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Article

Two Step Random Access Latency Improvement in Congested beyond 5G Networks

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Abstract: It has been recently proposed to enhance the performance of random access procedure (RAP) by downsizing the current four step RAP (4s-RAP) to two step RAP (2s-RAP) in order to address ultra reliable low latency communications (URLLC) in 5G and beyond 5G wireless networks. 2s-RAP reduces latency and signaling overhead by manifesting only one round trip between gNB (5G base station) and the UE (user equipment). However, the low latency goal of 2s-RAP is challenged by the increase in the number of UEs in the future wireless networks. Numerous UEs competing for limited random access resources would result in frequent collisions followed by multiple random access reattempts, resulting in increased delay. In this paper, we propose novel algorithms to improve the performance of 2s-RAP in a congested environment. In the proposed algorithms, the UEs can perform RAP reattempts in either 2s-RAP or 4s-RAP based on the channel conditions such that the chances of RAP failure due to poor channels are reduced. They can also transit to 4s-RAP from the initially selected 2s-RAP in order to alleviate the congestion in 2s-RAP. The proposed algorithms are probabilistically analyzed based on collision probabilities and success rates. We employ our derived mathematical equations, as well as carry out simulation evaluations, to present the performance results effectively.

Keywords: two step random access procedure; delay; collision probability; 5G communications

1. Introduction

5G and beyond wireless networks are expected to deliver the promise of low latency communications. Indeed, the ultra-reliable and low latency communications (URLLC) scenario has been explicitly specified as one of the three important use cases for 5G wireless along with enhanced mobile broadband (eMBB) and massive machine type communications (mMTC). According to researchers, the 5G-New radio (NR) is a combination of several radio access technologies to address expected high data demands at low power consumption with low latency [1]. Low latency control is also one of the key features in 6G communications [2]. The low latency requirement coaxes the need for faster random access procedure (RAP). A Two Step Random Access Procedure (2s-RAP) has been recently introduced in the 3GPP release 16 with the aim of reducing signaling overhead and latency [3]. The legacy RAP is originally designed as a four step procedure (4s-RAP). 2s-RAP can be regarded as the enhanced version of the legacy 4s-RAP and offers to speed up the procedure for the UE's initial connection establishment with the 5G base station, the gNB.

In the contention-based 4s-RAP, the UE first transmits a randomly selected preamble to the base station (BS) in step1 and this is known as Msg1 (Message 1) [4]. On detecting the received preamble,

the BS transmits random-access response (RAR), also known as Msg2 in step 2. Through RAR, the BS confirms the detected preamble. It also assigns temporary address and uplink PUSCH (Physical Uplink Shared Channel) resources for transmission of Msg3 from the UE in the subsequent step [5]. The Msg3 in step 3 is UE's response to RAR and includes UE identity (UEID) for contention resolution (CR). Finally, the Msg4 from BS to UE in step 4 uses received UEID to resolve any possible contention that might have arisen due to the same preamble transmission by multiple UEs in step 1. Thus, the 4s-RAP manifests two round trips between BS and UE that are accomplished by elaborate control signaling. The 2s-RAP curtails the round trip between gNB and the UE to just one. Thus, only one uplink message, the MsgA, transpires from UE to the gNB. The preamble transmission (Msg1) as well as the PUSCH transmission that includes UEID (Msg3 in 4s-RAP) are accomplished by single MsgA in 2s-RAP. The tasks accomplished by RAR (Msg2) and CR (Msg4) in 4s-RAP are achieved by MsgB in 2s-RAP that is transmitted from the gNB to UE. However, 2s-RAP is not a simple amalgamation of 4s-RAP steps. Some processes are combined and others are completely skipped to reduce the procedure to two steps while ensuring that the contention resolution is achieved.

RAP adopts the multi channel slotted ALOHA protocol where the UEs share physical random access channel (PRACH) resources to transmit the randomly chosen preambles from the set of shared preambles in step 1 [5]. While the RAP resources in 5G and beyond would remain limited [6], the number of UEs are expected to increase which would result in frequent RAP failures. The possibility of myriad of activated UEs competing for limited random access (RA) preambles challenges the low latency goal of 2s-RAP. When the number of UEs that attempt RAP is high, then the RAP would often fail due to frequent collisions of preambles. The RA reattempts would increase the overall delay in such a congested environment even though 2s-RAP is applied. Thus, we believe that the novel 2s-RAP should be analyzed while also considering the several possible RA reattempts due to frequent failures. Moreover, all the UEs cannot be expected to perform 2s-RAP, especially the UEs that observe poor channel conditions. Such UEs, even if they perform 2s-RAP, have a high chance of RAP failure. Frequent channel variations are expected as mmWave enabled 5G wireless is prone to spotty coverage and propagation challenges. The UEs with poor channels would unnecessarily contribute to 2s-RAP congestion. Moreover, 2s-RAP also requires dedicated resources for PUSCH transmission. Thus, it is reasonable to perform 4s-RAP when the UE observes low channel quality. 3GPP also plans to support the same [6]. In this paper, we utilize the expected coexistence of 2s-RAP and 4s-RAP to improve the control plane latency that manifests due to random access essential for the RRC connection set up. Though some works have considered 2s-RAP for machine type communications [7–9], the performance enhancement of 2s-RAP for broadband communication while also considering its coexistence with 4s-RAP is not available in the literature to the best of our knowledge. In machine type communication, the objective is to transmit the uplink data quickly and not to establish a connection with the base station [9]. The RAP is fundamentally designed for link establishment between UE and BS before the scheduled access [10] and 2s-RAP beyond MTC has been given little consideration even though it offers agile initial link setup. Our main contributions are:

