation in these two cases. The delay bounds of RA of initial access for both uniform and beta distributed arrivals were derived in [13]. Lin et al. [14] evaluated the RA procedure with imperfect preamble detection probability and limited downlink resources. To make the analysis of this complex system tractable, the authors made some approximations and only captured the expected value of the system state rather than the probability distribution. Tyagi et al. used Poisson distribution to estimate the number of requests with the access barring and preamble contention in RA [15].

There are few studies focus on the transmission details of other SI with precise analysis. In our work, we list all the design options for SI acquisition. Furthermore, we analyze all cases with mathematical models and validate the theoretic models with simulation results. The proposed theoretic framework serves as the foundation to understand the emerging on-demand SI in 5G NR and provide insights in choosing the on-demand SIB option in different operational environments.

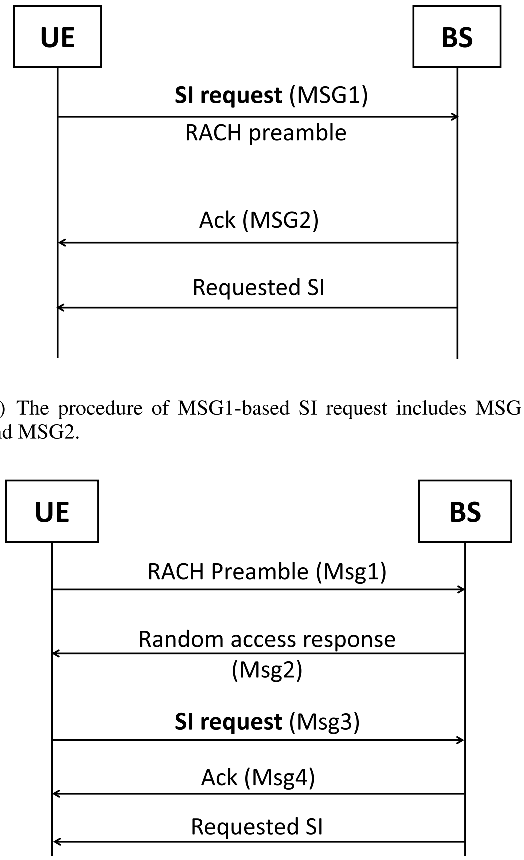
III. DISTRIBUTION OF ON-DEMAND SYSTEM INFORMATION

This section describes the SI acquisition process, which includes SI requesting and SI delivery. Among all the considered dimensions, only LBR is not mentioned in the standard since it is a UE implement issue. When a UE needs updated SI information. the UE may try to listen for the SIB passively or may proactively send SI request. As for the BS, it transmits the corresponding SIB after receiving the request. The process ends with the successful delivery of SIB or the failed UE SIB reception. In this section, we will describe the design options for SI request and SI delivery, respectively.

A. SI REQUEST

1) REQUEST MECHANISM

A UE could request the on-demand SI through the contention-based 4-step random access (RA) procedure [7]. Typically, the first message of the RA procedure is a RACH preamble (MSG1). After receiving the preamble, the BS transmits an RA response (RAR). In the third step, the UE uses the resource granted in the RAR to send the message 3 (MSG3) which contains the identification of the UE. At last, the BS delivers a contention resolution message to the UE. When more than one UE selects the same preamble in the first step, these UEs will receive the same granted physical resources in message 2 (MSG2). Due to the different identifications in MSG3 from each UE, the BS cannot recognize the different information overlapping in the same physical resource; thus, collision occurs, and the UEs fail to finish in the RA procedure. It is worth noting that this RA procedure can be applied to many events, such as initial access and the request for SI. Furthermore, RA resources are provided periodically. We configure the period of RA resources as the same period of SI window in our system; the UEs requesting SI will use RACH resource more efficiently. SI requests can be sent via MSG1 or MSG3. The signaling flow for the SI request is shown in Fig. 3.



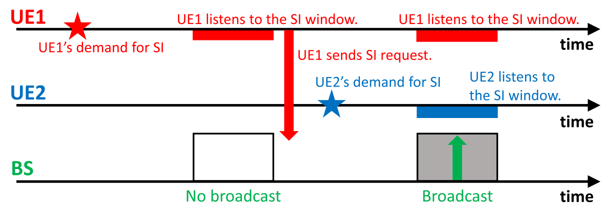
(a) The procedure of MSG1-based SI request includes MSG1 and MSG2.

(b) The procedure of MSG3-based SI request incldues MSG1, MSG2, MSG3 and MSG4.

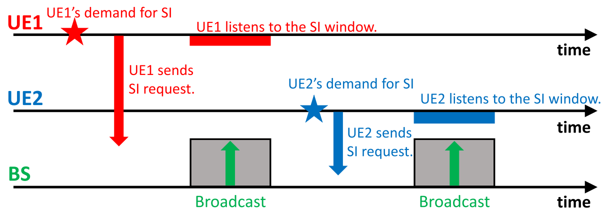
FIGURE 3. The message flows of two different SI request mechanisms.

a: MSG1-BASED REQUEST

In MSG1-based SI request, as shown in Fig. 3(a), UEs obtain the information of the preambles used for requesting SI from the *minimum SI*. One preamble can be used to acquire one SIB or a set of SIBs [8]. In our system, we bind one preamble to one SIB. One UE asks for one SIB at a time for simplification. At first, the UE sends the specific RACH preamble to request the SI (MSG1). After receiving the preamble, the BS acknowledges the request by MSG2 and broadcast the SIB in the SI window according to the received preamble. This method only involves the first two steps of RA procedure (i.e. The transmissions of MSG1 and MSG2). When more than one UE requests the same SI with the same preamble, the sequences of the preamble sent by different UEs could be successfully decoded by the BS without collision. Thus, the requests for the same SI will succeed. The advantage of the MSG1-based SI request is that this method can avoid



(a) On-demand broadcast SI delivery with LBR. In the first period, the SI demand of UE1 arrives. It first listens to the SI window and finds that the desired SI is not broadcast. Thus, UE1 sends an SI request and receives the SI in the second period. Without sending its request, UE2 could directly receive the SI with the LBR mechanism.



(b) On-demand broadcast SI delivery without LBR. The UEs send the requests immediately after the demands for SI arrive; thus, the UEs could receive the SI in the same period.

FIGURE 4. System operations with/without Listen Before Request (LBR).

RA collision and only needs the transmission of MSG1 and MSG2. Nevertheless, it requires a preamble reservation for SIBs, which may lead to performance issues when the RACH resource is insufficient.

b: MSG3-BASED REQUEST

The UE using the MSG3-based method sends the SI request in MSG3, in which the 4-step RA procedure is applied, as shown in Fig. 3(b). The UE first transmits a randomly selected RACH preamble. The BS responds MSG1 by delivering the RAR corresponding to each preamble. This means if more than one UE chooses the same preamble, they will receive the same RAR, which indicates the same physical resource used for MSG3. After BS transmits the RAR (MSG2), the UE uses the resource granted in RAR to send the SI request (MSG3). The packets with different information sent in the same physical resource will not be recognized by the BS, and the SI request fails. On the contrary, if there is no collision, the BS will deliver MSG4 and the requested SI after receiving the successful SI request. The benefit of using MSG3 to deliver SI requests is that the system does not need to reserve preambles. However, the SI request would fail when more than one UE chooses the same preamble.

2) LISTEN BEFORE REQUEST (LBR)

If the BS broadcast the on-demand SI, a UE can check the SI window before sending the request. If the required SI is broadcast in the SI window, the UE can save the power and physical resources of requesting. Otherwise, the UE sends the request in the next period and the delay is longer. This mechanism is called Listen Before Request (LBR). For example, UE1 and UE2 are in the same broadcast area, and they need the same SIB. The arrivals of their demands are shown in Fig. 4. In Fig. 4(a), when UE1's demand arrives in the first period, it starts LBR and monitors the SI window first. If it finds that the desired SI is not broadcast, it requests in the next period. In this case, if UE2's demand for the same SI also arrives and perform LBR in the second period, then UE1 and UE2 could both receive the broadcast SIB in SI window during the second period. Fig. 4(b) shows the case without LBR. UE1's demand arrives and requests the wanted SIB in the first period, and UE1 receives the SIB in the SI window of the first period. Later, UE2's demand arrives in the next period. UE2 requests and receives the required SIB in the second period. We can see that the broadcast resources used in the case with LBR are half of that in the case without LBR. Also, UE2 in the LBR case saves the power and resources for requesting SI. However, UE1 in the LBR case experiences longer delay and more power consumption.

B. *SI DELIVERY*

1) DELIVERY MECHANISMS

The delivery of SIBs from the BS to UE can also be broadcasting or unicasting. When the BS transmits SIBs through unicasting, it needs to identify the UE. For the UEs in Idle/Inactive mode, MSG1-based SI request does not provide the identification of UEs for the BS, so the SI request in the on-demand unicasting case can not be MSG1-based. On the other hand, the SI request in the unicasting case can be MSG3-based because MSG3 contains the UE ID. In contrast, the SI request can be either MSG1-based or MSG3-based in the broadcasting case. Moreover, the BS can broadcast to the UE under the whole cell area or just under the beam where it receives the request. Single-beam broadcasting and beam-sweeping in multiple beams lead to different broadcast area, number of receiving UEs, and transmission overhead.

a: UNICASTING

In the unicasting case, the UE requests SI in MSG3 and the required SIB can only be received by the UE who sent SI request. For example, the three UEs who need the same on-demand SIB are in the coverage of the BS, and UE1 and UE2 are in the same beam area, as shown in Fig. 5. In the unicasting case, only UE1 sends the SI request and the BS only unicasts the SIB to UE1. UE2 and UE3 could not receive the SIB. Furthermore, the transmission of SI is not broadcast in the SI window. The delay in the unicasting case only relates to the cycle of RA procedure, which could be shorter than the

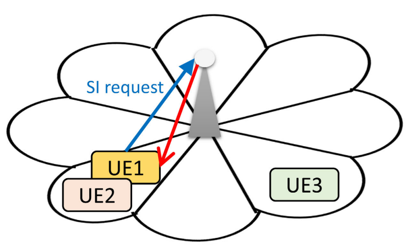


FIGURE 5. Illustrative example of unicasting SI delivery. If three UEs need the same SI, and UE1 sends the SI request to the BS. The BS unicasts the SI to UE1. In this case, UE2 and UE3 could not receive the SI.

period of SI window, so the delay could also be shorter than the broadcasting cases. However, we configure the period of RA and SI window to be the same in our evaluation, so the latency remains the same in the results. On the other hand, the signaling overhead increases significantly when the number of SI requests increases, which may have a negative impact on the system.

b: BROADCASTING WITH BEAM SWEEPING

When the BS uses beam sweeping, the broadcast area is covered by the total ν beams. In Fig. 6, UE1 delivers an SI request and the request is received by one of the BS beams. After receiving the SI request, the BS broadcasts the SIB with all beams no matter where the request came from in the beam sweeping case. All UEs receive the wanted SIB. It takes more bits to cover a larger broadcast area. Meanwhile, UEs have more opportunities to receive SI. When the BS broadcasts SI, all the UEs in the broadcast area can receive even if the UE which failed the SI request or has not requested yet, such as the UE2 and UE3 in the figure.

