<한국통신학회 초저지연/고효율 무선접속기술 워크샵>

MAC Protocols for Massive IoT Connectivity

2017년 8월 18일

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Introduction

❑ Internet of things (IoT) service

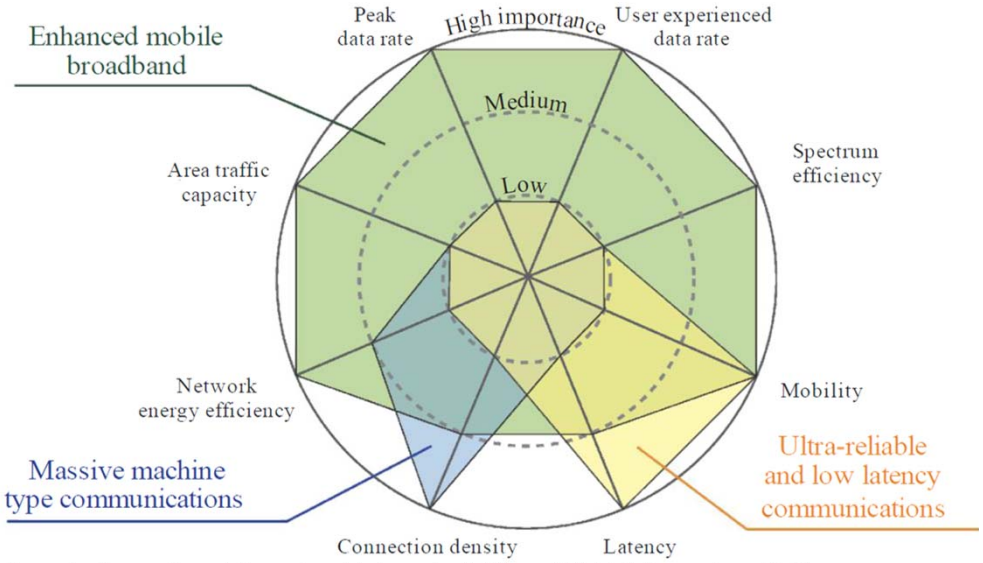
- ➢ Various objects become communication devices
  - ✓ Chance to increase mobile network provider's subscribers
  - ✓ Mobile network provider tries to cover the IoT service using mobile cellular networks [1]

- ➢ IoT service will increase the number of devices
  - ✓ Connection density ➔ one of key performance indicator (mMTC : Massive machine type communications)



• IoT Latin America





[1] 3GPP TR 45.820 v13.2.0, "Cellular System Support for Ultra-low Complexity and Low Throughput Internet of Things (CIoT)," November 2015.
[2] Recommendation ITU-R M.2083-0, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond", September 2015.

Massive Devices/Massive IoT Connectivity?

❑ ITU-T Working Party 5D [1]

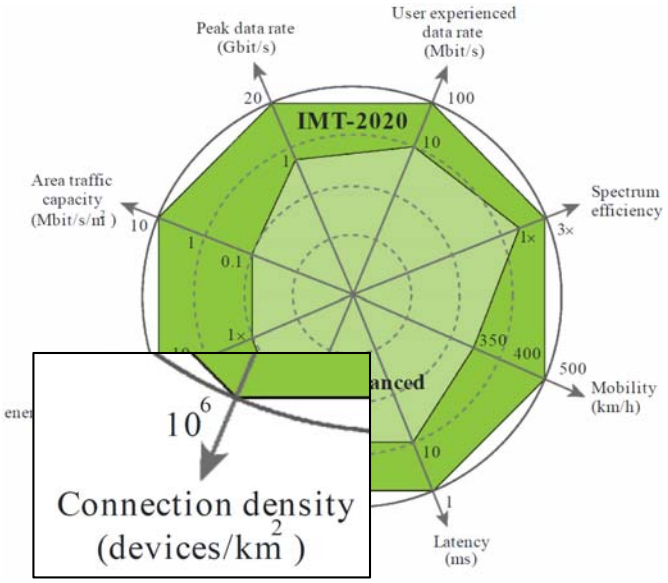
- ➢ mMTC : 1,000,000 devices per km^2

❑ 3GPP

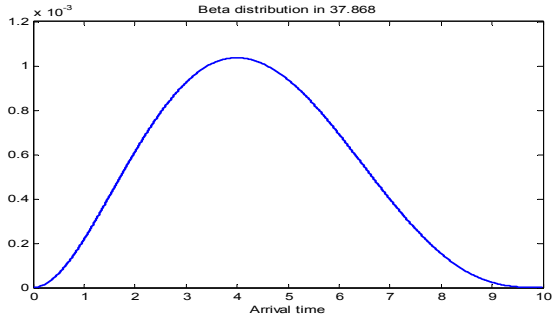
- ➢ TR 37.868 [2]
  - ✓ ~30,000 devices per sector with uniformly/Beta distributed arrival in 10 seconds
- ➢ TR 45.820 [3]
  - ✓ ~77,142 devices per sector with uniformly distributed arrival in a day

❑ 5GPPP : METIS-II

- ➢ 10~100 times more connected devices than 3GPP TR 37.868 [4], [5]
- ➢ 1,000,000 devices per km^2 [5]
- ➢ 4,000,000 devices per km^2 is available [6]



- Beta distributed arrival



- ITU-T : International Telecommunications Union Telecommunication
- 5GPPP : The 5G Infrastructure Public Private Partnership
- METIS-II : Mobile and wireless communications Enablers for the Twenty-twenty Information Society-II

[1] Recommendation ITU-R M.2083-0, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond", September 2015.
[2] 3GPP TR 37.868 V11.0.0, 3rd Generation Partnership Project;TSG RAN;Study on RAN Improvements for Machine-type Communications;(Release 11), September 2011.
[3] 3GPP TR 45.820 v13.2.0, "Cellular System Support for Ultra-low Complexity and Low Throughput Internet of Things (CIoT)," November 2015.
[4] https://5g-ppp.eu/kpis/
[5] ICT-317669-METIS/D1.1, "Scenarios, requirements and KPIs for 5G mobile and wireless system," April 2013.
[6] Michal Maternia and David Martin-Sacristan, "METIS-II Deliverable D2.3 Performance evaluation results", February 2017.

Property of IoT services

- **Long data generation interval**
  - Traffic generation intervals from 30 min. to 24 hours [1]
  - Frequent sleeping for energy saving
    - ➔ Devices can be in idle or idle-like state
    - ➔ **Data transmission from idle state requires random access**

- **Various application areas with large number of devices**
  - From periodic metering to emergency notification [2], [3]
    - ➔ Temporal traffic overload can be happen
    - ➔ **Require to alleviate traffic congestion**

- **Network requires a random access protocol which can alleviate traffic overload**

[1] 3GPP TR 45.820 v13.2.0, “Cellular System Support for Ultra-low Complexity and Low Throughput Internet of Things (CIoT),” November 2015.
[2] J. Choi, “On the Adaptive Determination of the Number of Preambles in RACH for MTC,” IEEE Communications Letters, vol. 20, no. 7, pp. 1385-1388, July 2016.
[3] S. Duan, V. Shah-Mansouri, Z. Wang, and V. W. S. Wong, “D-ACB: Adaptive Congestion Control Algorithm for Bursty M2M Traffic in LTE Networks,” IEEE Transactions on Vehicular Technology, vol. 65, no. 12, pp. 9847-9861, Dec. 2016.