- The aim of this paper is to explore methods to reduce the average 2s-RAP latency in the congested and dense networks while also considering 4s-RAP simultaneously. More specifically, we propose and analyze novel algorithms to decide whether UEs should attempt 2s-RAP or 4s-RAP such that the overall delay and success rate of RAP improves.
- The existing 3GPP proposal considers that, if an attempt by a UE fails, then it can reattempt the RAP with its initial choice of either 2s-RAP or 4s-RAP only. In the existing proposal, the UE does not have any flexibility to change its choice in case of reattempt after an RA attempt failure. However, we believe that the existing approach lacks dynamism and thus propose two novel algorithms.
- We first consider that the UEs can initiate RAP with either 2s-RAP or 4s-RAP based on the channel conditions. While 2s-RAP provides agility for UEs having good channel, the UEs with poor channel can select 4s-RAP so that the two step congestion can be reduced. Subsequently, at every

RAP reattempt, the choice of 2s-RAP or 4s-RAP is reaffirmed. The re-selection ensures that the chance of failure due to poor channels are reduced for the UEs attempting 2s-RAP. We call this novel proposal a Reasserting Algorithm (ReA).

- We also propose a novel Sequential Algorithm (SeA). Similar to ReA, the SeA as well the UEs can initiate with either 2s-RAP or 4s-RAP based on the channel conditions. However, in SeA, we propose that, if a 2s-RAP attempt by a UE fails, then it can reattempt with 2s-RAP itself without any channel reassessing. However, it can do so for the configured number of trials only after which it transits to 4s-RAP. SeA gives UEs a fair chance at 2s-RAP reattempts while at the same time controlling the 2s-RAP congestions if the failures persist.
- We also perform delay analysis for the existing base line case in accordance with the current 3GPP study on 2s-RAP [6]. For the existing case as well, the UE selects either 2s-RAP or 4s-RAP for the first trial based on the channel conditions. If an attempt by an UE fails, then it can reattempt the RAP with its initial choice only. Since the UE performing RAP reattempt follows the preceding choice, we call this base line case the Preceding Algorithm (PrA).
- We perform probabilistic analysis for the three protocols and compare the results in terms of delay and success rate for the different arrival rates. ReA, SeA, and PrA are also compared to legacy 4s-RAP to ascertain their advantages. We also validate our analysis with simulation studies. We also compare our results with existing work on 2-way RAP [11].

Though the proposed ReA and SeA are not very complex algorithms, they are practical and easily implementable. It is important to consider 2s-RAP and 4s-RAP simultaneously due to two main reasons: (1) mmWave spectrum is prone to spotty coverage and channel conditions may change (2) When number of contending UEs is more, it is reasonable to shift a few UEs to 4s-RAP from 2s-RAP to alleviate the congestion in 2s-RAP. We address a novel problem of deriving advantage of 2s-RAP in congested networks in an effective manner. The rest of the paper is organized as follows: in Section 2, we present the evolution of RAP from 4s-RAP to 2s-RAP while focusing on the related work. The numerical models for ReA, SeA, and PrA are presented in Section 3. Section 4 presents our numerical and simulation results and Section 5 concludes our work.

2. Evolution of the Random Access Process

2.1. Four Step RAP

The details of four step RAP are important here to understand which all messages can be combined or completely skipped to reduce the procedure to two steps while at the same time ensuring that the contention resolution is achieved.

- Step 1: Msg1

UE randomly selects one of the available preamble sequences associated with the PRACH Occasion [12]. It transmits the selected Preamble on the random access channel. This transmission carries no data bits. Some identity is needed for this UE so that the network can address it in the next step. The identity is called RA-RNTI (random access radio network temporary identity) and is implicitly specified by the timing of the preamble transmission. Some other UE can also select the same preamble sequence and may transmit at the same time [13]. Thus, it would also assume same the RA-RNTI. However, neither the network nor the UEs can be aware of this contention at this step.

- Step 2: Msg2

The gNB detects the transmitted preamble and derives the RA-RNTI based on the time slot in which the preamble was sent. The gNB transmits RA response (RAR) that carries (i) ID of successfully received preambles (ii) Temporary CRNTI (Cell Radio Network Temporary Identifier) (iii) PUSCH uplink grants for Msg3 (iv) timing advance [13]. The UE checks PDCCH

addressed to RA-RNTI and can subsequently receive MAC PDUs in PDSCH that contain the aforesaid information.

- Step 3: Msg3

UE saves the Temporary C-RNTI, applies timing advance, and then transmits the data to gNB using the PUSCH resources assigned in step 2. The MAC PDU (Medium access control (MAC) layer protocol data unit (PDU)) in PUSCH contains UEID. It is possible that more than one UE attempted RA using the same preamble on the same RA channel [13]. Even the UE whose preamble was not received by the gNB successfully would accept the RA response as the RA-RNTI and preamble ID in the RAR response in Msg2 matches. The contention resolution (CR) in step 4 is therefore needed to resolve this issue.

- Step 3: Msg4

The gNB responds Msg3 with the CR message that contains the UEID which was successfully received in step 3. The UE monitors PDCCH is addressed to Temporary C-RNTI. Similar to RAR, if multiple UEs transmitted the same preamble in step 1, they would receive the same Temporary C-RNTI and would decode this CR message. However, on verifying the echoed UEID in Msg4, the UE would become aware if its RA attempt was successful or not. The CR aids in unique identification of the UE that has been able to successfully transmit the preamble in step 1 [14].

2.2. Novel Two Step RAP

As there are only two steps, it is intuitive that one step is for the uplink from the UE and the other for downlink from the gNB. The corresponding messages are called as MsgA and MsgB, respectively.

