3GPP TSG RAN WG1 Meeting #125 **R1-2603707**
Dalian, China, May 18th – 22nd, 2026

Agenda Item: 10.5.1.2

Source: EURECOM

Title: PRACH and RACH procedure

Document for: Discussion and decision

1. Introduction

According to the SI for Release 20 6G, PRACH and RACH procedure is included to support multi-antenna system in 6G. New PRACH design and RACH procedure is necessary to make the multi-antenna system achieve the 6G requirements.

RAN1#124 has the following agreements.

> **Agreement**
>
> Study random access framework with the following aspects:
>
> - Enablement of energy efficient random access procedures (supporting SID objective 1b);
>   - Including both network and UE power saving
> - Coverage improvement (supporting SID objective 1d);
> - Support of random access for diverse device types and capabilities (supporting SID objective 1g);
> - System performance improvement from overhead reduction, simplification of signaling/configurations (supporting SID objective 1k);
> - Additionally consider following aspects
>   - random access latency;
>   - capacity
>   - detection reliability;
>   - high speed mobility;
> - Note: Other aspects identified during future discussions are not excluded.
>
> The following scenarios and assumptions beyond single carrier/TRP are considered for the study of above random access framework:
>
> - NTN
> - SBFD
> - multi-carrier
> - multi-TRP

- Note: whether/how to support one or more of the scenarios/assumptions, including whether any special handling or functionality needs to be introduced in support of the scenarios/assumptions is part of the study.

RAN1#124b has the following agreements.

Agreement

Adopt the following definition for miss detection probability-and false alarm probability for RAN1 study (not intended for 6GR requirements)

- Note: Definition of evaluation metrics are for the purpose of alignment of definition among companies. Companies are encouraged to provide information on evaluation metrics reported and the implication and importance of the evaluation metric in the contributions with evaluations.
- Miss detection probability
  - Total probability of following events (for a preamble transmission):
    - Not detecting the preamble for a RO that was sent among the target preambles of the detecting BS
    - Correct preamble detection but with the wrong timing estimation
      - For correct preamble detection, the (residual) timing estimation error should be less than CP/2 of data symbol, e.g., SCS = 30kHz, CP/2 = 1.2 us
- False alarm probability
  - Probability of detecting any target preamble for a RO when no transmission has occurred (only noise)

Adopt the following definition for metrics for evaluations for RAN1 study (not intended for 6GR requirements)

- Note: Not all metrics may be applicable for all evaluation scenarios, and it is up to companies to provide appropriate metric(s) for information. The definitions are for the purpose of alignment of definition among companies. Companies are encouraged to provide information on evaluation metrics reported and the implication and importance of the evaluation metric in the contributions with evaluations.
- Miss detection probability considering frequency estimation
  - Total probability of following events (for a preamble transmission):
    - Not detecting the preamble for a RO that was sent among the target preambles of the detecting BS

        - Correct preamble detection but with the wrong timing estimation and/or frequency estimation
            - For correct preamble detection,
                - the (residual) timing estimation error should be less than CP/2 of data symbol, e.g., SCS = 30kHz, CP/2 = 1.2 us, and
                - the (residual) frequency estimation error of PRACH detection should be less than some target value. Target value to be reported by company.

- Type 1 false detection probability (intra-cell)
    - Probability of detecting different preamble(s) for a RO than the one that was sent among the target preambles of the detecting BS.
- Type 1 false detection rate (intra-cell)
    - A = number of preamble(s) for a RO detected other than the one that was sent among the target preambles of the detecting BS
    - B = Sum of A for all ROs that contain preamble transmission
    - C = Total number of preamble transmission across all ROs
    - Type 1 false detection rate = B divided by C
- Type 2 false detection probability (inter-cell)
    - Probability of detecting any target preamble for a RO when no transmission has occurred in the cell of detecting BS and transmission has occurred in another cell
- Mixed false detection probability
    - Probability of detecting multiple preambles (two or more) of which one of the detected preamble is correctly detected (multiple preamble detection for the detecting BS) for a RO when only one preamble among the target preambles of the detection BS was sent.