MAC Protocols for Massive IoT devices

MAC Protocols for Massive IoT devices

- **MAC Protocol in 3GPP Cellular Networks**
  - Protocol stack and channel structure
  - Data transmission procedures
  - New radio

- **IEEE 802.11ah**
  - Restricted access window (RAW)

1) MAC Protocol in 3GPP Cellular Networks

❑ Conventional LTE

- ➢ Data transmission from idle state requires significant signaling
- ➢ RRC connection by random access ➔ initial attach ➔ authorization

  ➔ establishment of "context" (SRBs and DRBs) between device and P-GW/S-GW

  ➔ data transmission
- ➢ Overhead!!

- RRC : radio resource control
- SRB : signaling radio bearer
- DRB : data radio bearer

❑ Cellular IoT Evolved Packet System (CIoT EPS) optimization [1]

- ➢ Reduced signaling for small size data transmission
  - ✓ Control plane CIoT EPS optimization
    - Data can be delivered during signaling connection procedure
  - ✓ User plane CIoT EPS optimization
    - RRC suspend : Bearer establishment can be skipped by maintaining context

[1] 3GPP TS 24.301 V14.4.0 "3GPP; TSG Core Network and Terminals; Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3 (Release 14), June 2017.
[2] 3GPP TS 36.321 V14.3.0 "3GPP; TSG Radio Access Network; E-UTRA; Medium Access Control (MAC) protocol specification (Release 14), June 2017.

1) MAC Protocol in 3GPP Cellular Networks (cont.)

❑ Narrow-band IoT (NB-IoT) [2]

- ➢ Use the reduced signaling procedure in CIoT EPS optimization
- ➢ Define specialized channel structure for IoT devices with narrow band

❑ New radio

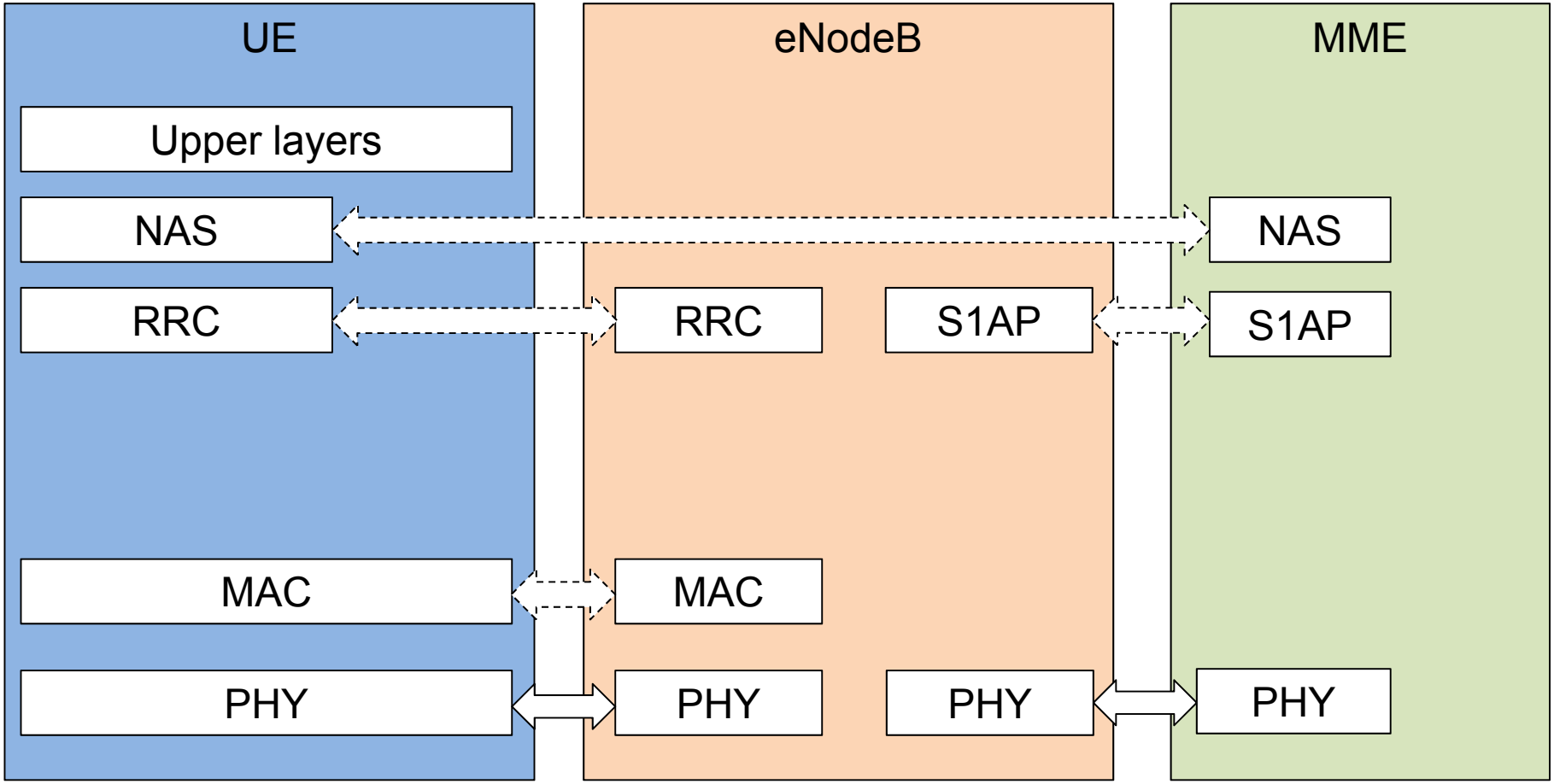
- ➢ Short slot duration / multiple slots per subframe
- ➢ New RRC state : RRC_INACTIVE

- RRC : radio resource control

[1] 3GPP TS 24.301 V14.4.0 “3GPP; TSG Core Network and Terminals; Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3 (Release 14), June 2017.
[2] 3GPP TS 36.321 V14.3.0 “3GPP; TSG Radio Access Network; E-UTRA; Medium Access Control (MAC) protocol specification (Release 14), June 2017.