- Step 1 (MsgA):

In MsgA, the UE is required to transmit the preamble using PRACH along with a data unit in PUSCH that contains UEID for contention resolution as shown in Figure 1 [15]. The data unit is sent in Msg3 in 4s-RAP and can be regarded as payload carried on PUSCH in 2s-RAP [3]. Thus, the network should not only reserve the preambles and PRACH resources but also PUSCH resources for MsgA transmission in 2s-RAP which are shared by all of the UEs attempting contention based RAP. The network can configure PUSCH resources to be associated with the PRACH resource based on predefined rules.

- Step 2 (MsgB):

When the gNB successfully receives the preamble as well as the MsgA PUSCH, it sends back a response to the UE as MsgB. As shown in Figure 1, MsgB contains UEID for contention resolution (which was Msg4 in 4s-RAP). The UE, after having transmitted MsgA, waits for the MsgB response from the gNB. If the received response contains the UEID, the one that it had sent in MsgA, then the RAP is considered to be successfully completed. However, if the correct response is not received, the UE can consider its RA attempt as unsuccessful and can re-transmit MsgA.

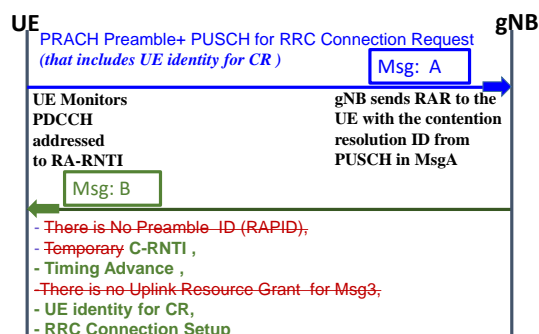


Figure 1. Two step RAP (2s-RAP).

2.3. Related Work

The 2s-RAP for beyond 5G communications has been recently introduced in 3GPP Release 16 [16]. In addition to reduced latency and signaling overhead, 2s-RAP would also improve power saving and thus authors in [3] have included the same in their survey on power saving techniques for beyond 5G networks. According to authors in [3], 2s-RAP would especially benefit small data transmissions that require the UE to wake up and send data intermittently. 2s-RAP for small data transmission is also considered in some recent works [7–9]; however, most of these existing works have been carried out for MTC and NB-IoT UEs that may not require more attempts and transmit intermittently small data packets. To address the URLLC services in MTC and NB-IoT, prioritization has been considered by several researchers [9,17–19]. In [9], the author has highlighted the reservation of narrowbands on the PUSCH for the 2s-RAP to cater to URLLC preambles that are detected by the base station. The authors in [18] propose the segregation of random access resources for uRLLC and eMBB traffic which they have termed as prioritized resource reservation. Condoluci et al. [8] showed that the two-message handshake can substantially reduce delay. However, work in [8] considered specially designed preamble set for MTC traffic. Several other efforts have also been made in performance improvement of RAP in terms of massive connectivity by considering Access class barring (ACB) with different back-offs depending upon the traffic priority [20], reserving resources for URLLC during the initial random access transmission [18], prioritized preamble reservation according to traffic [19] and dynamic reserved preambles and enhanced back-off [7]. However, the dynamics of 2s-RAP for broadband UEs is expected to be different as more access attempts may need to be carried out [9] and more frequently.

The strong coupling between reliability and latency for beyond 5G URLLC services is highlighted in [21]. It is emphasized that enhancing technological improvements aimed at lower latency would also result in the improvement of reliability [21]. To address URLLC in contention based uplink transmission, the authors in [22] deduce the optimal number for repetitive transmission so that high reliability is achieved at reasonable latency. Ref. [22] also considers the protocol of scheduled allocation for URLLC services. However, the proposed scheduled allocation approach would not benefit the sporadic RAP requests from broadband users. We would specifically like to mention work in [11] as it considers only two way communication between BS at UE instead of four way to address URLLC applications in ultra dense future networks. The authors in [11] advocate that the reduction of control plane latency, caused by the random access to set up for an RRC connection. Unlike predictable IoT traffic, the work in [11] primarily considers sporadic traffic in the small cell. Subsequently, they propose a two step handshake based RAP by upgrading the preamble such that it also contains some information. However, the new preamble design is cumbersome and would require novel methods of preamble generation and detection.

We believe that the random access efficiency in a congested broadband communications can be improved by designing of an optimal delay performance which in turn can be controlled by limiting the number of incoming requests. The proficient coexistence of 4s-RAP and 2s-RAP needs research attention especially considering the mmWave based B5G wireless networks that would result in frequent RAP failures due to spotty communication at high frequencies. Moreover, the coexistence would also mitigate the PUSCH reservation overheads that are required for 2s-RAP. To the best of our knowledge, the coexistence of 2s-RAP and 4s-RAP for broadband communications has not been studied in the literature.

3. System Model

Both 2s-RAP and 4s-RAP would be supported in a cell [6]. Typically, 64 preambles are available for RAP in one PRACH occasion. We consider that 10 out of 64 preambles are reserved for contention-free access. $\nu\%$ and $(1 - \nu)\%$ of $M = 54$ preambles are respectively allocated for 2s-RAP and 4s-RAP. The skewed distribution gives the flexibility to allocate more preambles for 2s-RAP for its prioritization. We consider that the UE intending to initiate the RAP makes the choice for its first random access

attempt based on its channel conditions and randomly selects a preamble from the subset of preambles associated with its choice. Let q_2 and q_4 be the probabilities of channel conditions, respectively, for 2s-RAP and 4s-RAP such that $q_2 + q_4 = 1$. Limited preamble space along with simultaneous random access by myriad of UEs would frequently result in collisions as many UEs might select the same preamble for MsgA transmission. Several RAP failures can be expected even when mechanisms like power ramping are applied. For our analysis, we consider that there are enough PUSCH resources for MsgA due to sufficient spectrum availability at mmWaves. Since the preamble space is limited, the choice of reattempts after the RAP failure requires careful analysis as presented in this section.