Agreement

- Study base sequences and preamble sequence generation/construction methods for 6GR PRACH taking into account one or more of the following aspects:
    - detection performance (possibly including TA estimation performance, handling of frequency offset, miss-detection, false alarm, false detection, auto-correlation/cross correlation properties, etc)
    - detection complexity for BS
    - implementation complexity for UE
    - Cubic metric/PAPR
    - supported sequence lengths & associated SCS of a sequence
    - [Preambles per random access occasion (RO)]
    - Inter-cell interference
    - Coexistence with 5G NR PRACH sequences

- Note 1: Benchmark various performance metric(s) and considerations against 5G NR PRACH design as baseline
- Note 2: base sequences for 5G NR PRACH are ZC sequence, and preamble sequence generation is done via (time domain) cyclic shift of a ZC root sequence (base sequence) to create a specific preamble sequence.
- Note 3: companies are encouraged to provide the following information:
  - detailed information for the sequence generation and construction of a preamble for PRACH
  - correlation properties (compared to NR PRACH sequences, including correlation with NR PRACH sequences)
  - Cubic metric/PAPR (at least compared to NR PRACH sequences)
  - Applicable scenarios

Agreement

- Study and Identify at least the following set of deployment scenario characteristics for 6GR RACH preamble format design:
  - target round trip time (RTT)/maximum cell radius
  - target time duration of preamble
  - target doppler/UE mobility
  - target duplex scheme, PRACH SCS, and frequency ranges
- Study and identify required preamble formats that correspond to the identified use cases.

Observation

Simplification of preamble formats compared to NR PRACH preamble formats is generally desired.

2. Discussion

In 5G, 4-step RACH and 2-step RACH procedures are used for initial access between the user equipment (UE) and the base station (BS/gNB).

2.1 4-step RACH procedure

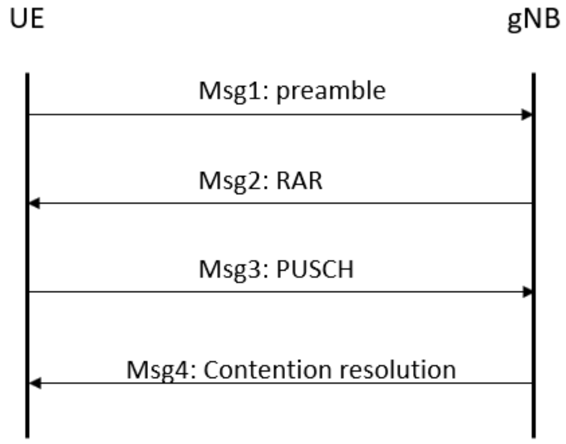

Figure 1: 4-step RACH procedure

When a UE wants to connect to the network for the first time or after a period of inactivity, it uses 4-step RACH procedure illustrated in Figure 1.

The UE sends Msg1 containing a random access preamble from a set of predefined preambles to the gNB on Physical random access channel (PRACH). The preambles are classified into two categories: Short Preamble Format and Long Preamble Format.

Upon receiving Msg1, the gNB sends Msg 2 (Random access response (RAR)) to response. Msg2 consists of several critical pieces of information, such as the Time Advance (TA) command for timing adjustment, the RAPID (Random Access Preamble ID) matching the preamble sent by the UE, and an initial uplink grant that configures resource for the UE to transmit data in Physical uplink shared channel (PUSCH). The gNB also assigns a temporary identifier called RA-RNTI (Random Access Radio Network Temporary Identifier) to the UE.

The UE uses the resources configured through the uplink grant in Msg2 to transmit Msg3 to the gNB on PUSCH carrying RRC messages such as RRC request, RRC reestablishment, RRC handover or pure data.

After processing Msg3, the gNB sends Msg4 to the UE. Msg4 is a MAC data for Contention Resolution. The Contention Resolution message contains the UE's identity, confirming that the gNB has correctly identified the UE, and contention has been resolved. At this step, network provide UE with C-RNTI (Cell Radio Network Temporary Identifier).