Simplified protocol stack

- UE : user equipment
- MME : mobile management entity
- NAS : non-access stratum
- RRC : radio resource control
- MAC : medium access control
- PHY : physical
- S1AP : S1 application protocol



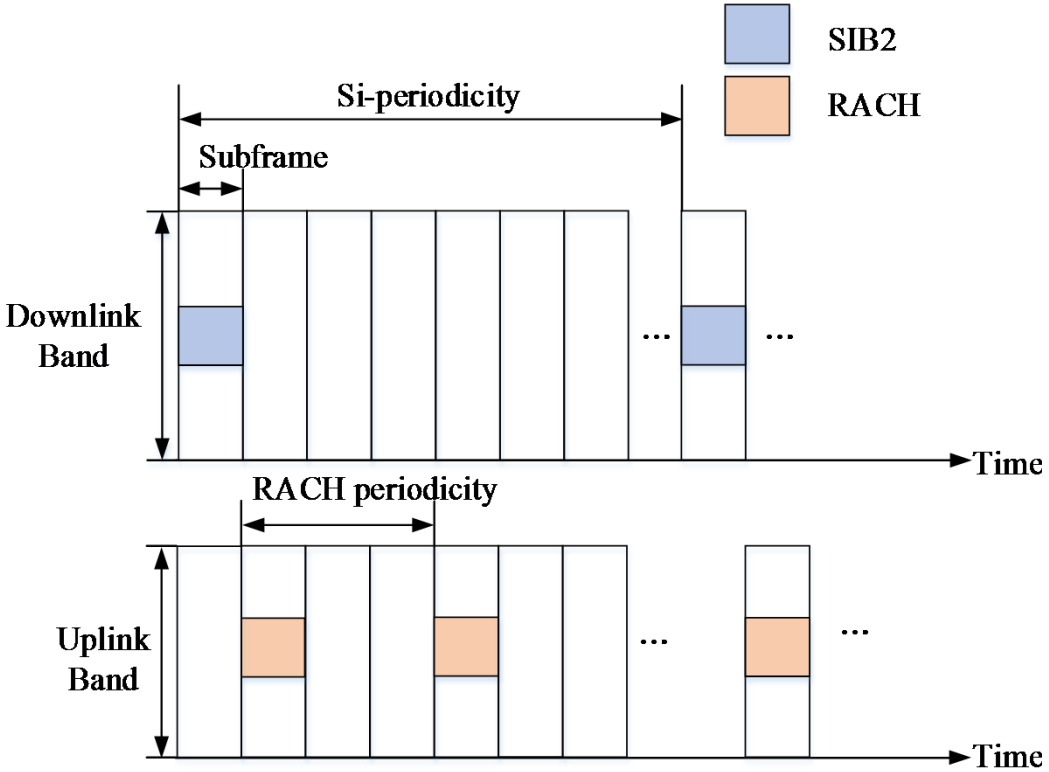
Conventional/CIoT LTE Channel Structure

❑ Downlink band

- ➢ Broadcast channels
  - ✓ Synchronization, etc...
- ➢ PDCCH, PDSCH
  - ✓ Control messages or downlink data
- ➢ System information blocks (SIBs)
  - ✓ SIB2 includes information about random access

❑ Uplink band

- ➢ PUSCH
  - ✓ Control messages or uplink data
- ➢ PRACH
  - ✓ Preambles
  - ✓ 6 RBs x 1~3 subframes per PRACH



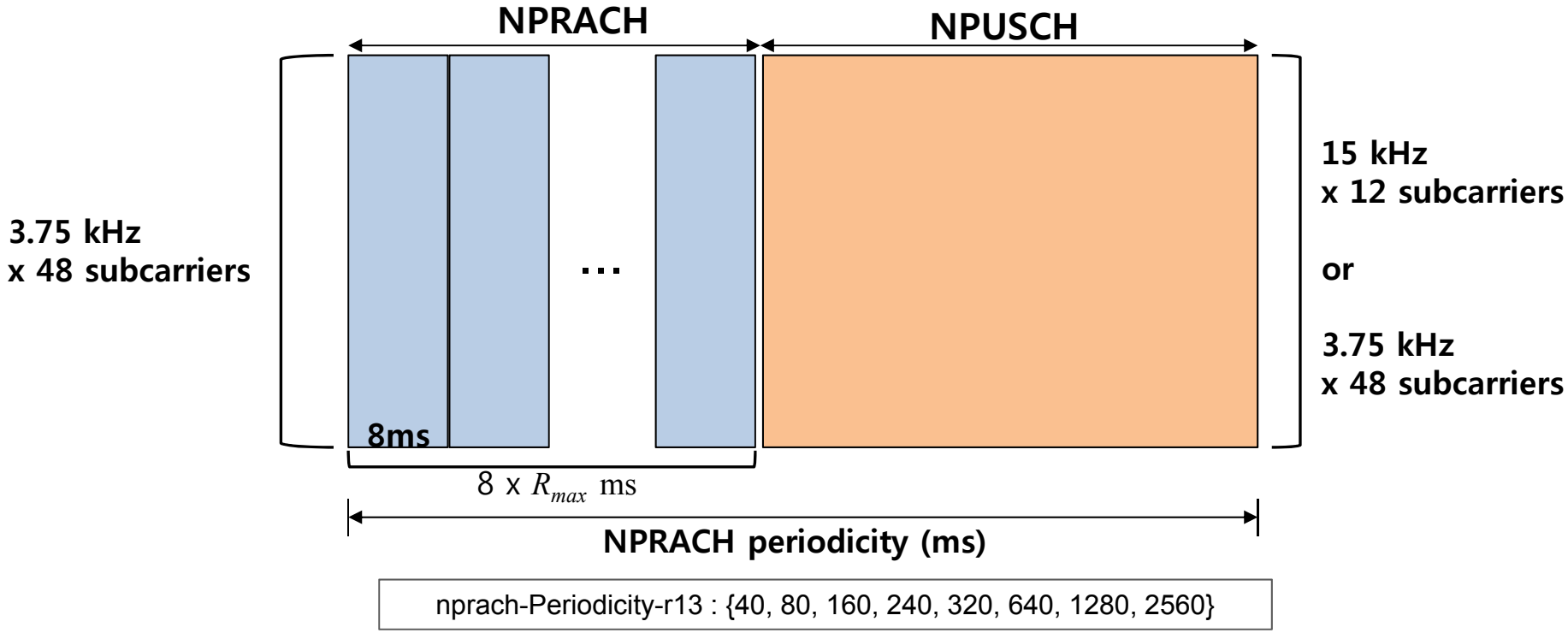
- PDCCH : Physical downlink control channel
- PDSCH : Physical downlink shared channel
- PUSCH : Physical uplink shared channel
- (P)RACH : (Physical) random access channel
- SIB2 : system information block-2

[1] 3GPP TS 36.211 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Physical channels and modulation (Release 14) June 2017.
[2] 3GPP TS 36.331 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Radio Resource Control (RRC); Protocol specification (Release 14)", June 2017.