3.1. Reasserting Algorithm (ReA)

We propose that, in ReA, the UE measures channel quality after every failure and is able to re-select either 2s-RAP or 4s-RAP for the subsequent attempts based on probabilities q_2 and q_4 , respectively. Thus, all the attempts/reattempts are always performed at the appropriate choice of either 2s-RAP or 4s-RAP. As a result, the failure due to poor channel is reduced for the UEs attempting 2s-RAP. Moreover, ReA prevents the unnecessary congestion of 2s-RAP by avoiding UEs whose channel deteriorates in reattempts. Algorithm 1 delineates the ReA proposal. In step 2, total preambles are first divided in two groups, one for 2s-RAP and the other for 4s-RAP. In step 3 and step 4, UE selects preambles based on its channel condition. Subsequently, it performs either 2s-RAP or 4s-RAP. Step 7 and Step 12 highlight that the channel re-selection is made at the RAP failure. Let the UE succeed in its RAP after n number of attempts where each RA trial is independent of the previous attempt. Out of a total of n RA attempts to achieve a success, let i be the number of attempts performed with 2s-RAP and j be the attempts with 4s-RAP. Since 2s-RAP is faster, we consider that D_2 and D_4 respectively delineate the delay for 2s-RAP and 4s-RAP such that $D_2 < D_4$. The average delay experienced by the UE over n reattempts can be expressed as

$$D_{avg}^{ReA}[n] = \sum_{i=0}^n \binom{n}{i} \left(iD_2 + (n-i)D_4 \right) q_2^i (1-q_2)^{n-i} \tag{1}$$

Subsequently, we can obtain the average delay experienced by the UE unconditioned on n as $D_{avg}^{ReA} = \sum_{n=1}^{\infty} D_{avg}^{ReA}[n] \mathbb{P}_r^{ReA}\{n\}$, where $\mathbb{P}_r^{ReA}\{n\}$ is the probability that RAP is a success in n attempts. Since the channel is measured at every reattempt, the RAP failure can be assumed to occur due to collision only (more than one UE selecting the same preamble). However, the number of preambles allocated to 2s-RAP and 4s-RAP are different and thus the collision probability in the two procedures would also be different. Assuming that new UEs initiate RAP based on Poission arrival with mean λ in both the cases, collision probabilities, respectively, for 2s-RAP and 4s-RAP can be obtained based on [16] as

$$\mathbb{P}_{C2} = 1 - e^{(-\lambda/(v*M))} \tag{2}$$

$$\mathbb{P}_{C4} = 1 - e^{(-\lambda/((1-v)*M))} \tag{3}$$

The UE after $(n-1)$ failures can succeed either in 2s-RAP or 4s-RAP. Thus, $\mathbb{P}_r^{ReA}\{n\}$ can be evaluated as

$$\mathbb{P}_r^{ReA}\{n\} = \left(\sum_{i=0}^{n-1} \binom{n-1}{i} \mathbb{P}_{C2}^i \mathbb{P}_{C4}^{n-1-i} \right) (1 - \mathbb{P}_{C2}) + \left(\sum_{i=0}^{n-1} \binom{n-1}{i} \mathbb{P}_{C4}^i \mathbb{P}_{C2}^{n-1-i} \right) (1 - \mathbb{P}_{C4}) \tag{4}$$

Collisions in 2s-RAP and 4s-RAP would not only increase the delay but would also affect the number of successful UEs. We can define success rate as the ratio of UEs that successfully accomplished

RAP to the total UEs (N) that initiated RAP at the given time. The success rate for ReA includes the total UEs that succeed, either with 2s-RAP or 4s-RAP. Assuming that j of N UEs that perform RAP succeed in 4s-RAP and the remaining in 2s-RAP, we can obtain the success rate as

$$\vartheta^{ReA} = \frac{1}{N} \sum_{j=0}^N \binom{N}{j} \left(j(1 - \mathbb{P}_{C2}) + (N - j)(1 - \mathbb{P}_{C4}) \right) q_2^j q_4^{(N-j)} \quad (5)$$

Though ReA has inherent advantage of dynamism, the challenge with ReA is that the UE needs to reassess the channel again and again which would add complexity and overheads in the practical system. For simplicity, we can consider the SeA algorithm as explained subsequently.

Algorithm 1 2s-RAP and 4s-RAP using reasserting algorithm (ReA)

- 1: Input: M, ν, q_2 & q_4
 - 2: 2s-RAP preambles: $M * \nu\%$
 - 3: 4s-RAP preambles: $M * (1 - \nu)\%$
 - 4: Check Channel Condition (q_2 & q_4)
 - 5: **if** $q_2 > q_4$ **then**
 - 6: Perform RAP using 2s-RAP
 - 7: **if** UE fails **then**
 - 8: Go to step 4
 - 9: **end if**
 - 10: **else**
 - 11: Perform RAP using 4s-RAP
 - 12: **if** UE fails **then**
 - 13: Go to step 4
 - 14: **end if**
 - 15: **end if**
 - 16: Calculate D_{avg}^{ReA} and ϑ^{ReA}
 - 17: Output: D_{avg}^{ReA} and ϑ^{ReA}
-