2.2 2-step RACH procedure

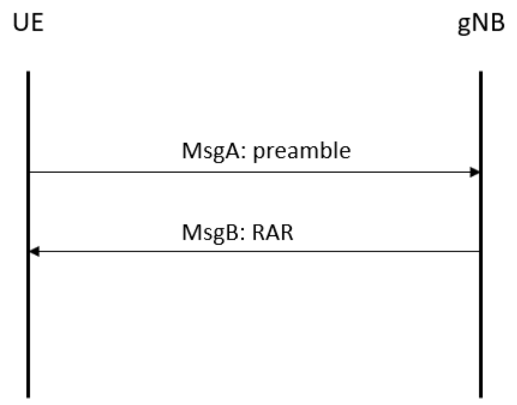

Figure 2: 2-step RACH procedure

The 2-step RACH procedure shown in Figure 2 was approved for 5G. The UE directly transmits a message A (MsgA) which is a combination of the PRACH preamble and a PUSCH transmission instead of waiting for the gNB to allocate PUSCH resources after PRACH reception. The goal is to reduce initial access time, i.e. the time required for the UE to transition into RRC_CONNECTED state. Message A consists of two parts: preamble on PRACH and RRC message/data on PUSCH. Both parts cannot be transmitted in the same slot. The minimum time gap between the preamble and the PUSCH transmissions is 2 or 4 symbols for 15/30kHz SCS and 60/120kHz SCS, respectively.

Figure 3 illustrates an example of MsgA structure with the mapping between the preambles and PUSCH occasions (POs). The example assumes 32 POs consisting of 16 time-frequency resources each with 2 DMRS configurations. The associated RACH occasion (RO) is one time-frequency resource with 32 different preambles. Every preamble is then directly mapped to a specific PO, first in frequency then DMRS and time domain. Hence, by detecting the preambles, the gNB knows exactly which PO to decode. In summary, the PRACH preamble has the following purposes: time-frequency synchronization and PUSCH resource identification.

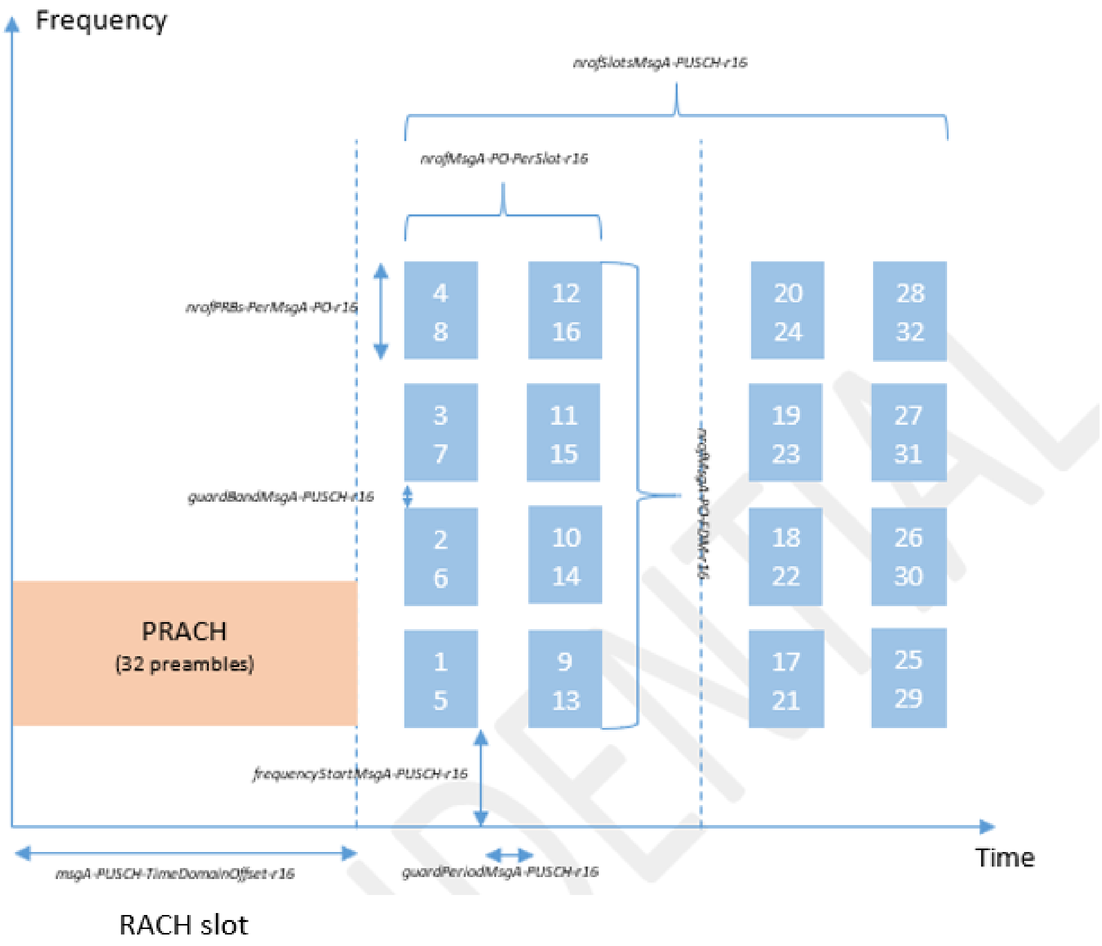

Figure 3: Channel structure of MsgA: mapping between preambles and PUSCH occasions