NB-IoT UL Channel Structure

❑ UL Channel Structure

- ➢ Contains NPRACH and NPUSCH (N : Narrowband-)
- ➢ NPRACH : Preambles
  - ✓ Single preamble occupies 8 ms and can be repeated up to R_{max} times for coverage extension
- ➢ NPUSCH : Control messages or data

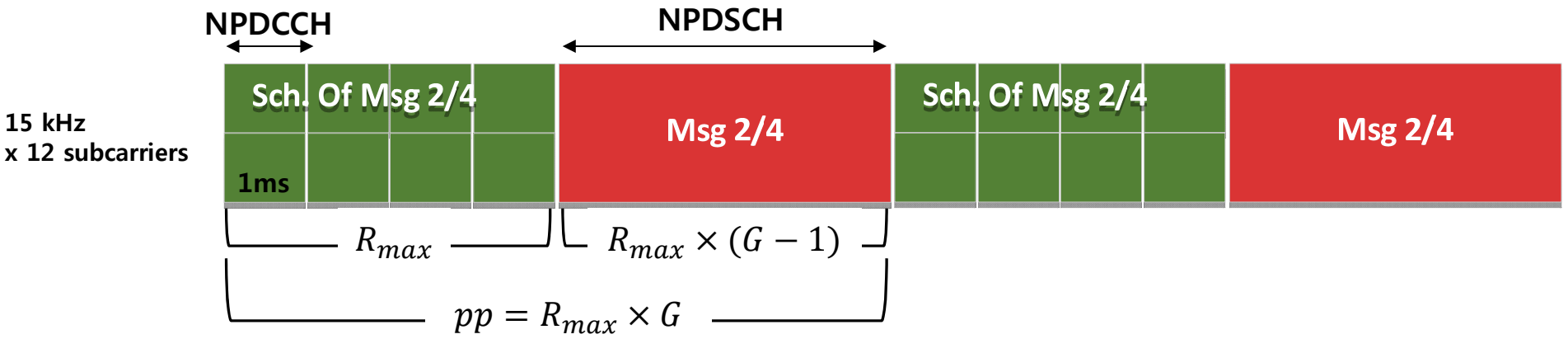


nprach-Periodicity-r13 : {40, 80, 160, 240, 320, 640, 1280, 2560}

[1] 3GPP TS 36.211 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Physical channels and modulation (Release 14) June 2017.
[2] 3GPP TS 36.213 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Physical layer procedures (Release 14)", June 2017.
[3] 3GPP TS 36.331 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Radio Resource Control (RRC); Protocol specification (Release 14)", June 2017.

NB-IoT DL Channel Structure

❑ DL Channel Structure



- R_{max} : Maximum number of repetitions
- G (npdcch-startSF-CSS-RA-r13) : Parameter for the amount of NPDSCH

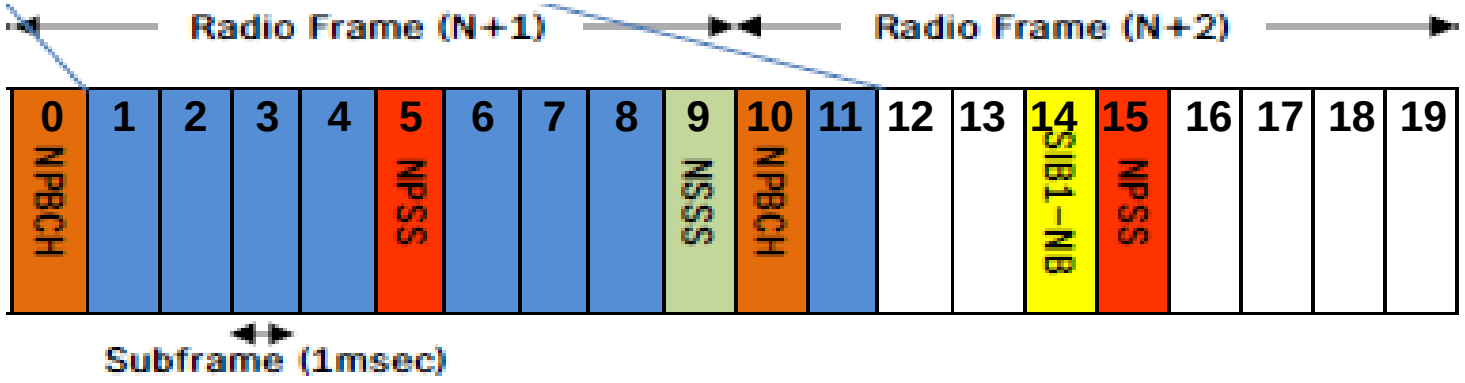
(R_{max}) npdcch-NumRepetitions-r13 : {1, 2, 4, 8, ..., 2048}
(G) npdcch-startSF-CSS-RA-r13 : {1.5, 2, 4, 8, 16, 32, 48, 64}

[1] 3GPP TS 36.211 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Physical channels and modulation (Release 14) June 2017.
[2] 3GPP TS 36.213 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Physical layer procedures (Release 14)", June 2017.
[3] 3GPP TS 36.331 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Radio Resource Control (RRC); Protocol specification (Release 14)", June 2017.

NB-IoT DL Channel Structure

❑ Control channels

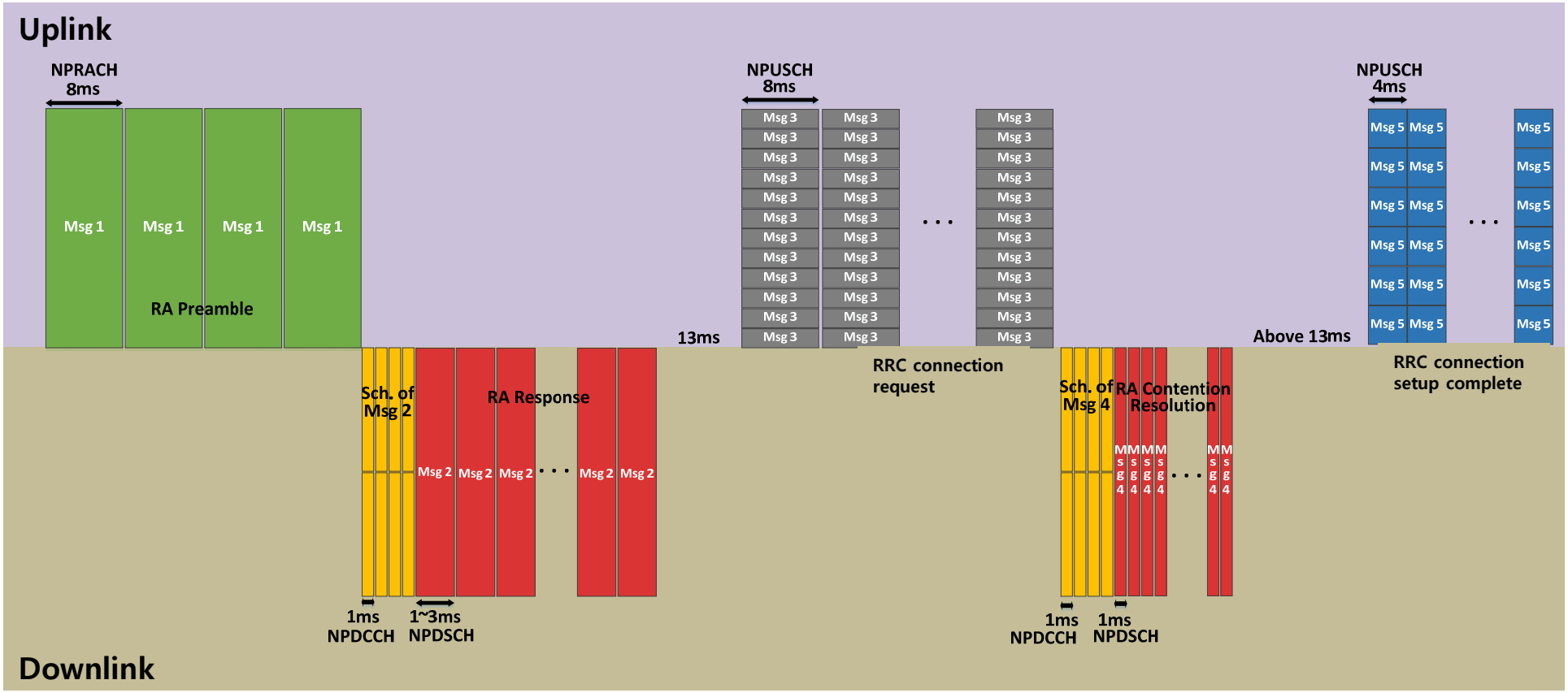
- ➢ 0,5,9,10,15 subframe in every 20 subframes ➔ control channel
  - ✓ #0, #10 : NPBCH(Narrowband Physical Broadcast Channel)
  - ✓ #5, #15 : NPSS(Narrowband Primary Synchronization Signal)
  - ✓ #9 : NSSS(Narrowband Secondary Synchronization Signal)
- ➢ SIBs are transmitted with their periodicity