3.2. Sequential Algorithm (SeA)

Algorithm 2 shows our SeA proposal. Similar to ReA, in step 2, total preambles are first divided into two groups, one for 2s-RAP and the other for 4s-RAP. In step 3, UE selects preambles based on its channel condition. However, in SeA, we propose that, if a 2s-RAP attempt by a UE fails, then it can reattempt with 2s-RAP itself but only for the fixed number of trials as highlighted in steps 5 to 9. After exhausting the configured number of 2s-RAP trials, the subsequent reattempts are made with 4s-RAP (step 10–12). Thus, instead of competing for 2s-RAP resources invariably, the UE persistently fails 2s-RAP transit to 4s-RAP for congestion control of 2s-RAP. In SeA, there are no channel reassessment overheads and UEs are given a fair chance at 2s-RAP reattempts. Let the total number of configured attempts in 2s-RAP be L_2 , after which the UE reattempts with 4s-RAP and competes with UEs that initiated with the 4s-RAP itself due to their channel conditions. The average delay would not only depend upon the total number of attempts n but also on its relation with L_2 . There are three possible cases: (i) UE initiates and succeeds with 2s-RAP in $n \leq L_2$ attempts; (ii) UE initiates with 2s-RAP and succeeds with 4s-RAP in $n > L_2$ attempts; and (iii) UE initiates and succeeds in n attempts with 4s-RAP only. The respective probabilities are $(\mathbb{P}_{r_{s22}}^{SeA}\{n\})$, $(\mathbb{P}_{r_{s24}}^{SeA}\{n\})$ and $(\mathbb{P}_{r_{s44}}^{SeA}\{n\})$. They can be obtained as

$$\mathbb{P}_{r_{s22}}^{SeA}\{n \leq L_2\} = \sum_{k=1}^{L_2} \binom{L_2}{k} \mathbb{P}_{C2} (1 - (1 - \mathbb{P}_{C2})q_2)^{k-2} ((1 - \mathbb{P}_{C2})q_2) \quad (6)$$

$$\mathbb{P}_{r_{s24}}^{SeA}\{n > L_2\} = \sum_{k=L_2+1}^n \binom{n}{k} \mathbb{P}_{C2}(1 - (1 - \mathbb{P}_{C2})q_2)^{(L_2-1)} (1 - (1 - \mathbb{P}_{C4})q_4)^{(k-L_2-1)}(1 - \mathbb{P}_{C4}q_4) \quad (7)$$

$$\mathbb{P}_{r_{s44}}^{SeA}\{n\} = \sum_{k=1}^n \binom{n}{k} \mathbb{P}_{C4}(1 - (1 - \mathbb{P}_{C4})q_4)^{(k-1)}(1 - \mathbb{P}_{C4}q_4) \quad (8)$$

Since L_2 is fixed, the UE is not required to remeasure channel for every reattempt. Thus, failure at any (re)attempt can occur either due to collision or due to a poor channel and thus the above equations include q_2 and q_4 . By multiplying $\mathbb{P}_{r_{s22}}^{SeA}\{n \leq L_2\}$ with $nD_2[n \leq L_2]$ and summing over all possible values of n , we can obtain the average delay for the first case as D_{avg1}^{SeA} . Similarly by using the product of $\mathbb{P}_{r_{s44}}^{SeA}\{n\}$ and $nD_2[n]$, we can obtain D_{avg2}^{SeA} as unconditioned delay observed when UE having started in 4s-RAP succeeds in 4s-RAP itself.

Algorithm 2 2s-RAP and 4s-RAP using sequential algorithm (SeA)

- 1: Input: M, L_2, n, ν, q_2 & q_4
 - 2: 2s-RAP preambles: $M * \nu\%$
 - 3: 4s-RAP preambles: $M * (1 - \nu)\%$
 - 4: Check Channel Condition (q_2 & q_4)
 - 5: **if** $q_2 > q_4$ **then**
 - 6: UE performs RAP using 2s-RAP
 - 7: $L_2 = L_2 - 1$
 - 8: **if** UE fails & $L_2 \geq 1$ **then**
 - 9: Go to step 6
 - 10: **end if**
 - 11: Perform RAP using 4s-RAP
 - 12: **if** UE fails **then**
 - 13: Go to step 11
 - 14: **end if**
 - 15: **else if** $q_2 < q_4$ **then**
 - 16: Go to step 11
 - 17: **end if**
 - 18: Calculate D_{avg}^{SeA} and ϑ^{SeA}
 - 19: Output: D_{avg}^{SeA} & ϑ^{SeA}
-

However, a UE can start with 2s-RAP but fails in L_2 . The probability that UE starts with 2s-RAP but fails in L_2 , which can be obtained as

$$\mathbb{P}_{r_{f22}}^{SeA}\{n\} = \mathbb{P}_{C2}((1 - (1 - \mathbb{P}_{C4})q_2)^{L_2-1}) \quad (9)$$

Subsequently, we can calculate D_{avg3}^{SeA} as the delay observed when the UE starts in 2s-RAP but succeeds in 4s-RAP as

$$D_{avg3}^{SeA} = \sum_{n=1}^{L_2} \mathbb{P}_{r_{f22}}^{SeA}\{n\}(nD_2) + \sum_{n=L_2+1}^{\infty} \mathbb{P}_{r_{s24}}^{SeA}\{n\}(nD_4) \quad (10)$$

Thus, by using $[q_2(D_{avg1}^{SeA} + D_{avg3}^{SeA}) + q_4D_{avg2}^{SeA}]$, we can obtain the average delay, D_{avg}^{SeA} , for SeA. The success rate for SeA can be evaluated as

$$\vartheta^{SeA} = ((1 - \mathbb{P}_{C2})(q_2N\mathbb{P}_{r_{s22}}^{SeA}) + (1 - \mathbb{P}_{C4})(q_2N\mathbb{P}_{r_{f22}}^{SeA} + q_4N))/N \quad (11)$$

Though SeA is not as dynamic as ReA, it still provides fair bit of flexibility compared to existing PrA while also providing simplicity.