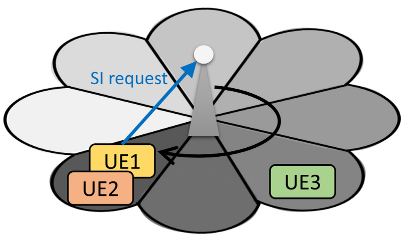


FIGURE 6. **Illustrative example of beam-sweeping broadcasting SI delivery. If three UEs need the same SI, and UE1 sends the SI request to the BS. The BS broadcasts the SI with beam sweeping, so all three UEs could receive the SI.**

c: SINGLE BEAM BROADCAST

The broadcast area is only the single-beam coverage when the BS applies single-beam broadcasting. The BS can only broadcast with a specific beam rather than all beams. In Fig. 7, after UE1 successfully sends the SI request, only the beam covering UE1 broadcasts the requested SI. In other words, the BS only replies to the SI request using the beam where it receives the request. Other UEs who are out of the coverage will not receive the broadcast SIB. In the example, both the UE1 and UE2 receive the required SI, but the UE3 under different beam area can not receive it. This design can still

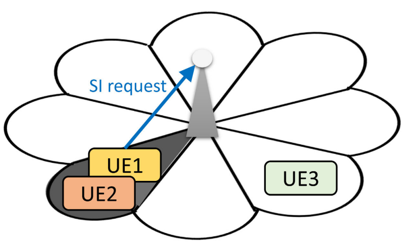


FIGURE 7. **Illustrative example of single-beam broadcasting SI delivery. If three UEs need the same SI, and UE1 sends the SI request to the BS. The BS broadcasts the SI on the beam which covers UE1 without beam sweeping. Therefore, UE1 and UE2 could receive the SI, but UE3 could not receive.**

deliver the SI to the UE which has sent the request and the BS can broadcast with fewer beams to save the physical resource. For UEs, this design decreases the probability of broadcast for every single beam. Comparing the illustrative examples in Fig. 6 and Fig. 7, UE3 only receives the SIB in the beam-sweeping broadcasting case, while UE1 and UE2 receive it in both cases.

IV. DESIGN OPTIONS

In the previous section, we described the technical components in SI acquisition protocol design. Now, we describe all the combinations of those technical components and summarize all the ten design options in Table 1. Protocol abbreviation is applied. For SI delivery, periodically broadcasting is denoted as "PB", on-demand broadcasting is denoted as "OB", and on-demand unicasting is denoted as "OU". In broadcasting delivery, beam-sweeping is annotated with "S"; on the contrary, single-beam broadcasting is annotated without "S". For SI request, MSG1-based and MSG3-based SI are denoted as "M1" and "M3", respectively. When LBR (Listen Before Request) is applied, "L" is used.

A. PB

This is the method used in LTE. The BS broadcasts all SIBs according to the configured periods and here we configure the period of all SIBs to be the same. The UE only needs to monitor the broadcast channel where the BS broadcasts the SI. There is no SI request, so this method is not MSG1/MSG3-based and cannot apply LBR. Furthermore, the BS has no information about where the requirement of SI from, so the BS broadcasts over the whole cell with beam sweeping.

B. OB (M1, S, L)

This case is the MSG1-based on-demand broadcast with beam sweeping and LBR. When the requirement of SI arrives, the UE checks the nearest SI window whether the SIB is transmitted. Rather than sending a request directly, LBR has the probability to save the physical resource and power. If the UE does not receive the wanted SI, it would send the preamble for SI request in the next period. In the case that UE fails to acquire the SI before request, this failure increases the total delay. For the BS, it broadcasts the SI with all BS beams after receiving the request. The beam sweeping increases the total number of broadcast in each BS beam, which leads to better performance of LBR.

C. OB (M1, S)

At first, the UE directly sends the preamble to indicate the SI it requires after the demand for that SI appears. The BS replies by MSG2 and broadcasts the requested SIB in the next SI window. The difference between this case and the OB (M1, S, L) is the UE behavior LBR. As mentioned above, beam sweeping benefits the LBR. However, when there is no LBR, the broadcast SIBs are only received by the UE which sent the SI request. The increment of the broadcast area does not lead to additional successful SI delivery. However,

TABLE 1. The design options for all possible cases.

Case	Abbreviation	Delivery occasion	Casting method	UE request message	Beam sweeping	LBR	Related work
1	PB	Periodic	Broadcast	NA	Yes	No	[10]*, [11]†
2	OB (M1, S, L)	On-demand	Broadcast	MSG1	Yes	Yes	NA
3	OB (M1, S)	On-demand	Broadcast	MSG1	Yes	No	[12]‡
4	OB (M1, L)	On-demand	Broadcast	MSG1	No	Yes	NA
5	OB (M1)	On-demand	Broadcast	MSG1	No	No	[12]‡
6	OB (M3, S, L)	On-demand	Broadcast	MSG3	Yes	Yes	NA
7	OB (M3, S)	On-demand	Broadcast	MSG3	Yes	No	[11]†
8	OB (M3, L)	On-demand	Broadcast	MSG3	No	Yes	NA
9	OB (M3)	On-demand	Broadcast	MSG3	No	No	NA
10	OU	On-demand	Unicast	MSG3	No	No	[10]*, [11]†

∗: In this work, signaling overhead and energy consumption are evaluated, but delay was not considered. RA procedure was not considered, either.
†: This work only provides simulation for performance evaluation. No analytical model is proposed.
‡: This work focus on the improvement of broadcasting rather than the on-demand mechanism. RA procedure was not considered.

the signaling overhead increases because of the additional transmission.

D. OB (M1, L)

This case can be regarded as the OB (M1, S, L) (case 2) without beam sweeping. The UE checks the SI window first after the UE's demand for the SIB appears. If the BS is broadcasting the SIB that the UE wants, the UE receives it. Otherwise, if the BS is not broadcasting the SIB that the UE requires, the UE starts to request in the next period. The UE sends the preamble in the first step, receives the acknowledgment in MSG2, and gets the SIB in the SI window. This procedure looks the same for UEs in case 2, but the difference is the probability of receiving SIBs. The beams that did not receive the successful SI request may deliver the SIB in case 2, but would not deliver the SIB in this case. Only the successful SI request in the beam's coverage evokes the BS to broadcast the SIB via that beam. The removal of beam sweeping saves the signaling overhead but decreases the number of successful SI receptions during listening, which may cost more delay and UE power.

E. OB (M1)

In this case, when the UE needs the SIB, it directly sends the specific preamble to request the SIB. The BS will reply by an RAR, and then broadcast the required SI to the beam area where it received the preamble in the next SI window. All the UEs can finish the delivery process in a period and only need to transmit a preamble. The pros of this mechanism are a shorter delay and power saving for UEs. Besides, the single-beam broadcasting is more efficient than the beam sweeping case because the UE which did not send the request would not monitor the SI window. However, the reservation of preambles wastes the physical resources when the resources are not used.

F. OB (M3, S, L)

UEs, in this case, use the MSG3-based SI request and monitor the SI window before sending the request. The BS broadcasts the SIB over the whole cell area after receiving at least one successful SI request. When the SI requirement occurs, the UE listens to the next SI window to check if the SIB that the UE wants is broadcast. If the UE receives the needed SIB, the process ends; otherwise, the UE sends the request in the next period. First, the UE sends a randomly selected preamble. The BS responds to the preamble by the RAR. The UE then sends the SI request in MSG3 with the resource granted in RAR. After sending MSG3, the UE sets a timer and waits for MSG4. Meanwhile, the BS transmits MSG4 after receiving MSG3. However, MSG3 may collide when more than one UE sends the distinct MSG3 in the same physical resource. This collision happens when more than one UE selects the same preamble because the resource used in MSG3 is related to the preamble that the UE sent. When MSG3 collides, the BS will not deliver MSG4 and the timer UE set will expire. However, the UE still has the chance to receive the required SIB if somebody else successfully requests the SIB and the BS will broadcast that. Therefore, the UE checks the next SI window no matter whether the SI request succeeds or not. In this case, the MSG3-based SI request is used, which costs more UE power than the MSG1-based method due to the increment of steps. On the contrary, the combination of beam sweeping broadcast and LBR can effectively save the UE delay and the number of transmissions.

G. OB (M3, S)

This case is similar to OB (M1, S), but the SI request is MSG3-based. The UE transmits one randomly selected preamble when it needs a SIB. The BS receives the preamble and replies to the UE with MSG2 that assigns a resource for MSG3. After the UE receives MSG2, it delivers MSG3 and waits for MSG4. The preamble collision may happen and the UE will not receive MSG4. However, the UE may still receive the broadcast SIB if the transmission of SIB is triggered by other successful SI requests. Therefore, all UEs will check the SI window, which means all UEs consume the same amount of energy. The case without LBR saves UE's time on average. Beam sweeping increases the probability of receiving, which compensates for the failure of SI request.