[1] 3GPP TS 36.213 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Physical layer procedures (Release 14)", June 2017.

Message Exchanges with NB-IoT Channel Structure

❑ NB-IoT 전체 채널 구조



RACH and SIB2

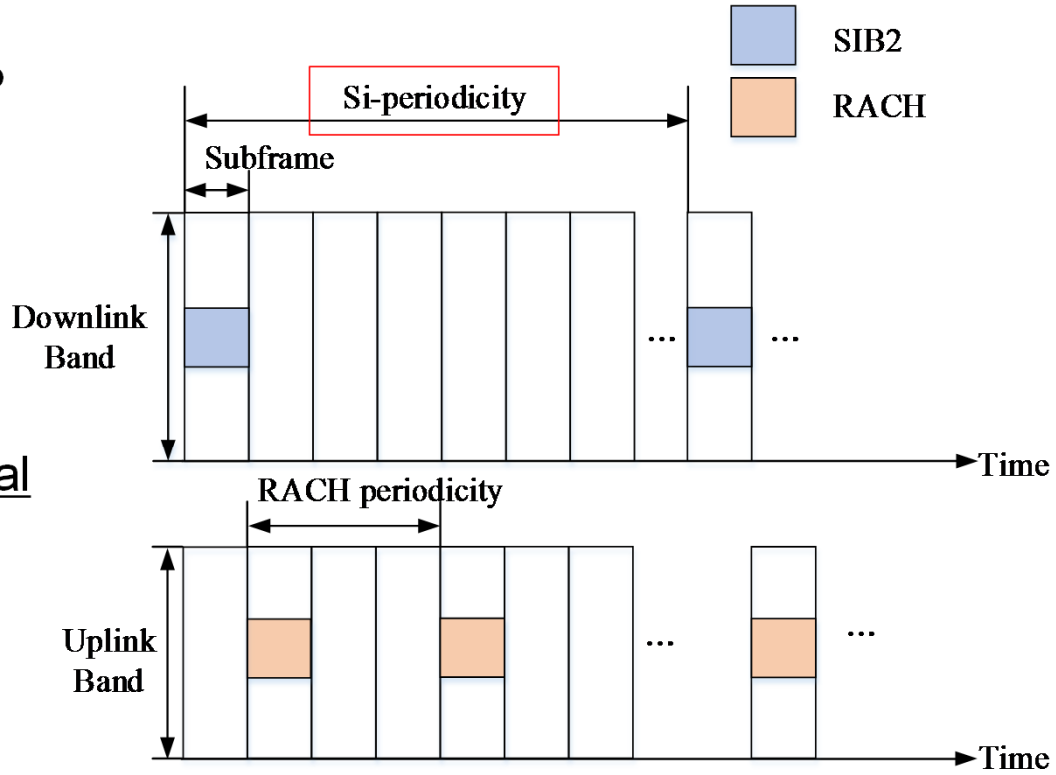
❑ SIB2 interval [1]

- ➢ Defined by “si-periodicity” in 3GPP TS 36.331
- ➢ Conventional LTE
  - ✓ 80 ~ 5120 subframes
- ➢ NB-IoT
  - ✓ 640 ~ 40960 subframes
- ➢ Can be longer than PRACH interval

❑ PRACH interval [2]

- ➢ Conventional LTE / CIoT
  - ✓ 1 ~ 20 subframes
- ➢ NB-IoT
  - ✓ 40 ~ 2560 subframes

- Example : Conventional LTE / CIoT



[1] 3GPP TS 36.331 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Radio Resource Control (RRC); Protocol specification (Release 14)", June 2017.
[2] 3GPP TS 36.211 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Physical channels and modulation (Release 14) June 2017.

From Initialization to Data Transmission for IoT devices

❑ Initial procedures

- ➢ Initial attach
- ➢ Authentication
- ➢ NAS security setup for encryption, integrity

❑ Entering idle mode

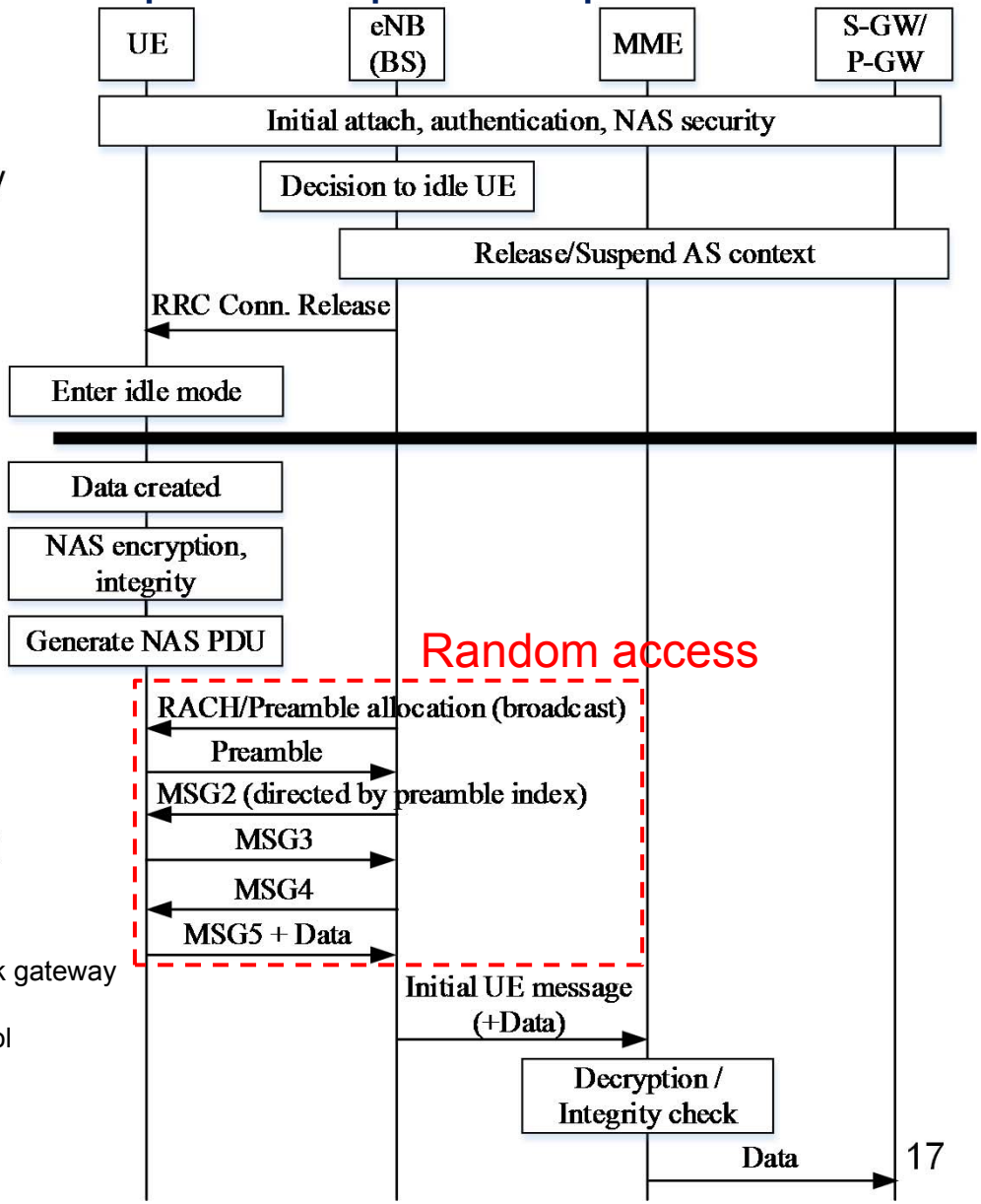
- ➢ Decided by eNodeB
- ➢ NAS security context can be maintained
- ➢ RRC connection can be maintained
  - ✓ when rrc-Suspend is set