3.3. Preceding Algorithm (PrA)

PrA is a simple segregation of 2s-RAP from 4s-RAP and can be considered as the baseline case. PrA is delineated in Algorithm 3. The analysis of PrA approach is important to understand the 3GPP compliant current system of coexistence of 2s-RAP and 4s-RAP. To the best of our knowledge, this analysis is also not available in the literature. In PrA, once the preambles are mapped, the UEs attempting 2s-RAP as well as their associated preambles are not related to UEs attempting 4s-RAP and preambles mapped to 4s-RAP as clear from step 6 and step 7 in Algorithm 3. While the UE's decision to perform 2s-RAP can change in the proposed ReA and SeA, it remains fixed for PrA. PrA treats 2s-RAP and 4s-RAP independently. Thus, the average delay observed by 2s-RAP and 4s-RAP can be individually evaluated in PrA as

$$D_{avg1}^{PrA} = \sum_n \sum_{l=0}^{n-1} \binom{n}{l} \left(l D_2 \mathbb{P}_{C2} (1 - (1 - \mathbb{P}_{C2}) q_2)^{(l-2)} ((1 - \mathbb{P}_{C2}) q_2) \right) \tag{12}$$

$$D_{avg1}^{PrA} = \sum_n \sum_{l=0}^{n-1} \binom{n}{l} \left(l D_2 \mathbb{P}_{C4} (1 - (1 - \mathbb{P}_{C4}) q_4)^{(l-2)} ((1 - \mathbb{P}_{C4}) q_4) \right) \tag{13}$$

The average delay for PrA can be obtained as $D_{avg}^{PrA} = D_{avg1}^{PrA} q_2 + D_{avg2}^{PrA} q_4$. Finally, we can evaluate the success rate for PrA, as

$$\vartheta^{PrA} = ((1 - \mathbb{P}_{C2}) q_2 N + (1 - \mathbb{P}_{C4}) q_4 N) / N \tag{14}$$

Table 1 tabulates the comparison between proposed ReA, SeA and PrA. It also delineates the comparison with respect to only 2s-RAP and 4s-RAP along with the existing work in [11]. While ReS provides higher flexibility and mitigates the effect of channel variations at every step, SeA allows limited attempts in 2s-RAP thus providing partial flexibility. Moreover, in SeA, though the channel is not assessed at every failure, the effect of a varying channel is partially mitigated as the device whose channel deteriorates with reattempts ultimately moves to 4s-RAP. These advantages are manifested by other schemes.

Algorithm 3 2s-RAP and 4s-RAP using preceding algorithm (PrA)

- 1: Input: M, ν, q_2 & q_4
 - 2: 2s-RAP preambles: $M * \nu\%$
 - 3: 4s-RAP preambles: $M * (1 - \nu)\%$
 - 4: UE Checks q_2 & q_4
 - 5: Based on q_2 & q_4 select 2s-RAP or 4s-RAP
 - 6: Perform RAP based on selected process (2s-RAP or 4s-RAP)
 - 7: **if** UE fails **then**
 - 8: Go to step 6
 - 9: **end if**
 - 10: Calculate D_{avg}^{PrA} and ϑ^{PrA}
 - 11: Output: D_{avg}^{PrA} and ϑ^{PrA}
-

Table 1. Table of comparison.

Random Access	Number of Messages	Flexibility	Preamble Redesign	Effect of Channel Variations
ReA	For some UEs 2 and for some UEs 4 (Selection of 2s-RAP or 4s-RAP is not fixed)	High	No	Low
SeA	For some UEs 2 and for some UEs 4 (Number of times 2s-RAP is selected per UE is fixed)	Partial	No	Partial
PrA	For some UEs 2 and for some UEs 4 (Selection of 2s or 4s step is fixed)	Low	No	Not considered
2s-RAP	For all UEs 2	Low	No	Not considered
4s-RAP	For all UEs 4	Low	No	Not considered
[11]	For all UEs 2	Low	Yes	Not considered

4. Performance Evaluations

In this section, we first present the numerical results for the proposed ReA and SeA while comparing them to baseline PrA algorithms as well as legacy 4s-RAP. Subsequently, we validate our analysis through simulation results. We used Matlab to analyze the performance of proposed algorithms. The numerical results are obtained by implementing Equations (1) to (14). To prioritize 2s-RAP, $\nu = 0.6$ is considered. For our analysis, we consider two cases: (i) $q_2 = 0.5$ such that the probabilities of channel conditions for 2s-RAP and 4s-RAP are same (ii) $q_2 = 0.8$, where the probability of channel conditions for 2s-RAP is high. We assume that the delay for one attempt/reattempt with 2s-RAP and 4s-RAP to be $D_2 = 1$ and $D_4 = 2$, respectively, for the simplicity and the algorithms can be easily adapted to the actual situation. The considered parameters are given in Table 2.