H. OB (M3, L)

The UE listens to the SI window first when the UE needs the SIB. If the required SIB is broadcast in the SI window, the UE will receive it. Otherwise, the UE goes through the RA procedure to request SI. First, the UE sends a preamble. The BS receives the preamble that the UE randomly selected and replies with MSG2. After the UE receives MSG2, it sends MSG3 to request SI. If the collision happened, MSG4 would not be sent. However, the UE still listens to the SI window to check if the BS broadcasts the required SIB. If MSG3 did not collide, the UE will receive MSG4 from the BS and receive the wanted SIB in the next SI window. This process is almost the same as the OB (M1, S, L). The only difference is that the BS only broadcasts SIBs by the beam area where it received the successful SI request rather than all BS beams. This difference saves the BS's signaling overhead but decreases the probability that UE receives the required SIB.

I. OB (M3)

This case can be thought of as the OB (M3, S) without beam sweeping. At first, the UE delivers the randomly selected preamble without checking the SI window when it requires a SIB. After the preamble received by the BS, the BS delivers an RAR. Then the UE sends MSG3 to indicate the need of SI. If MSG3 is successfully received by the BS, the BS will broadcast the requested SIB by the beam that received MSG3. Since the SIB is broadcast in this case, the UE failed to request SI has the probability to receive the broadcast SIB. But the decrement of the broadcast area reduces that probability.

J. OU

The last one is the on-demand unicast case. The BS needs the UE ID in MSG3 to identify the UE. Therefore, the SI request of a unicast case can only be MSG3-based. Further, beam sweeping and LBR are meaningless since other UEs cannot recognize the unicasted packet toward a specific UE. The UE can only receive the SIB requested by itself. At first, the UE randomly selects a preamble and transmits the preamble to the BS. The BS replies an RAR and the UE sends the SI request in the resource granted in the RAR. MSG3 may collide and the SI request fails. If the SI request is successfully received by the BS, the BS will deliver an ACK (MSG4) and the required SI to the UE which requested the SI. With unicasting, the number of SIB deliveries is proportional to the number of successful SI requests. Thus, the signaling overhead of unicasting significantly increases when the number of SI requests is large.

V. THEORETIC MODELS FOR COMPARATIVE PERFORMANCE ANALYSIS

In this work, we aim to create a theoretic framework to quantitatively evaluate the system performance. In the proposed performance analysis framework, we will first quantitatively analyze the performance of protocol components. Then, we will investigate the ten design options, as listed in Table 1. In the proposed performance evaluation framework, we derive and compare the ten protocol options with three performance metrics: (1) signaling overhead (Ωs) (2) SI delay (Ωd) (3) power consumption (Ωp).

In the mmWave 5G system, we formulate the performance models with one BS which uses ν beams to cover its serving area. There are K kinds of SIB (SIBi, $i \in \{1, 2, \ldots, K\}$). We consider the arrival of SI demands from the view of BS. For the BS, the arrival of one kind SI, i.e. SIBk, demands under a BS is a Poisson process with the arrival rate λ. The arrival of SIBk demands is also uniformly distributed over the cell. We configure the arrival of each kind SIB is identical. Thus, the arrival rate of all SI demands under a BS is λK. Moreover, let the period of the SI window be T_b for all SIBs. We configure the BS to always respond to the successful SI request in a period and the physical channel is ideal. Thus, only the RA procedure causes the probability of failure.

A. ANALYSIS OF PROTOCOL COMPONENTS

First, we will look into the performance of the following three protocol design components in this sub-section.

- SI Request mechanisms using MSG1 or MSG3
- Beams weeping and mmWave broadcasting
- SI Request with LBR (Listen Before Request)

1) MSG1/MSG3-BASED

All the MSG1-based SI requests in our model succeed because MSG3 is not delivered in the request process. UEs will receive the required SI in the next SI window. In the view of the BS, it receives the preamble when at least one UE sends the SI request in an SI period T_b. Therefore, the successful probability of SI request is 1 when there is any request in the period. Let the number of Poisson distributed SIBk requests sent in T_b in the broadcast area be N. The broadcast area is where one broadcast message covered. We have a more detailed discussion about the broadcast area in the next sub-section. The probability that a SIBk request is successfully sent by MSG1-based method, i.e. α_1, is

$$\alpha_1(N = n) = \begin{cases} 1, & n > 0 \\ 0, & otherwise \end{cases} \tag{1}$$

On the other hand, the MSG3-based SI request transmission completes only when MSG3 does not collide. Thus, we need to consider both the probability of collision and the number of requests involved in the contention. The M SI requests are all involved in the preamble contention. Let the number of available preambles be δ. The probability that another UE selects one different preamble is $(1 - \frac{1}{\delta})$. This means that other UEs choose the other $(\delta - 1)$ RACH preambles. The number of other UEs is $M - 1$, where M is the total number and the 1 represents the UE itself. Thus, the probability that one UE sends a successful MSG3-based SI request, i.e. α_3, is

$$\alpha_3(M = m) = \begin{cases} (1 - \dfrac{1}{\delta})^{m-1}, & m > 0 \\ 0, & otherwise \end{cases} \tag{2}$$

2) BEAM SWEEPING

The broadcast area is where one broadcast message covered. Thus, the broadcast area is decided by the broadcast mechanism, i.e. the area of broadcasting with beam sweeping and single-beam broadcasting are the whole-cell coverage and the single-beam coverage. The BS will broadcast the SI when it receives at least one SI request from the UEs in the broadcast area. On the basis of the assumption that the SI requests are uniformly distributed over the cell area, the larger the broadcast area, the higher the probability that the BS receives successful SI requests. When there are N SIBk requests in the broadcast area, the probability that the BS receives at least one successful SI request is β_i, where $i \in \{1, 3\}$ represents the probability in the MSG1 and MSG3-based cases. We have

$$\beta_i(N = n) = 1 - (1 - \alpha_i)^n \tag{3}$$

Equation (3) means at least one UE successfully sends the SI request in the broadcast area.

3) LBR

In the cases with LBR, the UE monitors the channel first before directly sending the SI request. We use the β_i derived from (3). Let the probability that the BS broadcasts one kind of SIB with LBR in period t be γ_L^t. The probability of broadcasting with LBR can be solved using Markov Chain:

$$\begin{bmatrix} \gamma_L^{t+1} \\ 1-\gamma_L^{t+1} \end{bmatrix} = \begin{bmatrix} 0 & \beta_i \\ 1 & 1-\beta_i \end{bmatrix} \begin{bmatrix} \gamma_L^{t} \\ 1-\gamma_L^{t} \end{bmatrix} \tag{4}$$

Because of LBR and our system configurations, the BS only broadcasts the SI when it did not broadcast in the last period and it successfully receives the SI request. When the BS broadcast in the last period, all UEs received the SIB in the last period. In the current period, only the UEs with new demands for SI need the SIB. The UEs with new demands for SI only monitor the SI window, so no one sends SI request and no SIB is broadcast. In the transition matrix, we can see the probability that transferring from broadcast state to broadcast state is 0 because the UEs have already received the SIB in the last period t and no UE will send the request in period $t + 1$. The probability that transferring from no broadcast state to broadcast state is β_i because the probability that the BS successfully receives the SI request is β_i when the BS did not broadcast in the last period t. By the definition of the transition matrix, the probability that transferring from broadcast state to no broadcast state is 1. And the probability transferring from no broadcast state to no broadcast state is $1 - \beta_i$. Solve the (4) in steady-state and we have

$$\gamma_L = \frac{\beta_i}{1 + \beta_i} \tag{5}$$

The BS will broadcast the SIBk after it receives a successful SI request in the case without LBR. Therefore, the probability that the BS broadcasts SIBk is the same as the probability that the BS received a successful SI request.

$$\gamma_{L'} = \beta_i \tag{6}$$

For the latter analysis, we discuss the number of preambles used for one kind of SIB, i.e. SIBk, in one BS beam area, i.e. M_p, and the number of the successful SIBk requests in one BS beam area, i.e. M_s, here. Since these two values are related to the RA procedure before the SI delivery, they are only related to the LBR design and the request mechanism, not the delivery mechanism. We discuss the M_p and M_s in the cases with LBR, i.e. $M_{p(i,L)}$ and $M_{s(L)}$. The notations used for the cases without LBR are $M_{p(i,L')}$ and $M_{s(L')}$. The i shown in M_p is 1 or 3, which indicates the MSG1 or MSG3-based SI request.

First, we discuss the $M_{p(1,L)}$ in the MSG1-based delivery. The number of the used preambles is 1 when there is one or more SI request. And the probability that there is at least one SIBk request is $(1 - e^{-\frac{\lambda T_b}{\nu}}) \times (1 - \gamma_L)$. It means there is at least one arrival of UEs' demands for SIBk in this period and the BS did not broadcast in the last period. Therefore, the expected value of $M_{p(1,L)}$ is

$$E[M_{p(1,L)}] = (1 - e^{-\frac{\lambda T_b}{\nu}}) \times (1 - \gamma_L) \tag{7}$$

In the case without LBR, the number of used preambles is 1 when there is one or more arrivals of the demands for SIBk.

$$E[M_{p(1,L')}] = (1 - e^{-\frac{\lambda T_b}{\nu}}) \tag{8}$$

Second, we consider the MSG3-based case. Let the arrival rate of all SIBk demands in T_b be $\lambda_M = \frac{\lambda K}{\nu}$. The probability that a preamble is randomly selected by a UE from the total δ preambles is $\frac{1}{\delta}$. When there are Q request attempts, the probability that a preamble is selected by at least one UE is $1 - (1 - \frac{1}{\delta})^Q$. With this probability, the expected number of the preambles used is

$$E[M_{p(3)}] = \sum_{q=0}^{\infty} P(Q = q) \times \delta(1 - (1 - \frac{1}{\delta})^q) \tag{9}$$

In the cases with LBR, the UEs sent MSG1 only when the required SIB was not broadcast in the last period. Therefore, we multiply the probability that there was no broadcast in the last period by the $P(Q = q)$. Thus, we have

$$E[M_{p(3,L)}] = \sum_{q=0}^{\infty} \frac{(\lambda_M T_b)^q e^{-\lambda_M T_b}}{q!} (1 - \gamma_L)\delta(1 - (1 - \frac{1}{\delta})^q) \tag{10}$$

$$= (1 - \gamma_L)\delta(1 - e^{-\frac{\lambda_M T_b}{\delta}}) \tag{11}$$

In the cases without LBR, Q equals to the number of UEs' demands for SIBk. By (9), the expected number of the used preambles in cases without LBR, i.e. $E[M_{p(L')}]$, is

$$E[M_{p(3,L')}] = \sum_{q=0}^{\infty} \frac{(\lambda_M T_b)^q e^{-\lambda_M T_b}}{q!} \delta(1 - (1 - \frac{1}{\delta})^q)$$
$$= \delta(1 - e^{-\frac{\lambda_M T_b}{\delta}}) \tag{12}$$