❑ Data transmission from idle state

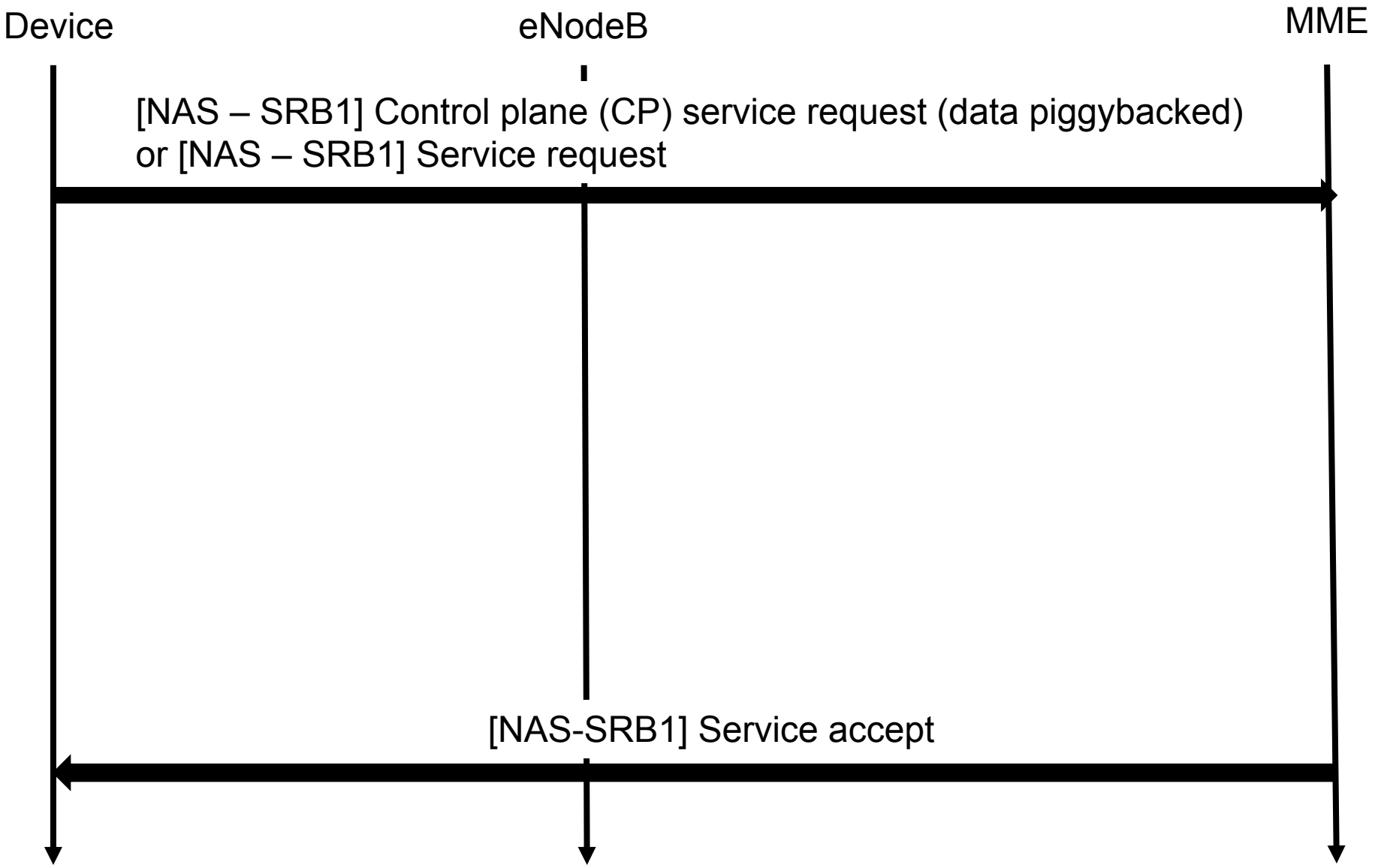
- ➢ Based on the random access
- ➢ If initial attach is skipped, then authentication and NAS security is done in this step

- UE : user equipment
- eNB : enhanced node B
- BS : base station
- MME : mobile management entity
- S-GW : serving gateway
- P-GW : packet data network gateway
- NAS : non-access stratum
- RRC : radio resource control
- MSG : message