The gNB receives the MsgB and there are 4 cases that can happen:

- Case 1: The gNB detects the preamble from the UE and successfully decodes the payload. It notifies the UE of contention resolution by sending a successful Random Access Response (RAR) in MsgB with a TA command which is an integer value greater than or equal to zero.
- Case 2: The gNB detects a single preamble but fails to decode the payload. Using the preamble reception time, it sends back a fallback RAR in MsgB to the UE with the TA command and an uplink grant for the payload retransmission.
- Case 3: The gNB detects multiple identical preambles from UEs. There is no fallback RAR because the gNB is unable to specify the preamble reception time of each UE. Therefore, the gNB transmits a backoff indication to UEs that will attempt random access again.
- Case 4: The gNB fails to detect the preamble. There is no RAR to the UE.

2.3. New PUSCH format for RACH procedure

The current MsgA transmission in the 2-step RACH procedure has a shortcoming where preamble and PUSCH are in two transmissions in different slots and cannot be transmitted in the same slot as shown in Figure 3 that might cause latency in RRC connection (request, reestablishment, handover) for the time-sensitive applications. It also causes an increase of overhead, resource and energy consumption due to two separate transmissions.

In order to deal with the shortcomings of the current RACH procedure, the new PUSCH formats are used for MsgA of the 2-step RACH procedure which allows the information for the UE detection, synchronization (provided by preamble in the conventional 2-step RACH procedure) and data part for RRC connection to be transmitted in a single PUSCH transmission.

A new PUSCH format is illustrated in Figure 4 as an example for the proposed PUSCH formats. The proposed PUSCH (noted as PUSCH++ in Figure 4) has the same format as PRACH format 0 for long preamble. Other PRACH formats (format 1, 2, 3) for long preamble sequence where there are repetitions of the sequence also can be used for the new PUSCH formats.

This PUSCH has a length of 839 that accounts for 839 resource elements (REs) in a duration of 800 μs with SCS of 1.25 kHz. The proposed PUSCH contains DMRS and data in 839 REs. DMRS is used by the BS (aNB) to detect the UE and calculate timing advance (TA) as preamble sequence in the conventional 2-step RACH procedure. Data part in the proposed PUSCH of MsgA includes the messages for RRC connection as PUSCH in the conventional 2-step RACH procedure. Therefore, MsgA in the proposed scheme only contains one PUSCH with DMRS and data part instead of one preamble and one PUSCH in the conventional 2-step RACH-procedure where DMRS of the proposed PUSCH assumes the function of preamble and data of the proposed PUSCH carries the same content as PUSCH transmission in the conventional 2-step RACH procedure. DMRS and data are transmitted together in the proposed PUSCH so MsgA is transmitted in a single transmission instead of two transmissions in different slots in the conventional 2-step RACH procedure where one transmission is for preamble transmission and one transmission is for data (PUSCH) transmission.

In Figure 4, in PUSCH with length of 839, there are 419 REs used for DMRS and 420 REs used for PUSCH data. DMRS configuration is Type 1 as DMRS configuration Type 1 for normal PUSCH where DMRS is allocated to every second subcarriers. The lengths of DMRS and data in Figure 4 are only an example. The lengths of DMRS and data can vary based on the requirements of the UE detection (based on DMRS) and data decoding of different applications and channel condition. To determine DMRS and data lengths, one option is that the aNB configures DMRS and data resources in the proposed PUSCH for the UE based on the requirements of the UE detection and data decoding, channel condition and the configuration of other UEs in the cell.