By the definition of α, we can say that α is the successful probability of each SI request, as mentioned in (2). Thus, the expected number of successful SIBk requests is

$$E[M_s] = \sum_{m=0}^{\infty} m \times P(M = m) \times \alpha_3(M = m) \quad (13)$$

In the cases with LBR, the SIBk request only occurs when there was no broadcast SIBk in the last period, so the probability $(1 - \gamma_L)$ is included in the $P(M = m)$. With the results of (2) and (13), the $E[M_s]$ in the cases with LBR is

$$\begin{aligned} E[M_{s(L)}] &= \sum_{m=0}^{\infty} m \times \frac{(\lambda_M T_b)^m e^{-\lambda_M T_b}}{m!}(1-\gamma_L)(1-\frac{1}{\delta})^{m-1} \\ &= \lambda_M T_b(1-\gamma_L)e^{-\frac{\lambda_M T_b}{\delta}} \end{aligned} \quad (14)$$

The $E[M_s]$ in the case without LBR, i.e. $E[M_{s(L')}]$, is similar to $E[M_{s(L)}]$. The only difference is that the UEs send requests no matter whether the BS broadcast in the last period. Therefore, we have

$$\begin{aligned} E[M_{s(L')}] &= \sum_{m=0}^{\infty} m \times \frac{(\lambda_M T_b)^m e^{-\lambda_M T_b}}{m!} \times (1-\frac{1}{\delta})^{m-1} \\ &= \lambda_M T_b e^{-\frac{\lambda_M T_b}{\delta}} \end{aligned} \quad (15)$$

B. PERFORMANCE EVALUATION METRICS

We will evaluate the ten design options with three performance metrics: signaling overhead, delay, and UE power consumption. The signaling overhead is considered to be the total bits transmitted in an SI period. We use the delay to present the expected time from an SI request arrival to the reception of the required SIB, and sum up the total power consumed by all UEs under the BS as the UE power consumption. We use Ωs_n, Ωd_n and Ωp_n to represent the signaling overhead, delay, and UE power consumption in the case n respectively. Table 2 summarizes all the notations used in the following analysis.

1) SIGNALING OVERHEAD, Ωs

We use B_1, B_2, B_3, B_4 to represent the size of MSG1, MSG2, MSG3, MSG4. B_{SI} is the size of one SIB, and we configure the size of all kinds of SIB to be the same. In the PB case, only the broadcast SIB is transmitted, so we have

Lemma 1: The signaling overhead for the periodic broadcast case is

$$\Omega s_1 = B_{SI} \times \nu \times K$$

The physical resources used by each BS beam are the same, so we multiply the size of SIB by the number of BS beams. Furthermore, as we configure the size of all SIBs to be the same, we multiply the signaling overhead of one SIB by K.

In the MSG1-based OB cases, three messages are delivered. The first one is the RACH preamble. The preambles are reserved in the MSG1-based cases. Therefore, the signaling overhead of MSG1 is a fixed number, i.e. $B_1 \times \nu \times K$. Second, MSG2 is transmitted by the BS beam where the BS received the preamble, so the signaling overhead of MSG2 is related to the number of used preambles, known as M_p. At last, the SIB is broadcast when the BS received requests in the broadcast area. The BS will broadcast the SIB once it received the request, so the probability that the BS receives the request is equal to the probability that the BS broadcasts, i.e. γ.

Lemma 2: The signaling overhead for the MSG1-based OB case is

$$\Omega s_i = (B_1 + B_2\, E[M_p] + B_{SI}\, \gamma) \times \nu \times K, \ i \in \{2, 3, 4, 5\}$$

The MSG3-based OB cases utilize the RA procedure. In the RA procedure, MSG1 is the randomly selected preamble, MSG2 is replied according to the preamble, and MSG3 is delivered in the physical resource assigned by MSG2. Therefore, the signaling overhead of MSG1, MSG2, and MSG3 are proportional to the number of used preambles, i.e. M_p. As for MSG4, it is transmitted if the SI request in MSG3 succeeded. Thus, the number of MSG4 equals to the number of successful SI requests, i.e. M_s. The signaling overhead of transmitting SIB is similar to that in the MSG1-based cases.

Lemma 3: The signaling overhead for the MSG3-based on-demand broadcast case is

$$\begin{aligned} \Omega s_i = ((B_1 + B_2 + B_3)&E[M_p] + B_4\, E[M_s] \\ &+ B_{SI} \times \gamma) \times \nu \times K, \ i \in \{6, 7, 8, 9\} \end{aligned}$$

The UEs in the OU case go through the RA procedure, so the analysis of MSG1, MSG2, MSG3 and MSG4 in the OU case is the same as the analysis in the MSG3-based OB cases. Only the delivery of SIB is different. The number of unicast SIBs is proportional to the number of the successful SI requests and is also the same as the number of MSG4.

Lemma 4: The signaling overhead for the on-demand unicasting case is

$$\Omega s_{10} = ((B_1 + B_2 + B_3)E[M_p] + (B_4 + B_{SI})E[M_s]) \times \nu \times K$$

2) DELAY, Ωd

Owing to the configurations in our system, the expected delay for the UEs that successfully receive the required SI is only related to the LBR design. When there is no LBR, the delay is $\frac{T_b}{2}$, which is proved in the appendix. When there is LBR, the UE has the chance to finish in that period or the next period. The delay for the successful and failed listening are $\frac{T_b}{2}$ and $\frac{T_b}{2} + T_b$ respectively.

Lemma 5: The delay in the case without LBR is

$$\Omega d_i = \frac{T_b}{2}, i \ \in \{1, 3, 5, 7, 9, 10\}$$

Lemma 6: The delay in the case with LBR is

$$\Omega d_i = \frac{T_b}{2} + (1 - \gamma_L)T_b, i \in \{2, 4, 6, 8\}$$

TABLE 2. The notations used in the analysis.

Notation	Description
δ	The number of preambles
K	The number of *other SI*'s kinds
λ	The arrival rate of one kind SIB under one BS
T_b	The period of the SI window
ν	The number of BS beams
$B_1/B_2/B_3/B_4$	The size of MSG1/MSG2/MSG3/MSG4
B_{SI}	The size of one SIB
M	The number of all SI requests in T_b in one beam area
$M_{p(i,L)}$	The number of preambles used in one beam area in the MSGi based case with LBR, $i \in \{1,3\}$
$M_{p(i,L')}$	The number of preambles used in one beam area in the MSGi based case without LBR, $i \in \{1,3\}$
$M_{s(L)}/M_{s(L')}$	The number of successful SIBk requests in T_b in one beam area with/without LBR
N	The number of SIBk requests sent in T_b in the broadcast area
Ωs_i	The signaling overhead that the system consumes in a period in case i, $i \in \{1, 2, ..., 10\}$
Ωd_i	The delay for a UE from the SI demand to receiving the wanted SIB in case i, $i \in \{1, 2, ..., 10\}$
Ωp_i	The power UEs consume for receiving SIBk in a period in case i, $i \in \{1, 2, ..., 10\}$
e_1/e_3	The energy consumed by the UE when the UE transmits the MSG1/MSG3
e_2/e_4	The energy consumed by the UE when the UE receives the MSG2/MSG4
e_{SI}	The energy consumed by the UE when the UE receives the SIB
α_i	The probability that one UE successfully sends an MSGi based SIBk request, $i \in \{1,3\}$
β_i	The probability that the BS receives more than one successful MSGi based SIBk request, $i \in \{1,3\}$
$\beta_{i,S}/\beta_{i,S'}$	The probability that the BS receives more than one successful MSGibased SIBk request in the case with/without beam sweeping, $i \in \{1,3\}$
$\gamma_L/\gamma_{L'}$	The probability that one BS beam broadcasts the SIBk in the cases with/without LBR
γ_X	The probability that one BS beam broadcasts the SIBk in X case; X is the abbreviation of the case

3) UE POWER CONSUMPTION, Ωp

We consider the UE power consumption for all UEs that require a specific kind of SIB, namely SIBk, and sum up the power in each step. In the PB case, the UE only receives the SIBk in the SI window. In the OB case, since the UE which fails the SI request still has the opportunity to receive the SIBk, all UEs monitor the SI window after sending the SI request. All UEs consume the same amount of transmitting power and receiving power. However, the UE in the unicasting case cannot receive the SIBk when the request is failed, and the SI window is not applied in this case. We discuss the details for each case in the following subsection.

C. ANALYSIS OF ALL DESIGN CASES

Now, we will analyze the performance with all ten design options one-by-one.

1) PB

The BS broadcasts all SIBs in each period, i.e. $\gamma_{PB} = 1$. By Lemma 1 and 5, we get

$$\Omega s_1 = B_{SI}\nu K$$
$$\Omega d_1 = \frac{T_b}{2}$$

The UEs receive the SI in the SI window and do not need to request. Therefore, only the power used for receiving SIB is consumed.

$$\Omega p_1 = e_{SI}\lambda$$

2) OB(M1, S, L)

UEs apply LBR and use MSG1 to request SI, and the BS broadcasts with beam sweeping. In this case, the UEs will monitor the SI window first after the UE's demand arrives. If the wanted SIB is not broadcast in the SI window, they send the preamble to request the SI. The BS broadcasts the SIB with beam sweeping after receiving the corresponding preamble.