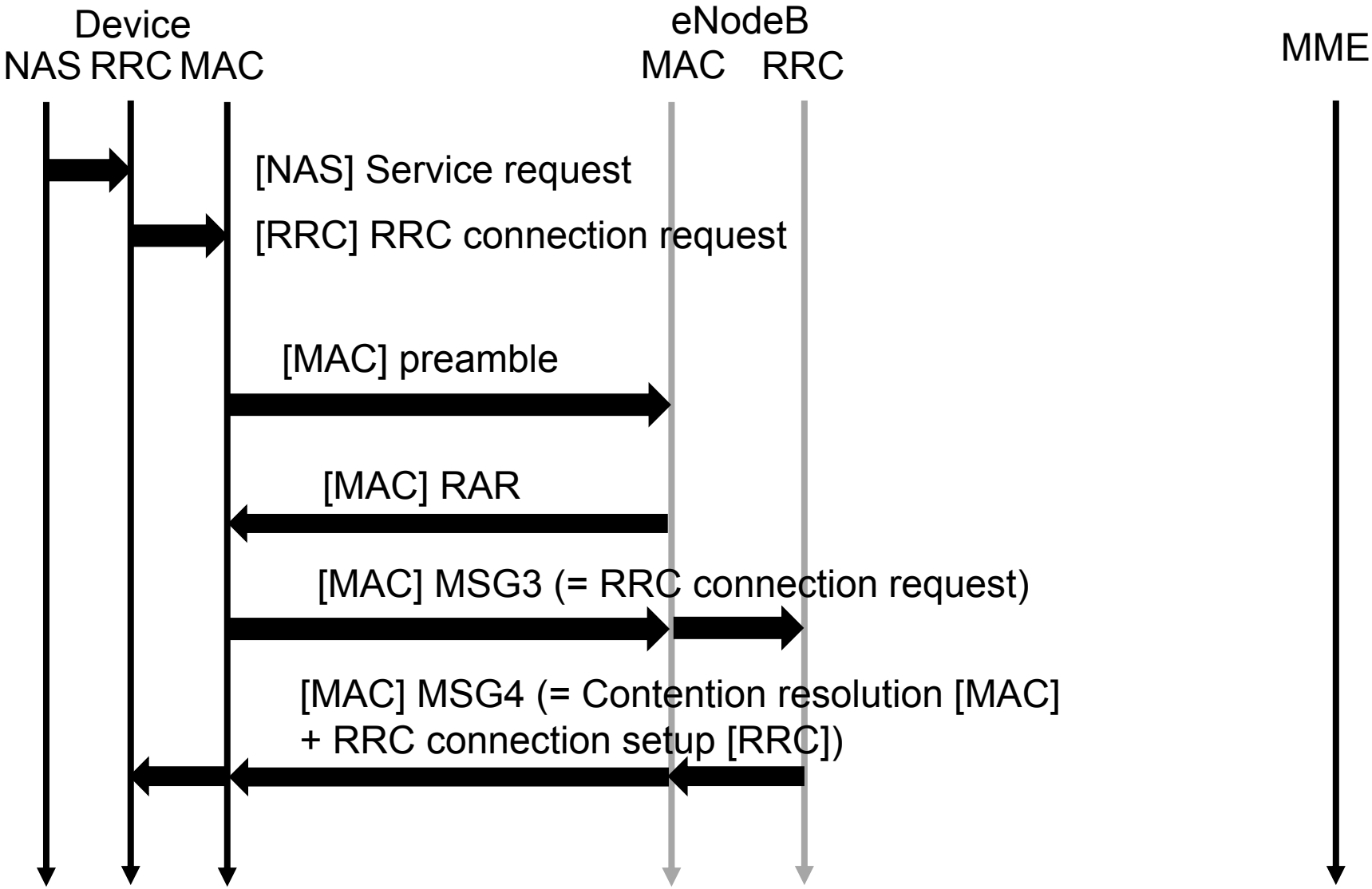
● **Example : Control plane EPS optimization**



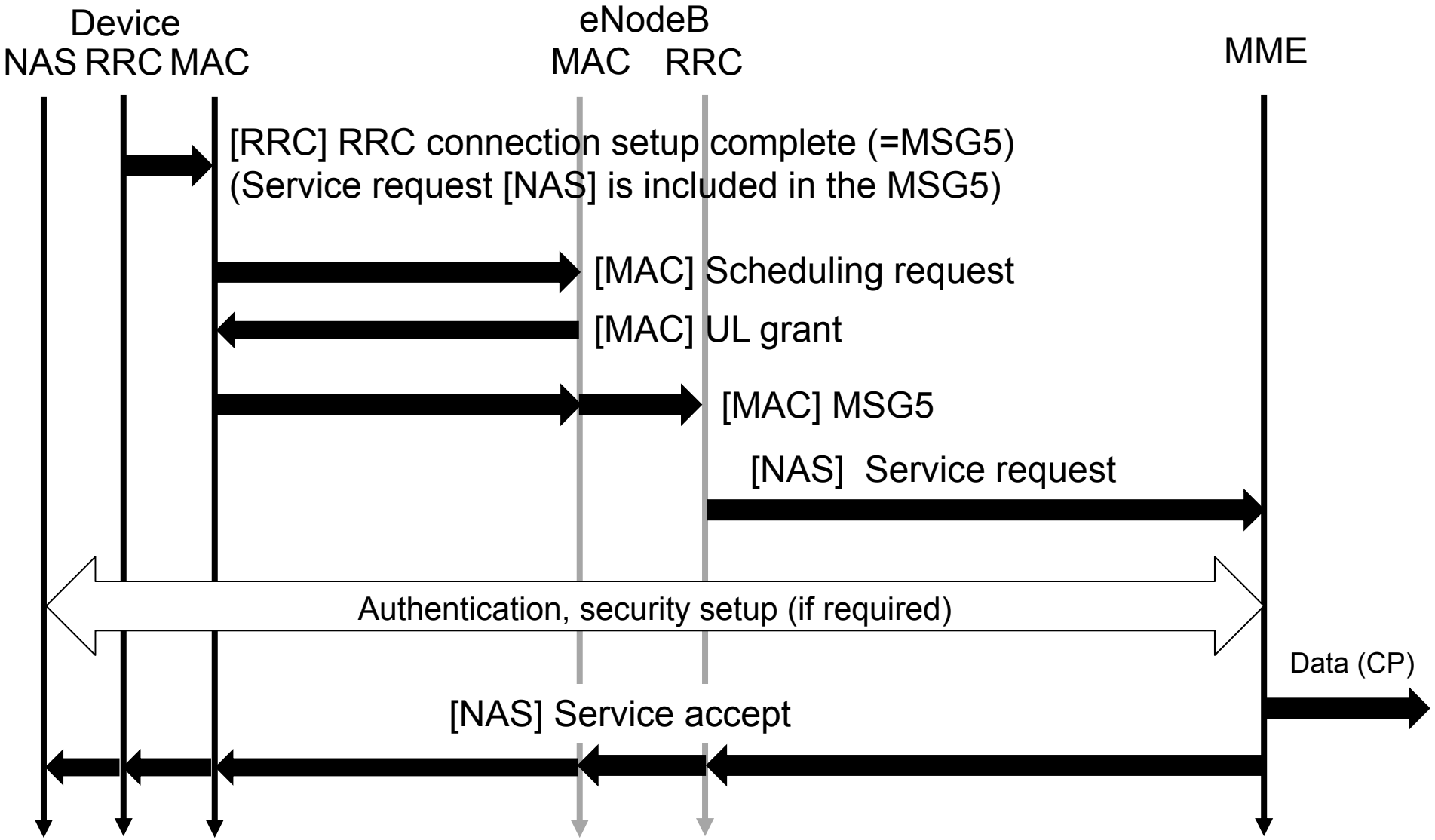
Data Transmission Procedure (detailed : objective)