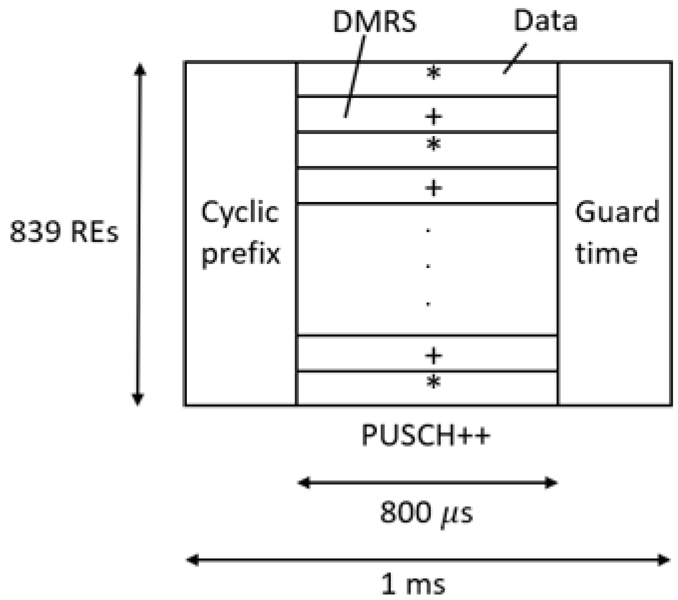

Figure 4: New long PUSCH format

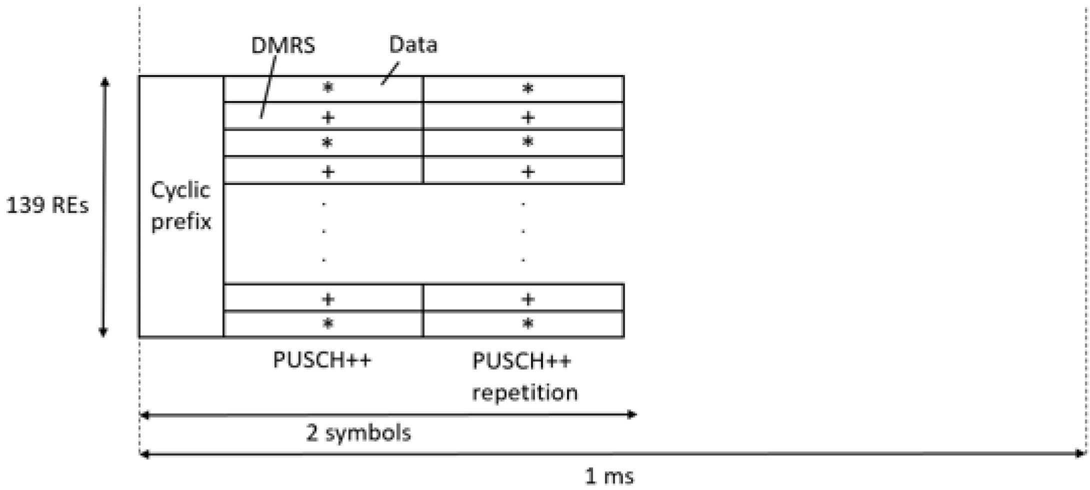

Figure 5: New short PUSCH format

Figure 5 illustrates an example for the proposed PUSCH (noted as PUSCH++ in the figure) with the same format of PRACH for short preamble (format A1 in this example). Other PRACH formats (A2, A3, B1, B2, B3, B4, C0, C2) also can be used for the proposed PUSCH formats.

The length of the proposed PUSCH is 139 that accounts for 139 subcarriers in a duration of one symbol in SCS of 15 kHz, 30 kHz, 60 kHz and 120 kHz. The proposed PUSCH is repeated one time with the same content as the first PUSCH in an occasion so the total duration of PUSCH format A1 is 2 symbols. There is no cyclic prefix or guard period between these two PUSCH. There is cyclic prefix at the beginning of the first PUSCH and no guard period at the end of the second PUSCH. 139 subcarriers of PUSCH contains DMRS and data. DMRS is used by the aNB to identify the UE and do synchronization between the aNB and the UE as short preamble sequence in the conventional 2-step RACH procedure. Data part contains the messages of RRC connection such as connection request, reestablishment, handover as PUSCH in the conventional 2-step RACH procedure. Therefore, MsgA with the proposed PUSCH is transmitted in a single transmission instead of two transmissions in the conventional 2-step RACH procedure.