In the following analysis of the cases with LBR, we first configure the α and β without considering LBR. The influence of LBR is only considered in γ. Thus, when we analyze α and β in each case. The arrival of SI demand is equal to the arrival of SI requests because the UEs without performing LBR directly send SI requests. According to the property of Poisson distribution, the probability that more than one SIBk request arrives in T_b with arrival rate λ, i.e. $P(N > 0)$, is $1 - e^{-\lambda T_b}$. Combining (1) and (3), we get

$$\begin{aligned}\beta_{1,S} &= P(N=0)(1-(1-0)^0) \\ &\quad + \sum_{n=1}^{\infty} P(N=n)(1-(1-1)^n) \\ &= 1 - e^{-\lambda T_b} \qquad (16)\end{aligned}$$

With the $\beta_{1,S}$, we get the stable state probability of broadcasting in this case by (5):

$$\gamma_{OB(M1,S,L)} = \frac{1 - e^{-\lambda T_b}}{2 - e^{-\lambda T_b}} \qquad (17)$$

The expected number of used preambles in (7) or (8) is utilized for analyzing the signaling overhead in this and the following MSG1-based cases. By Lemma 16, the signaling overhead is

$$\Omega s_2 = (B_1 + B_2\, E[M_{p(1,L)}] + B_{SI}\ \gamma_{OB(M1,S,L)})\nu K$$

As for the delay, the probability that the UE receives the required SIB in the second period is equal to the probability that the BS does not broadcast in that first period. By Lemma 6, the delay is

$$\Omega d_2 = \frac{T_b}{2} + (1 - \gamma_{OB(M1,S,L)})T_b$$

The analysis of UE power consumption is similar to the analysis of delay. The power consumed by the UEs receiving SIBk in the first period is $e_{SI}\lambda T_b$. When the UE receives the SI in the second period, we can divide the power consumption into four parts. First, the power that UEs consumes when listening to the SI window in the first period is $e_{SI}\lambda T_b$. Second, the power used for transmitting the preamble is $e_1\lambda T_b$, and the power consumed by the UE for receiving MSG2 is $e_2\lambda T_b$. Last, the power consumed for receiving the SIB in the SI window is $e_{SI}\lambda T_b$. Thus, we can get the total power consumption by summing up the power multiplied by the probability of each case.

$$\Omega p_2 = e_{SI}\lambda + (1 - \gamma_{OB(M1,S,L)})(e_1 + e_2 + e_{SI})\lambda$$

3) OB(M1, S)

In this case, the SI request is sent when the UE needs the SI. The BS broadcasts the SIB in the next SI window. As a result, the probability of broadcasting equals to the probability of a successful SI request. By (16), we get

$$\gamma_{OB(M1,S)} = \beta_{1,S} = 1 - e^{-\lambda T_b} \tag{18}$$

The three metrics of this case are

$$\begin{aligned}\Omega s_3 &= (B_1 + B_2\, E[M_{p(1,L')}] + B_{SI}\, \gamma_{OB(M1,S)})\nu K\\ \Omega d_3 &= \frac{T_b}{2}\\ \Omega p_3 &= (e_1 + e_2 + e_{SI})\lambda\end{aligned}$$

4) OB(M1, L)

Let the arrival rate of SIBk demands in a beam area is $\frac{\lambda}{\nu}$. The transmission is similar to that of OB(M1, S, L), but with different broadcast area. $\beta_{1,S'}$ is similar to the results in (16). We replace the λ with $\frac{\lambda}{\nu}$ and get

$$\beta_{1,S'} = 1 - e^{-\frac{\lambda T_b}{\nu}} \tag{19}$$

We put the $\beta_{1,S'}$ in (5) and get

$$\gamma_{OB(M1,L)} = \frac{1 - e^{-\frac{\lambda T_b}{\nu}}}{2 - e^{-\frac{\lambda T_b}{\nu}}} \tag{20}$$

The signaling overhead is

$$\Omega s_4 = (B_1 + B_2\, E[M_{p(1,L)}] + B_{SI}\, \gamma_{OB(M1,L)})\nu K$$

The delay is

$$\Omega d_4 = \frac{T_b}{2} + (1 - \gamma_{OB(M1,L)})T_b$$

And the UE power consumption is

$$\Omega p_4 = e_{SI}\lambda + (1 - \gamma_{OB(M1,L)})(e_1 + e_2 + e_{SI})\lambda$$

5) OB(M1)

This MSG1-based on-demand broadcast does not apply beam sweeping and LBR. The result is like the results of OB (M1, S) case. Only the broadcast area is different. We substitute λ in (18) for $\frac{\lambda}{\nu}$. The probability of broadcasting is

$$\gamma_{OB(M1)} = \beta_{1,S'} = 1 - e^{-\frac{\lambda T_b}{\nu}} \tag{21}$$

We have

$$\begin{aligned}\Omega s_5 &= (B_1 + B_2\, E[M_{p(1,L')}] + B_{SI}\, \gamma_{OB(M1)})\nu K\\ \Omega d_5 &= \frac{T_b}{2}\\ \Omega p_5 &= (e_1 + e_2 + e_{SI})\lambda\end{aligned}$$

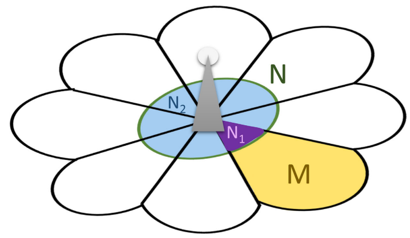


FIGURE 8. The example illustrates the variables we used when analyzing the MSG3-based cases. *M* is the number of all SI requests in a beam area. N_1 is the number of SI requests for one kind of SIB, namely SIBk, in the same beam area as *M*. N_1 is included in *M*. N_2 is the number of SI requests for SIBk in the other beam areas.

6) OB(M3, S, L)

This is the MSG3-based on-demand broadcasting with beam sweeping and LBR. We first calculate the successful probability of SI requests. Combining (2) and (3), we have

$$\beta_3(M = m, N = n) = 1 - (1 - (1 - \frac{1}{\delta})^{m-1})^n \tag{22}$$

In the cases with beam sweeping, we divide the number of SI requests for SIBk in the broadcast area, i.e. N, into two parts. One is the requests contained in M, i.e. N_1 and the other part is independent of M, i.e. N_2. We have $N = N_1 + N_2$, as shown in Fig. 8. M is the total number of SI requests that compete for the radio resources in a beam area, whose arrival rate, i.e. λ_M, is $\frac{\lambda K}{\nu}$. N_1 is the number of the SI requests for SIBk in the same beam area as M with arrival rate $\lambda_1 = \frac{\lambda}{\nu}$. And the N_2 is the number of the requests for SIBk that in the other beam areas. The arrival rate of N_2, i.e. λ_2, is $\frac{\lambda(\nu-1)}{\nu}$. By these distributions and (22), we have the probability that the BS successfully receiving at least one SIBk request:

$$\begin{aligned}\beta_{3,S}&(M = m, N_1 = n_1, N_2 = n_2)\\ &= 1 - (1 - (1 - \frac{1}{\delta})^{m-1})^{(n_1+n_2)}\\ \beta_{3,S} &= \sum_{m=1}^{\infty}\sum_{n_1=0}^{m}\sum_{n_2=0}^{\infty} \frac{((\lambda_M - \lambda_1)T_b)^{(m-n_1)} e^{-(\lambda_M-\lambda_1)T_b}}{(m-n_1)!}\\ &\quad \times \frac{(\lambda_1 T_b)^{n_1} e^{-\lambda_1 T_b}}{n_1!} \times \frac{(\lambda_2 T_b)^{n_2} e^{-\lambda_2 T_b}}{n_2!}\\ &\quad \times [1 - (1 - (1 - \frac{1}{\delta})^{m-1})^{(n_1+n_2)}]\end{aligned} \tag{23}$$

We use (5) to get the probability of broadcast in the case with LBR.

$$\gamma_{OB(M3,S,L)} = \frac{\beta_{3,S}}{1 + \beta_{3,S}} \tag{24}$$

Furthermore, we apply the $E[M_{p(3,L)}]$ in (11) and $E[M_{s(L)}]$ in (14) to the signaling overhead, as Lemma 16, and the γ in these two equations are both $\gamma_{OB(M3,S,L)}$.

By Lemma 16, the signaling overhead is

$$\begin{aligned}\Omega s_6 = ((B_1 + B_2 + B_3)E[M_{p(3,L)}] + B_4\, E[M_{s(L)}]\\ + B_{SI} \times \gamma_{OB(M3,S,L)})\nu K\end{aligned}$$

By Lemma 6, the delay is

$$\Omega d_6 = \frac{T_b}{2} + (1 - \gamma_{OB(M3,S,L)})T_b$$

In the MSG3-based cases, the preamble collision will be detected by the UE when the UE does not receive MSG4. When the preamble collides, the UE tries to receive MSG4, but it fails. The UE still consumes the power used for receiving MSG4.

For MSG3-based request, when the MSG3 collides, the UE would still finish the 4-step procedure. The UE always consumes the power to monitor the channel for MSG4. However, no matter the MSG4 is received or not, the UE still has the chance to receive the broadcast SIB. Thus, all UEs will monitor the SI window. For these reasons, the UEs who succeed or fail to receive the SI consume the same amount of power. Therefore, the power UEs consumed is

$$\Omega p_6 = e_{SI}\lambda + (1 - \gamma_{OB(M3,S,L)})(e_1 + e_2 + e_3 + e_4 + e_{SI})\lambda$$

7) OB(M3, S)

The difference between this case and the previous one is the action LBR. Since the β used here does not consider the LBR, the probability of successful SI request is the same as that of OB(M3, S, L). Also, the probability of broadcast equals to the probability that the BS successfully receives the SI request in the case without LBR.

$$\gamma_{OB(M3,S)} = \beta_{3,S} \tag{25}$$

As for the expected number of used preambles and the successful SIBk requests, we use the result of (12) and (15) in this case that without LBR. The results of this case are

$$\begin{aligned}\Omega s_7 &= ((B_1 + B_2 + B_3)E[M_{p(3,L')}] + B_4\, E[M_{s(L')}] \\ &\quad + B_{SI} \times \gamma_{OB(M3,S)})\nu K \\ \Omega d_7 &= \frac{T_b}{2} \\ \Omega p_7 &= (e_1 + e_2 + e_3 + e_4 + e_{SI})\lambda\end{aligned}$$

8) OB(M3, L)