Table 2. Performance parameters

Parameter	Value
Arrival Rate (λ)	0.01~25
Total number of preambles	64
Reserved preambles	10
No. of Preamble for 2s-RAP ($\nu\%$)	60% of Total preamble
No. of Preamble for 4s-RAP ($(1 - \nu)\%$)	40% of Total preamble
Delay for 2s-RAP (D_2)	1 ms
Delay for 4s-RAP (D_4)	2 ms
Probability of 2s-RAP Channel Condition (q_2)	[0.5 & 0.8]
L_2	5

Figures 2–4 show the average access delay for increase in the arrival rate λ for $q_2 = 0.2$, $q_2 = 0.5$ and $q_2 = 0.8$, respectively. At every point, the arrival rates for both 2s-RAP and 4s-RAP are considered the same. When the arrival rate is low, the contention is reasonable, resulting in almost constant average delays. However, the increase in λ results in frequent collisions as the number of preambles are limited. Ultimately, the system becomes overwhelmed with extremely high delays. However, the point of saturation is different for the three algorithms. It is clear from figures that the existing base line PrA performs even worse than the legacy 4s-RAP as the total preambles are divided among 2s-RAP and 4s-RAP, while UEs follow simple and static selection of 2s-RAP and 4s-RAP. For $q_2 = 0.8$, Figure 4 shows that, when a higher number of UEs attempt with 2s-RAP in PrA, then the delay performance is similar to legacy 4s-RAP. Performance enhancement due to our proposed ReA and SeA compared to baseline PrA is prominent in the figures. ReA performs the best as the channel is ascertained at every reattempt and thus failures due to poor channels are avoided. As expected, $q_2 = 0.8$ or $q_2 = 0.2$ has little effect on ReA due to the (re)measurement of channel. In SeA, UEs have more opportunity for success in 2s-RAP than PrA as $L_2 = 5$ number of reattempts with 2s-RAP are allowed. Thus, SeA also performs better than PrA as well as 4s-RAP without reassessment overheads. When $q_2 = 0.8$, SeA performs even better as not only are more UEs trying to access with 2s-RAP where there is less delay, but they also do

so for several configured reattempts. Since 4s-RAP is the legacy system in LTE, the comparison with respect to 4s-RAP is also shown. 2s-RAP in itself would only be the scaled down version of 4s-RAP and therefore is not explicitly provided in the paper to avoid cluttering.

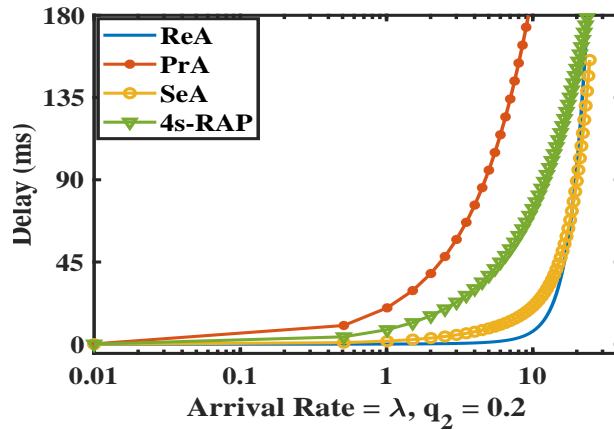


Figure 2. Average delay ($q_2 = 0.2$).

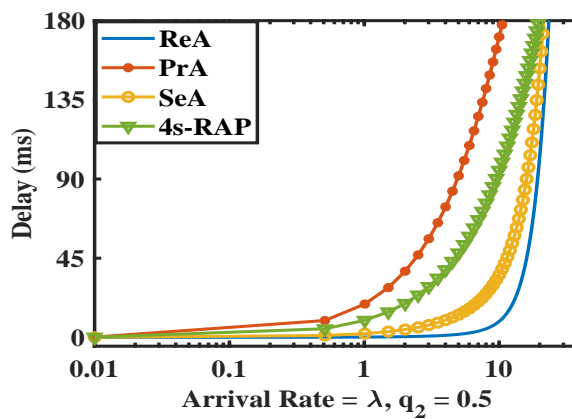


Figure 3. Average delay ($q_2 = 0.5$).

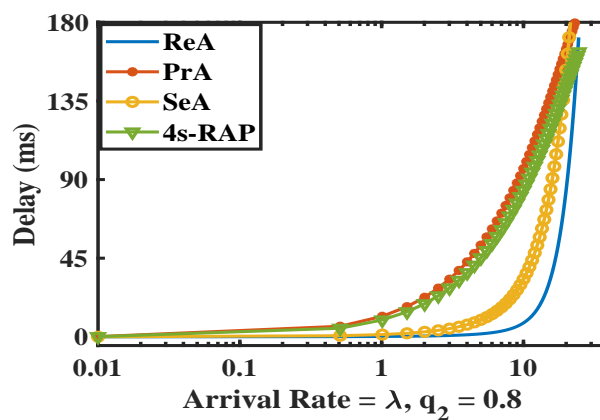


Figure 4. Average delay ($q_2 = 0.8$).

Figure 5 shows the success rate for our proposed ReA and SeA as well as baseline PrA and legacy 4s-RAP. We consider $q_2 = 0.5$. The success rates for ReA again shows the best results as failures due to poor channels are avoided by channel reassessments. For the given number of UEs, the probability of RAP being a success is the highest for ReA, which portrays a tightly coupled coexistence of 2s-RAP

and 4s-RAP. The success rate for SeA, the base line PrA, and 4s-RAP are much lower as failure can take place due to collision as well as poor channel conditions. The success rates for these cases are in similar ranges for the low arrival rate. In SeA, the UEs, after having failed with 2s-RAP for L_2 attempts, move to 4s-RAP and increase their congestion. Skewed value of ν allocates less preambles to 4s-RAP while high arrival rate along with several carryforwards from 2s-RAP increases number of contending UEs in 4s-RAP. Thus, SeA experiences a lower success rate as arrival increases. In legacy 4s-RAP, the preambles are not divided into subgroups so, with higher arrival, its success rate is slightly better.