An example of DMRS and data allocation in short PUSCH format A1 is shown in Figure 5. In 139 resource elements (REs) in one PUSCH++, there are 69 REs for DMRS and 70 REs for data. DMRS configuration follows DMRS configuration Type 1 where DMRS is allocated to every second subcarriers. DMRS is generated from a Zadoff-Chu sequence as the conventional PUSCH transmitted with Transform Precoding then cyclic shift is applied to the root sequences. The resource allocation for DMRS and data can be changed to adapt to channel condition and different applications with different requirements of DMRS detection and data decoding. The aNB configures DMRS and data resources in the proposed PUSCH for the UE based on the requirements of the UE detection and data decoding, channel condition, the configuration of other UEs in the cell.

Observation 1: The separation of RACH and PUSCH transmissions in 4-step and 2-step RACH procedures causes latency, overhead, energy and resource consumption.

Proposal 1: Study 4-step and 2-step RACH procedures in 6G.

Proposal 2: A new PUSCH format for MsgA is used in 2-step RACH procedure where two transmissions in different slots of preamble and PUSCH are replaced by a single PUSCH transmission.

Proposal 3: DMRS in the new PUSCH assumes the role of preamble in the conventional 2-step RACH procedure for UE detection and synchronization.

Proposal 4: Data in the new PUSCH contains the same messages (RRC messages) as data in PUSCH in the conventional 2-step RACH procedure.

Proposal 5: The new PUSCH has the same formats as PRACH for long and short preambles.

2.4. Increase RACH capacity

Long preambles have 838 root sequences and short preambles have 138 root sequences. A small number of root sequences of short preambles causes a small re-use pattern size and limits the cell range that a BS (aNB) can support. The problem is more severe if the number of preamble sequences in a RACH occasion are increased more than the current number of 64 sequences.

Smaller cyclic shifts can be used to generate more additional sequences but it makes preamble detection performance decrease. To increase RACH capacity without affecting detection performance, the proposed scheme is to aggregate (add) two preamble sequences to generate a new sequence. For example, we have two sequences a and a' generated from one or two root sequences by applying cyclic shift. We add these two sequences to generate a new aggregating sequence: b = $\alpha \times$ a + $\alpha' \times$ a' where α and α' are the power coefficients and $\alpha^2 + \alpha'^2 = 1$. To guarantee the detection performance of the aggregating sequences, we do not generate a sequence by adding two sequences that are the same. By adding two sequences to generate a new one, if we have N sequences, we increase the number of sequences from N to (N–1)*N/2 sequences. As shown in Figure 6, with 4 sequences, we can generate 6 sequences by aggregating these sequences. The aggregating sequences have a similar peak to average power ratio and also provide a similar detection performance as the original sequences.

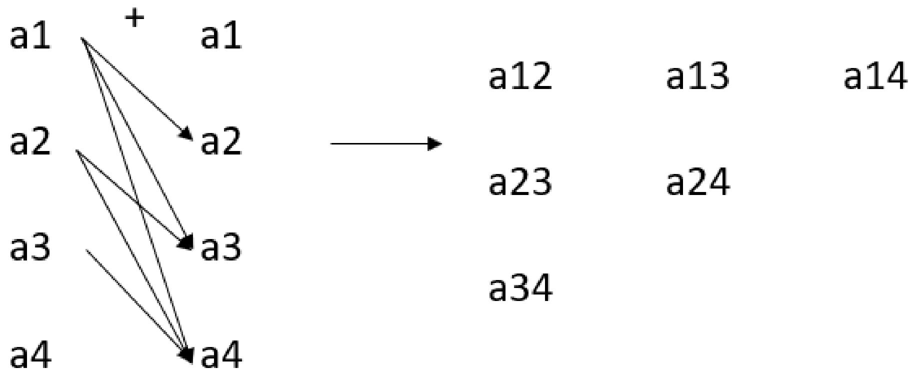

Figure 6: Aggregating two sequences to generate the new sequences

By aggregating two sequences, we only need 13 sequences in a cell to have 64 sequences in a RACH occasion instead of using 64 sequences in the conventional procedure. This aggregating scheme allows a larger re-use pattern size to support the cells with larger cell range that have more neighbor cells.

Proposal 6: Aggregating two preamble sequences to generate a new sequence so that preamble sequence capacity increases.

An increase number of preamble sequences number allows the enhancements in the initial access procedure.

a. Contention-free RACH

An increase number of preamble sequences allows an increase of preamble sequences in a RACH occasion to be more than a conventional number of 64. It allows each UE in a RACH occasion to have a dedicated sequence. When each UE has a dedicated sequence, the UE carries out RACH procedure without contention.