The N in (22) is included in M in the cases without beam sweeping, which means $N = N_1, N_2 = 0$. Therefore,

$$\begin{aligned}\beta_{3,S'} = \sum_{m=1}^{\infty}\sum_{n=0}^{m}&\Big(\frac{((\lambda_M - \lambda_1)T_b)^{(m-n)}e^{-(\lambda_M-\lambda_1)T_b}}{(m-n)!} \\ &\times \frac{(\lambda_1 T_b)^n e^{-\lambda_1 T_b}}{n!} \times [1 - (1 - (1 - \frac{1}{p})^{m-1})^n]\Big)\end{aligned} \tag{26}$$

The probability of broadcast is

$$\gamma_{OB(M3,L)} = \frac{\beta_{3,S'}}{1 + \beta_{3,S'}} \tag{27}$$

Then, we use the $E[M_{p(L)}]$ and $E[M_{s(L)}]$ in (11) and (14) to calculate the signaling overhead, and replace the γ with $\gamma_{OB(M3,L)}$. The metrics are

$$\begin{aligned}\Omega s_8 &= ((B_1 + B_2 + B_3)E[M_{p(3,L)}] + B_4\, E[M_{s(L)}] \\ &\quad + B_{SI} \times \gamma_{OB(M3,L)})\nu K \\ \Omega d_8 &= \frac{T_b}{2} + (1 - \gamma_{OB(M3,L)})T_b \\ \Omega p_8 &= e_{SI}\lambda + (1 - \gamma_{OB(M3,L)})(e_1 + e_2 + e_3 + e_4 + e_{SI})\lambda\end{aligned}$$

9) OB(M3)

We can see this case as OB (M3, L) without L. Thus, the probability of broadcast equals to the probability that the BS is successfully requested, as what in (26).

$$\gamma_{OB(M3)} = \beta_{3,S'} \tag{28}$$

The signaling overhead is

$$\begin{aligned}\Omega s_9 = ((B_1 + B_2 + B_3)E[M_{p(3,L')}] + B_4\, E[M_{s(L')}] \\ + B_{SI} \times \gamma_{OB(M3)})\nu K\end{aligned}$$

The delay is

$$\Omega d_9 = \frac{T_b}{2}$$

The power UEs consumed is

$$\Omega p_9 = \lambda(e_1 + e_2 + e_3 + e_4 + e_{SI})$$

10) OU

The UE only receives the required SI when it successfully sends the SI request in the RA procedure. The total arrival rate of all SIB requests in one beam area is $\lambda_u = \frac{\lambda K}{\nu}$ and the arrival rate for SIBk included is $\lambda_{uk} = \frac{\lambda}{\nu}$. By the probability of successful RA in (2), we have

$$\gamma_{OU} = \beta_3 = \sum_{m=0}^{\infty} P(M = m)\beta_3(m) \tag{29}$$

The $E[M_p]$ in Lemma 16 is $E[M_{p(L')}]$. Besides, the expected number of M_s in OU case is the same as the $E[M_{s(L')}]$ in (15). The reason is that the RA procedure in the different cases are the same, so we repeatedly use the same value. The results are

$$\begin{aligned}\Omega s_{10} &= ((B_1 + B_2 + B_3)E[M_{p(3,L')}] \\ &\quad + (B_4 + B_{SI})E[M_{s(L')}])\nu K \\ \Omega d_{10} &= \frac{T_b}{2} \\ \Omega p_{10} &= \lambda(e_1 + e_2 + e_3 + e_4) + \frac{E[M_{s(L')}]e_{SI}}{T_b}\end{aligned}$$

VI. PERFORMANCE EVALUATION

In this section, we show the simulation and analytical results of all the possible design options listed in Table 1, which cover the options from the related work and 3GPP specification. As shown from Fig. 9 to Fig. 14, the simulation results (colored symbols) are closely approximated to the analytical results (colored lines). For simplicity, we omit the legends of analytical results, which are the lines with the same color as the symbols used for the simulation results for each design option. We discuss the effects of different arrival rates of SI demand to the performance metrics, including signaling

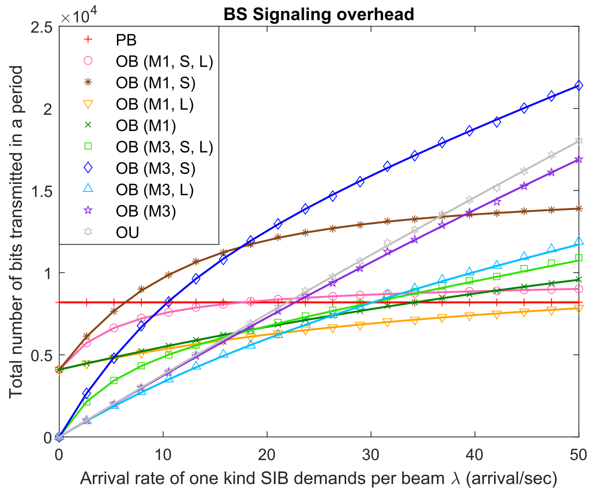


FIGURE 9. The signaling overhead of the 10 delivery options changes over the arrival rate of UEs' demands. The signaling overheads of the on-demand cases increase when the SI request arrival rate becomes greater, while The signaling overhead of PB does not change with the arrival rate of UE's demand.

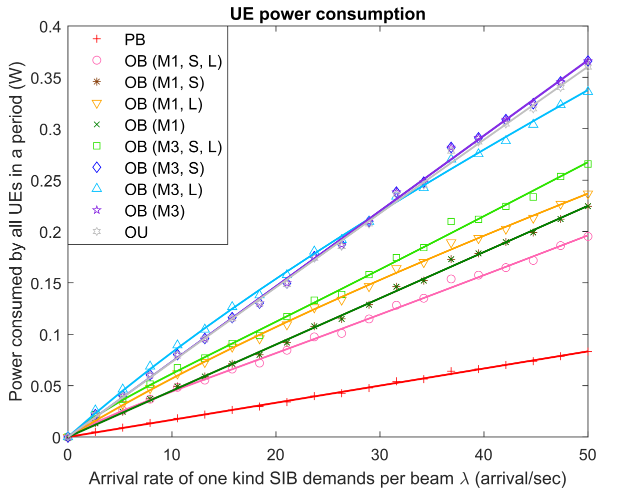


FIGURE 11. The UE power consumption of 10 cases all increases with the arrival rate of SI demand. PB consumes the least UE power. For the on-demand cases, MSG1-based SI requests can save more UE power than MSG3-based SI requests. LBR can also save UE power consumption, while the beam sweeping only saves UE power when the UEs apply LBR.

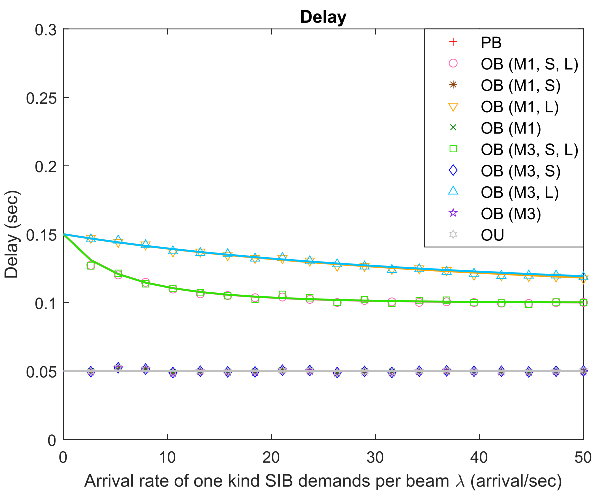


FIGURE 10. The delay of the 10 delivery options has three kinds of distribution. The delay of cases without LBR is half of the period over all arrival rates. The delay of cases with LBR converges to the length of a period as the arrival rate increases. Among them, the delay of cases with both LBR and beam sweeping converges faster than that of cases without beam sweeping.

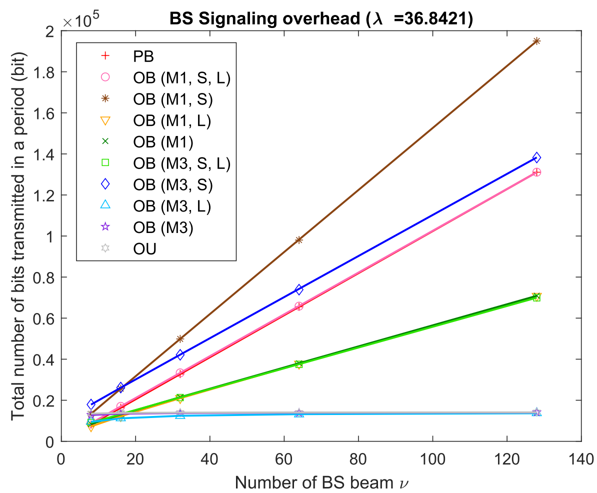


FIGURE 12. The signaling overhead of the 10 delivery options with different numbers of BS beams. All broadcast cases transmit more signals when the number of beams increases. Only the signaling overhead of OU does not change with the number of BS beams. Both MSG1-based SI requests and beam sweeping lead to a higher rate of increase. MSG3-based single-beam broadcasting cases are similar to OU when the number of BS beams is great enough.

overhead, delay and UE power consumption. Furthermore, we also show the results of the three metrics with various numbers of BS beams. The simulation parameters are listed in Table 3.

A. METHODOLOGY

We implement the simulator in MATLAB based on 3GPP TS 38.300 specification [7]. Other SI in 5G NR includes SIB2 to SIB9, so we set K equal to 8. The number of preambles is set according to 3GPP TS 38.211 [16]. The size of packets is configured based on 3GPP TS. 38.321 [17]. (Since the standardization of SI has not completed yet, we also reference some settings in the LTE systems.) According to 3GPP documents [18], [19] and previous work [10], UE transmission and reception power is set to 1167 mW and 167 mW respectively; moreover, transmission time is set to 1ms and reception time is set to 10 ms. The simulation parameters are summarized in Table 3. The simulation results are compared to analytical results. For the same SI acquisition scheme, the analytical results are drawn as lines using the same color as the marks of the simulation results.