To validate the proposed analysis, we perform the system level simulations using Matlab. The simulation setup is explained as follows:

- In the first step, the active UEs are randomly distributed and can select either 2s-RAP or 4s-RAP for the first attempt based on a randomly chosen value of 'q'. For attempt/reattempt, the UE competes for preambles allocated to its selection along with the newly activated UEs that are generated based on Poisson.
- To perform random access, the 'N' active UEs select the preambles for transmission. The selected preamble is checked. If two or more UEs select the same preamble in the same time slot, then it results in a collision. The UE can successfully transmit if its selected preamble is different from other UEs.
- The collided UEs are carried forward to the next time slot. They can reattempt using either 2s-RAP preambles or 4s-RAP preambles based on ReA, SeA, and PrA logic. For ReA, UE randomly selects a value of 'q' and, based on specified channel probability, it can be considered either in 2s-RAP or 4s-RAP. For SeA, after 2s-RAP failure, it keeps selecting preambles allocated to 2s-RAP until ' $L = 5$ ' attempts are expired. For PeA, the UE re-selects the preambles associated with the initial choice only.
- We use slotted Aloha such that there are N number of UEs for a given number of preambles at the start of every simulation slot. For obtaining N, we consider the UEs that have already collided and are required to reattempt RAP along with the newly activated UEs.
- The simulations are repeated 10,000 times. At the end of simulation, the number of attempts in both 2s-RAP and 4s-RAP are recorded and average delay is calculated.

Figure 6 shows the simulation results for ReA, SeA, and PrA algorithms and analytical results. The graphs show that simulation results are similar to the analytical results, thus validating our modeling. Figure 7 presents the comparison of proposed algorithms with a 2-way random access scheme presented in [11]. We considered the same parameters e.g., arrival rate, TTI length, and number of UEs as in [11]. In Figure 7, the trend of our proposed algorithm follows a similar pattern as in [11]. The delay obtained by ReA is less than a 2-way random access scheme [11] without the complexities of preamble redesign and is in accordance with the 3GPP specifications. We would finally like to highlight that 2s-RAP in congested broadband communication is a very new topic and presents a considerable research opportunity. As our future work, we can consider dynamic preamble allocation for 2s-RAP and 4s-RAP such that more preambles can be dynamically allocated to 2s-RAP. If the arrival rate for 2s-RAP increases even more, preambles can be allocated to it for faster access. Moreover, different arrivals for 2s-RAP and 4s-RAP can also be considered which would be closer to a practical system. We can also extend this work by considering implementation of the Markov decision process, such that UEs have flexibility in choosing either of the three algorithms for the best results.

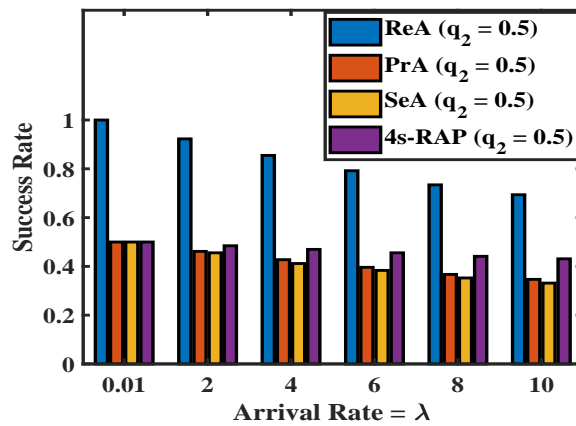


Figure 5. Success rate ($q_2 = 0.5$).

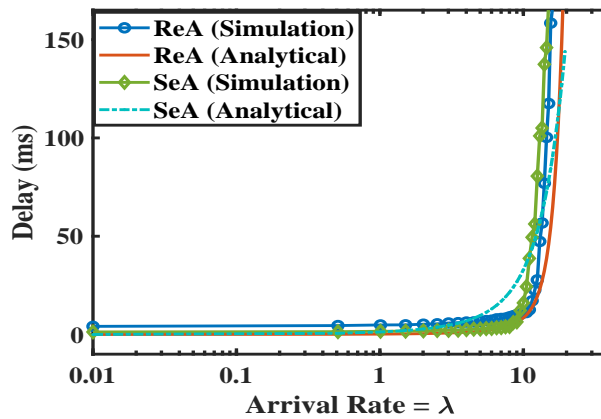


Figure 6. Simulation results.

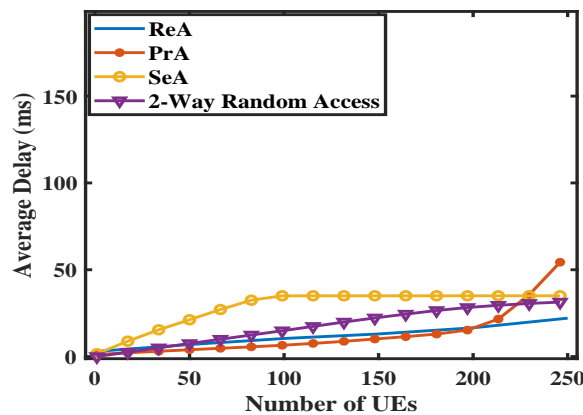


Figure 7. Average delay for random access.

5. Conclusions

In this paper, we have analyzed the novel two step random access procedure (2s-RAP) that can reduce the latency of random access and uplink transmission. However, the 2s-RAP cannot be considered in isolation and is expected to coexist with legacy 4s-RAP to alleviate challenges of mmWaves and congestion. In the recent 3GPP proposal, the UE does not have any flexibility to change its initial choice of 2s-RAP or 4s-RAP in the case of reattempt after a failure. We propose two novel algorithms for performance enhancement of 2s-RAP in congested environments while exploiting its coexistence with the 4s-RAP. In the proposed Reasserting Algorithm (ReA), UEs perform RAP

re-attempts in either 2s-RAP or 4s-RAP based on the channel conditions such that the chances of RAP failure due to poor channel are reduced. The second proposed algorithm, Sequential Algorithm (SeA), allows for configuring more re-attempts in 2s-RAP. We also present the comparison with respect to legacy four step RAP. The analytical results are verified through simulations.

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