In case contention-based RACH is used as 5G, more preamble sequences in a RACH occasion reduces collision probability when more than one UE selects the same preamble.

Both contention-based RACH and contention-free RACH are considered in 6G.

When each UE is assigned a dedicated sequence, the aNB can identify UE's ID without decoding data in PUSCH.

Proposal 7: Study an increase of preamble sequences in a RACH occasion to be more than 64 sequences in 5G.

Proposal 8: Study contention-based RACH and contention-free RACH in 6G.

Observation 2: Dedicated preamble sequences for the UEs allows the aNB to have the UE's ID without decoding PUSCH.

Proposal 9: Study dedicated preamble sequences for the UEs

b. Reuse factor

An increase in number of sequences allows a higher reuse factor among the cells so that the inter-cell interference is mitigated.

Observation 3: RACH capacity's increase allows a higher reuse factor among the cells for a given cell radius.

c. RACH partitioning

With an increase in number of sequences, specific sets of sequences can be dedicated to the specific functionalities such as small data transmission as described in Section 2.5, RedCap, time sensitive traffic, etc. Furthermore, specific sets of RACH occasions also can be dedicated to the specific functionalities such as small data transmission (Section 2.5), RedCap, time sensitive traffic, etc.

Proposal 10: Specific sets of sequences and RACH occasions are dedicated to specific functionalities such as small data transmission, RedCap, etc.

2.5. Small data transmission

PUSCH++ can be used to transmit user-plane data when MsgA is used for Small Data Transmission. User-plane data is included in the data part of PUSCH++. If the UE is in RRC_INACTIVE state, the UE can transmit data in PUSCH++ without changing from RRC_INACTIVE state to RRC_CONNECTED state. The use of MsgA for Small Data Transmission is indicated from the UE to the aNB through the specific DMRS sequences in PUSCH++. Several DMRS sequences are configured by the aNB so that they are only used if PUSCH++ contains user-plane data in Small Data Transmission. Another option to indicate the use of MsgA for Small Data Transmission is to dedicate to the UE the specific PUSCH++ occasions to transmit user-plane data.

Proposal 11: New PUSCH format (PUSCH++) is used to transmit user-plane data when the UE is in RRC_INACTIVE state without changing to RRC_CONNECTED state.

Proposal 12: Specific DMRS sequences are used to indicate PUSCH++ containing user-plane data in Small Data Transmission.

Proposal 13: The specific PUSCH++ occasions are assigned to the UE to transmit user-plane data.

3. Conclusion

Observation 1: The separation of RACH and PUSCH transmissions in 4-step and 2-step RACH procedures causes latency, overhead, energy and resource consumption.

Observation 2: Dedicated preamble sequences for the UEs allows the aNB to have the UE's ID without decoding PUSCH.

Observation 3: RACH capacity's increase allows a higher reuse factor among the cells for a given cell radius.

Proposal 1: Study 4-step and 2-step RACH procedures in 6G.

Proposal 2: A new PUSCH format for MsgA is used in 2-step RACH procedure where two transmissions in different slots of preamble and PUSCH are replaced by a single PUSCH transmission.

Proposal 3: DMRS in the new PUSCH assumes the role of preamble in the conventional 2-step RACH procedure for UE detection and synchronization.

Proposal 4: Data in the new PUSCH contains the same messages (RRC messages) as data in PUSCH in the conventional 2-step RACH procedure.

Proposal 5: The new PUSCH has the same formats as PRACH for long and short preambles.

Proposal 6: Aggregating two preamble sequences to generate a new sequence so that preamble sequence capacity increases.

Proposal 7: Study an increase of preamble sequences in a RACH occasion to be more than 64 sequences in 5G.

Proposal 8: Study contention-based RACH and contention-free RACH in 6G.

Proposal 14: Study dedicated preamble sequences for the UEs

Proposal 10: Specific sets of sequences and RACH occasions are dedicated to specific functionalities such as small data transmission, RedCap, etc.

Proposal 11: New PUSCH format (PUSCH++) is used to transmit user-plane data when the UE is in RRC_INACTIVE state without changing to RRC_CONNECTED state.

Proposal 12: Specific DMRS sequences are used to indicate PUSCH++ containing user-plane data in Small Data Transmission.

Proposal 13: The specific PUSCH++ occasions are assigned to the UE to transmit user-plane data.