B. DIFFERENT ARRIVAL RATE OF SI DEMANDS

As mentioned in the previous section, the arrival rate of all SIBk demands, i.e. λ, is defined from the view of the BS. For

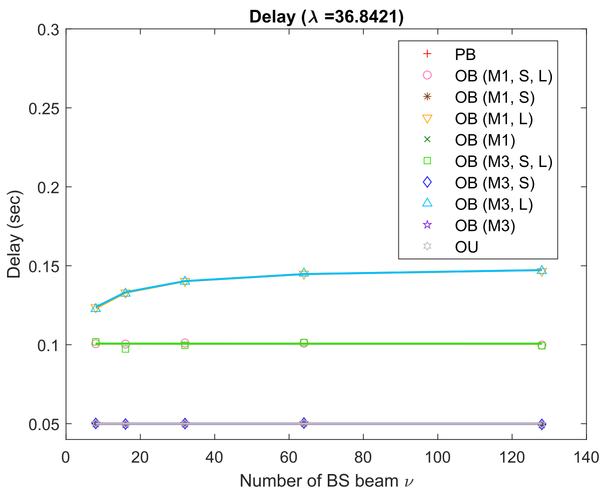


FIGURE 13. **The delay of the 10 delivery options with different numbers of BS beams. Delay of the case without LBR and delay of the broadcast case with LBR do not vary with the number of BS beams. Only the single-beam broadcasting cases with LBR have longer delays when the number of BS beams increases because the increment of beams decreases the probability of broadcast for each beam.**

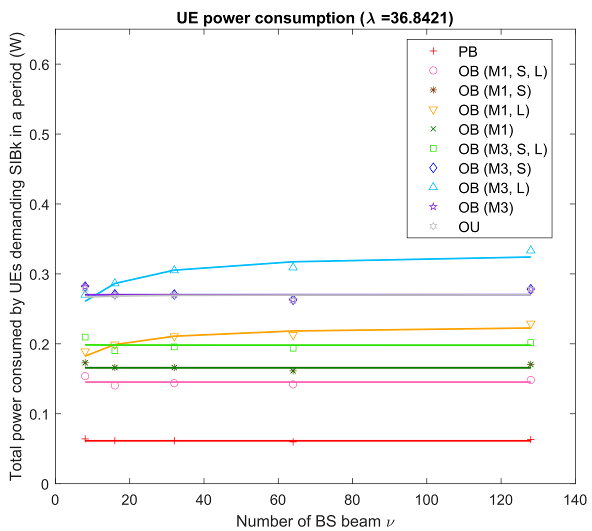


FIGURE 14. **The UE power consumption of 10 cases with different numbers of BS beams. Only OB(M1, L) and OB(M3, L) consume more UE power when the number of BS beams increases. It is because these two cases combine the LBR and single-beam broadcasting, which leads to a lower probability of broadcast as the BS has more beams.**

TABLE 3. **Parameters used in the simulation.**

Parameter	Setting	Parameter	Setting
ν	8	K	8
p	64	T_b	0.1 s
Simulation time	1000 period	B_1	64 bit
B_2	56 bit	B_3	48 bit
B_4	184 bit	B_i	128 bit
e_1	1.1667 mJ	e_2	1.6667 mJ
e_3	1.1667 mJ	e_4	1.6667 mJ
e_{SI}	1.6667 mJ		

the BS, when the arrival rate of SI demands is high enough, **PB** must be the best choice. Therefore, we consider the range of the λ from 1 arrival/sec to 50 arrival/sec to see how the system benefits from the on-demand mechanism.

1) SIGNALING OVERHEAD

We can see the signaling overhead of all cases in Fig. 9. When the arrival rate is less than 22, **OB (M3, L)** has the lowest signaling overhead. As the arrival rate is in the interval between 22 and 50, **OB (M1, L)** has the lowest signaling overhead. We have some points about this result. First, since the reserved preambles are seldom used when the arrival rate is low, the size of reserved preambles is larger than the size of the additional messages, i.e. MSG3 and MSG4, in the MSG3-based approach. Thus, the MSG3-based method saves more signaling overhead than the MSG1-based one when the arrival rate is low. However, as the arrival rate increases, the size of the additional messages used in the MSG3-based method becomes larger than the size of the reserved preambles used in the MSG1-based method. Also, when the arrival rate grows greater, the signaling used by the SI request and ACK messages becomes more than the fixed signaling used by the periodic broadcast case. Second, no beam sweeping reduces the additional signaling used for SIB transmission when the arrival rate is low. Few arrivals of SI demands indicate the few receptions of the additional broadcast SIBs, so most of the additional broadcast SIBs are redundant. Third, the LBR can save the signaling overhead. The reason is that applying LBR reduces the number of SI requests and the listening action does not increase any transmission.

2) DELAY

The results of the delay are shown in Fig. 10. **PB**, **OB(M1, S)**, **OB(M1)**, **OB(M3, S)**, **OB(M3)** and **OU** have the lowest delay. There are only three types of delay distributions in our system. Among them, the two types of longer delays are caused by LBR. UEs with LBR have the probability to request and receive SIB in the next period after the arrival of their SI demands, which results in a longer delay. The delay of these four cases converge to 0.1s as the arrival rate increases, and the different rate of convergence is caused by the broadcast mechanism. UEs in the cases with beam sweeping have a higher probability of SIB reception, so the delay is lower.

3) UE POWER CONSUMPTION

As shown in Fig. 11, **PB** saves the most UE power among all cases because UEs in PB do not need to request SI. They only need to receive SIB, while UEs in other cases transmit additional messages to request SI. We observe that the cases applying MSG1-based SI requests have lower UE power consumption than the cases applying MSG3-based SI requests. The reason is that MSG3-based methods need additional messages, i.e. MSG3 and MSG4, to finish the SI request. The transmission of these messages costs more receiving and transmitting power. Another observation is that beam sweeping saves UE power only when the UEs apply LBR. This effect results in the overlap between OB(M1, S) and OB(M1) because the extra broadcast of SI caused by beam sweeping would not be received by extra UEs when UEs do not employ LBR. The reason is the same for the overlap

TABLE 4. Conclusions of the best delivery options for each metric under the case that the gNB has 8 beams.

Metric \Arrival rate	0∼22	22∼50
Signaling overhead	OB(M3, L)	OB(M1, L)
Delay	PB, OB(M1, S), OB(M1), OB(M3, S), OB(M3), OU	
UE power consumption	PB	

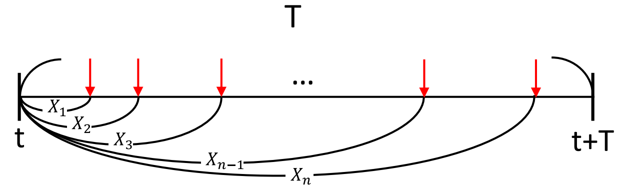


FIGURE 15. The Poisson arrival in the time interval $[t, t+T]$.

between the results of OB(M3, S) and OB(M3). When the UEs apply LBR, beam sweeping can increase the probability of successful SI acquisition. Moreover, the case with LBR consumes less UE power than the case without LBR when the arrival rate is great enough. For example, OB(M1, S, L) has less UE power consumption than OB(M1, S) when the arrival rate is greater than 10. LBR can save UE power because the UE that receives the SIB during the first period after its SI demand's arrival saves the power used for SI requests. When the arrival rate is low, the probability of broadcasting is also low. Thus, UEs have a higher probability to request SI in the second period after their SI demands' arrivals, which results in extra power used for listening in the first period.

4) CONCLUSIONS OF SI DELIVERY POLICIES

As we have shown in the previous subsections, there are trade-offs between these performance metrics. On the basis of the analysis results, we summarized the best SI delivery policies for different optimization targets in Table 4. Although the table is mainly based on the numerical results of the scenario suggested by 3GPP and may not match the results of the real cases, it still could be a guideline.

C. DIFFERENT NUMBER OF BS BEAMS

When considering the results varying with different number of BS beams ($\nu = 8, 16, 32, 64, 128$), we set the total arrival rate of one kind SIB demands under a BS (λ) as 36.84, which corresponds to the $\lambda = 36.84$ in Fig. 9, 10 and 11.

1) SIGNALING OVERHEAD

We have some observations for the results in Fig. 12. First, the signaling overheads of broadcast cases increase when the number of BS beams increases, but each broadcast case has a different rate of increase. The signaling overhead of OB(M3) and OB(M3, L) look flat in Fig. 12, but they both increase with the number of beams. Second, since the case with MSG1-based SI request reserves RACH preambles, the signaling overhead of the MSG1-based case increases more with the number of BS beams than the similar case with MSG3-based SI request. For example, the signaling overhead of OB(M1, S) increases more than the signaling overhead of OB(M3, S) when the number of BS beams increases. Third, the beam sweeping design also results in a higher rate of increase than the single-beam broadcasting. As the number of total BS beams increases, signaling overhead increases. In addition, beam-sweeping case has higher overhead than the single-beam broadcasting. Last, the signaling overhead of two MSG3-based on-demand single-beam broadcasting cases, i.e. OB(M3, L) and OB(M3), is closed to the result of OU, when the number of beams increases, as shown in Fig. 12. The area covered by one BS beam becomes smaller when the BS has more beams. When the area is small enough, only one UE receives the SI broadcast by one beam. This transmission is similar to unicast. Moreover, LBR does not work in unicast, so LBR will not affect the results when the single-beam broadcasting case is similar to the unicast.

2) DELAY

The delay of the case without LBR is equal to $\frac{T_b}{2}$, which is not related to the number of BS beams. For the cases with LBR, delay of the case applying beam sweeping does not change with the number of BS beams either. Because the area covered by beam sweeping does not change, the number of beams the BS used for broadcast does not affect the receiving part. In contrast, the case applying single-beam broadcasting with LBR has a longer delay when the BS has more beams. The beam covers a smaller area when the number of BS beams is greater. A smaller area means less arrival rate of SI demands per beam, which causes the lower probability of broadcast for one beam and longer delay.

3) UE POWER CONSUMPTION

The changes of UE power consumption with the number of BS beams are similar to the results of delay because these two metrics are the properties of UE. Only the single-beam broadcasting cases with LBR have more UE power consumption as the number of BS beams increases. When the system applies LBR, the lower probability of broadcast causes more failures of the first step, listening to the SI window before sending an SI request.

VII. CONCLUSION

In this paper, the emerging 5G NR system information acquisition mechanisms are studied. This is the first performance evaluation framework that systematically analyzes the design options for 5G SI acquisition. All the ten possible design options are evaluated with signaling overhead, delay and power consumption. The analytical results derived from the proposed mathematical models are closely approximated by the simulation results. The best SI delivery policies of the three metrics with different arrival rates are concluded in Table 4. The performance evaluation frameworks serve as a guide to decide suitable SI operation configurations in different 5G deployment scenarios.

APPENDIX

A. DERIVATION OF THE EXPECTED AVERAGE DELAY OF THE DELIVERY OPTIONS WITHOUT LBR

Let the arrival rate of the Poisson process be λ. Consider the average time from the start of the interval t to the arrival is X. Thus, the average delay from the arrival to the end of the time interval $t+T$ is $T-X$. As the figure, we assume the X of the i^{th} arrival in the interval be X_i, and there are n arrivals. The relation between X and X_i is

$$X = \frac{X_1 + X_2 + X_3 + \ldots + X_n}{n} \tag{30}$$

To get the expected number of the average delay $T - E[X]$, we first derive the $E[X]$.

The cumulative distribution function (CDF) of the n Poisson arrivals' X_i is

$$\begin{aligned}
&F_{X_1,X_2,X_3,\ldots,X_n}(x_1, x_2, x_3, \ldots, x_n)\\
&= \frac{1}{\frac{(\lambda T)^n e^{-\lambda T}}{n!}} \times \lambda x_1\, e^{-\lambda x_1} \times \lambda(x_2 - x_1)e^{-\lambda(x_2-x_1)}\\
&\quad \times \lambda(x_3 - x_2)e^{-\lambda(x_3-x_2)} \times \ldots\\
&\quad \times \lambda(x_n - x_{n-1})e^{-\lambda(x_n-x_{n-1})} \times e^{-\lambda(T-x_n)}\\
&= \frac{n!}{T^n} x_1(x_2 - x_1)(x_3 - x_2)\ldots(x_n - x_{n-1})
\end{aligned} \tag{31}$$

This equation means that the distribution of the n Poisson arrivals is one arrival in the time interval $[t, t + x_1]$, one in the time interval $[t + x_1, t + x_2]$, ..., one in the time interval $[t+x_{n-1}, t+x_n]$, and no arrival in $[t+x_n, T]$. Moreover, since the memoryless property of Poisson distribution, we set $t = 0$ in the following proof.

The probability density function (PDF) is the differential of the CDF, so we get the PDF

$$\begin{aligned}
&f_{X_1,X_2,X_3,\ldots,X_n}(x_1, x_2, x_3, \ldots, x_n)\\
&= \frac{\partial}{\partial x_n \partial x_{n-1} \ldots \partial x_1} \frac{n!}{T^n} x_1(x_2 - x_1)(x_3 - x_2)\ldots(x_n - x_{n-1})\\
&= \frac{n!}{T^n}
\end{aligned} \tag{32}$$

Therefore, the expected value of X is

$$\begin{aligned}
E[X] &= E[\frac{X_1 + X_2 + \ldots + X_n}{n}]\\
&= \int_0^T \int_0^{x_n} \ldots \int_0^{x_2} \frac{n!}{T^n} (\frac{x_1 + \ldots + x_{n-1} + x_n}{n})\\
&\quad \times dx_1 \ldots dx_{n-1} dx_n
\end{aligned} \tag{33}$$

We claim that the expected delay is $\frac{T}{2}$, which means $E[X] = T - \frac{T}{2} = \frac{T}{2}$. We prove it by induction as follows.

1) BASE CASE

When n=1, we get the $E[X]$ by (31) (32) (33).

$$E[X] = \int_0^T \frac{1}{T} x_1\, dx_1 = \frac{1}{T}\frac{T^2}{2} = \frac{T}{2}$$

The expected delay is $T - E[X] = \frac{T}{2}$.

2) INDUCTIVE HYPOTHESIS

Assume it's true when $n = k$. We have

$$\begin{aligned}
&E[X]\\
&= \int_0^T \int_0^{x_k} \ldots \int_0^{x_2} \frac{k!}{T^k} (\frac{x_1 + \ldots + x_{k-1} + x_k}{k}) dx_1 \ldots dx_{k-1} dx_k\\
&= \frac{(k-1)!}{T^k}\\
&\quad \times \int_0^T \int_0^{x_k} \ldots \int_0^{x_2} (x_1 + \ldots + x_{k-1} + x_k) dx_1 \ldots dx_{k-1} dx_k\\
&= \frac{T}{2}
\end{aligned} \tag{34}$$

From (34), we have the result of the integral.

$$\begin{aligned}
&\int_0^T \int_0^{x_k} \ldots \int_0^{x_2} (x_1 + \ldots + x_{k-1} + x_k) dx_1 \ldots dx_{k-1} dx_k\\
&\qquad = \frac{T}{2} \frac{T^k}{(k-1)!} = \frac{T^{k+1}}{2(k-1)!}
\end{aligned} \tag{35}$$

3) INDUCTIVE STEP

When $n = k + 1$,

$$\begin{aligned}
&E[X]\\
&= \int_0^T \int_0^{x_{k+1}} \ldots \int_0^{x_2} \frac{(k+1)!}{T^{k+1}}\\
&\quad \times (\frac{x_1 + \ldots + x_k + x_{k+1}}{k+1}) dx_1 \ldots dx_k dx_{k+1}\\
&= \frac{k!}{T^{k+1}} \int_0^T \int_0^{x_{k+1}} \ldots \int_0^{x_2} (x_1 + \ldots + x_k + x_{k+1})\\
&\quad \times dx_1 \ldots dx_k dx_{k+1}\\
&= \frac{k!}{T^{k+1}} \Big(\int_0^T \int_0^{x_{k+1}} \ldots \int_0^{x_2} (x_1 + \ldots + x_k) dx_1 \ldots dx_k dx_{k+1}\\
&\quad + \int_0^T \int_0^{x_{k+1}} \ldots \int_0^{x_2} x_{k+1} dx_1 \ldots dx_k dx_{k+1} \Big)\\
&= \frac{k!}{T^{k+1}} \Big(\int_0^T \frac{{x_{k+1}}^{k+1}}{2(k-1)!} dx_{k+1} + \int_0^T x_{k+1} \frac{{x_{k+1}}^k}{k!} dx_{k+1} \Big)\\
&= \frac{k!}{T^{k+1}} \Big(\frac{T^{k+2}}{2(k-1)!(k+2)} + \frac{T^{k+2}}{k!(k+2)} \Big) = \frac{T}{2}
\end{aligned} \tag{36}$$

By replacing the T in (35) with x_{k+1}, we can get the result $\frac{T}{2}$. The claim is proved.

REFERENCES

[1] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

[2] S.-Y. Lien, S.-L. Shieh, Y. Huang, B. Su, Y.-L. Hsu, and H.-Y. Wei, "5G new radio: Waveform, frame structure, multiple access, and initial access," *IEEE Commun. Mag.*, vol. 55, no. 6, pp. 64–71, Jun. 2017.

[3] F. Khan, Z. Pi, and S. Rajagopal, "Millimeter-wave mobile broadband with large scale spatial processing for 5G mobile communication," in *Proc. 50th Annu. Allerton Conf. Commun., Control, Comput. (Allerton)*, Oct. 2012, pp. 1517–1523.

[4] H. Shokri-Ghadikolaei, C. Fischione, G. Fodor, P. Popovski, and M. Zorzi, "Millimeter wave cellular networks: A MAC layer perspective," *IEEE Trans. Commun.*, vol. 63, no. 10, pp. 3437–3458, Oct. 2015.

[5] M. Giordani, M. Mezzavilla, and M. Zorzi, "Initial access in 5G mmWave cellular networks," *IEEE Commun. Mag.*, vol. 54, no. 11, pp. 40–47, Nov. 2016.

[6] C. Jeong, J. Park, and H. Yu, "Random access in millimeter-wave beamforming cellular networks: Issues and approaches," *IEEE Commun. Mag.*, vol. 53, no. 1, pp. 180–185, Jan. 2015.

[7] *Technical Specification Group Radio Access Network; NR; NR and NG-RAN Overall Description; Stage 2*, document TS 38.300, Version 15.6.0., 3GPP, Jun. 2019.

[8] *Technical Specification Group Radio Access Network; NR; Radio Resource Control (RRC) Protocol Specification*, document TS 38.331, Version 15.6.0, 3GPP, Jun. 2019.

[9] *On-Demand SI Delivery: Signaling Aspects*, document R2-1700011, 3GPP, Samsung, Jan. 2017.

[10] M. A. Ingale and A. Agiwal, "On demand system information delivery for 5G wireless system," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–6.

[11] *On-Demand System Information Acquisition*, document R2-164948, 3GPP, MediaTek Inc., Aug. 2016.

[12] A. Awada, D. S. Michalopoulos, and A. Ali, "An improved method for on-demand system information broadcast in 5G networks," in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Sep. 2017, pp. 18–23.

[13] M. Koseoglu, "Lower bounds on the LTE-A average random access delay under massive M2M arrivals," *IEEE Trans. Wireless Commun.*, vol. 64, no. 5, pp. 2104–2115, May 2016.

[14] G.-Y. Lin, S.-R. Chang, and H.-Y. Wei, "Estimation and adaptation for bursty LTE random access," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2560–2577, Apr. 2016.

[15] R. R. Tyagi, F. Aurzada, K.-D. Lee, and M. Reisslein, "Connection establishment in LTE-A networks: Justification of poisson process modeling," *IEEE Syst. J.*, vol. 11, no. 4, pp. 2383–2394, Dec. 2017.

[16] *Technical Specification Group Radio Access Network; NR; Physical Channels and Modulation*, document TS 38.211, Version 15.6.0., 3GPP, Jun. 2019.

[17] *Technical Specification Group Radio Access Network; NR; Medium Access Control (MAC) Protocol Specification*, document TS 38.321, Version 15.6.0., 3GPP, Jun. 2019.

[18] *Technical Specification Group Radio Access Network; NR; Study on UE Power Saving*, document TR 38.840, Version 16.0.0., 3GPP, Jun. 2019,

[19] *DRX Parameters in LTE*, document R2-071286, 3GPP, Nokia, Mar. 2017.

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