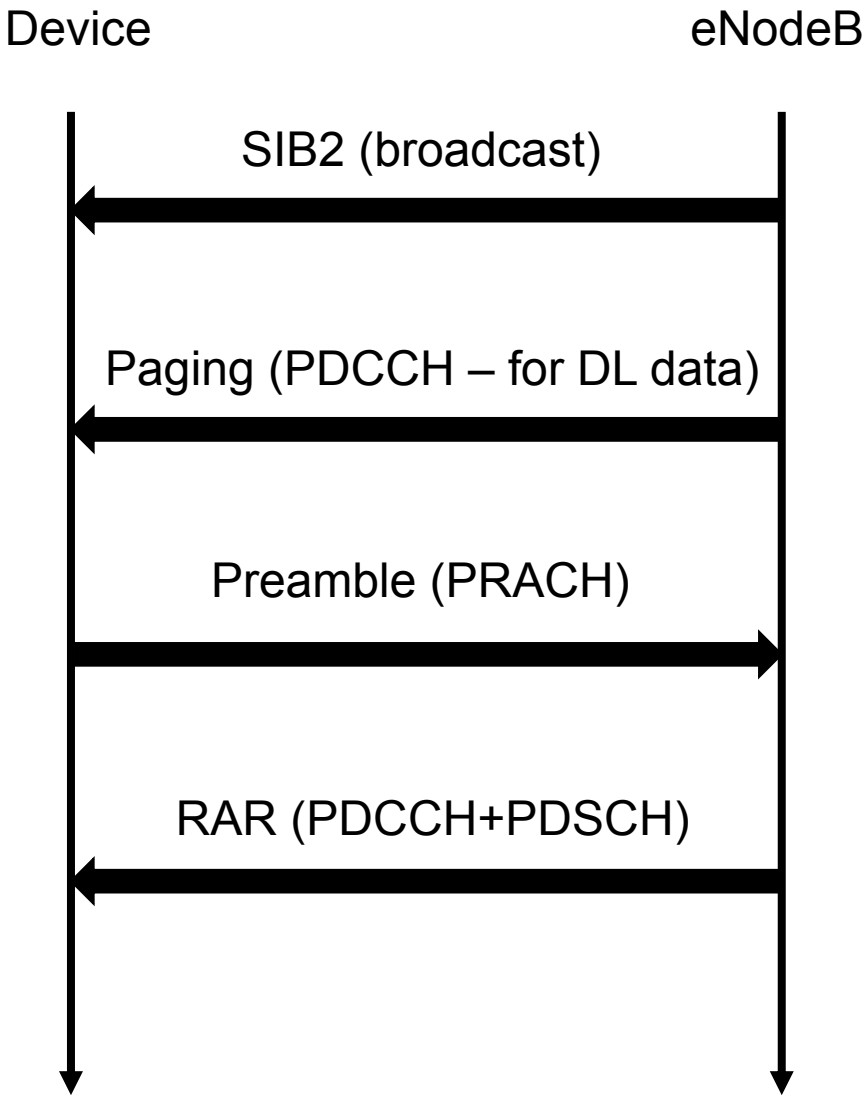
Data Transmission Procedure (detailed : actual(1))



Data Transmission Procedure (detailed : actual(2))



Random Access

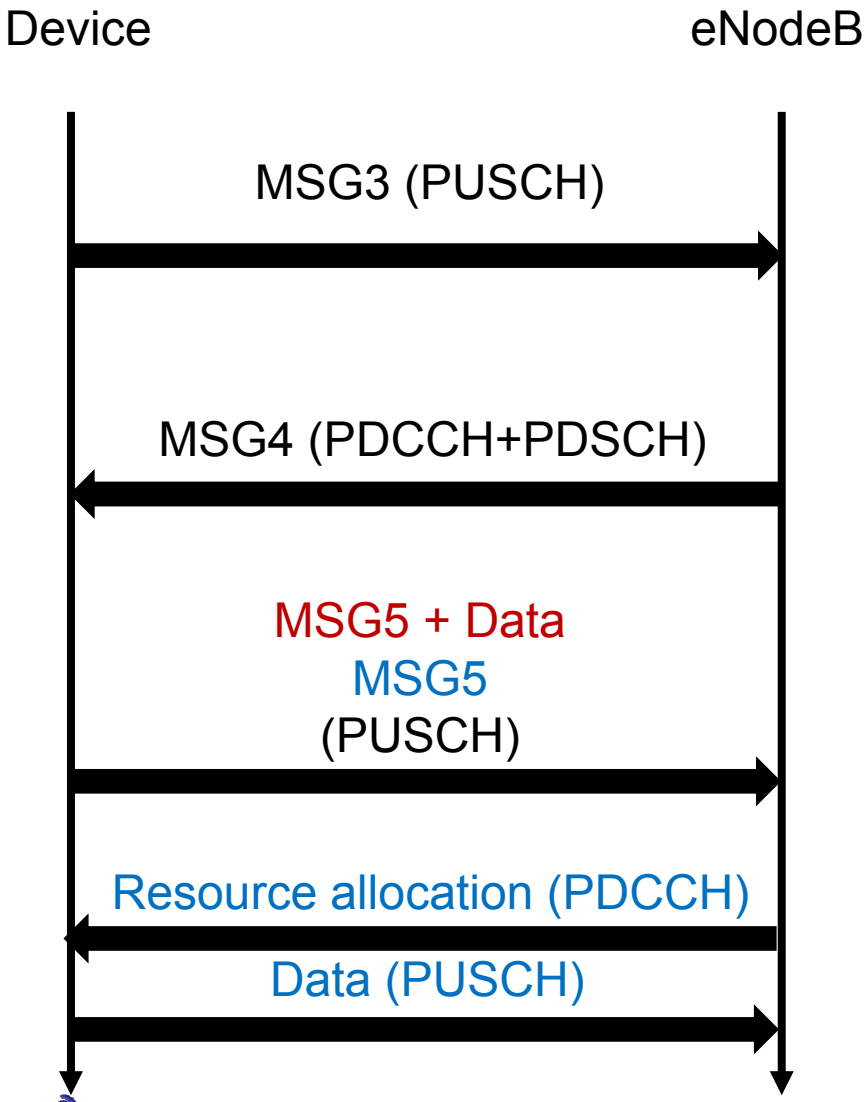


- **System Information Block 2 (SIB2)**
  - Time-frequency position of PRACH
  - Information for random access resources
  - Information for congestion control
- **Preamble**
  - Orthogonal signal/codes which can be detected even multiple devices are transmitted (Zadoff-Chu sequence / signal using single subcarrier)
- **Random access response (RAR)**
  - RA-RNTI : time-frequency position index of PRACH for a received preamble
  - TC-RNTI : temporary ID
  - UL-grant : resource to transmit MSG3
  - Timing alignment : for synchronization
    - RNTI : random network temporary identifier
    - RA- : random access –
    - TC- : temporary cell -

[1] 3GPP TS 24.301 V14.4.0 “3GPP; TSG Core Network and Terminals; Non-Access-Stratum (NAS) protocol for Evolved Packet System (EPS); Stage 3 (Release 14), June 2017.
[2] 3GPP TS 36.321 V14.3.0 “3GPP; TSG Radio Access Network; E-UTRA; Medium Access Control (MAC) protocol specification (Release 14), June 2017.
[3] 3GPP TS 36.331 V14.3.0, "3GPP; TSG Radio Access Network; E-UTRA; Radio Resource Control (RRC); Protocol specification (Release 14)", June 2017.

Random Access (cont.)

- EPS : Evolved Packet System
- RRC : Radio Resource Control



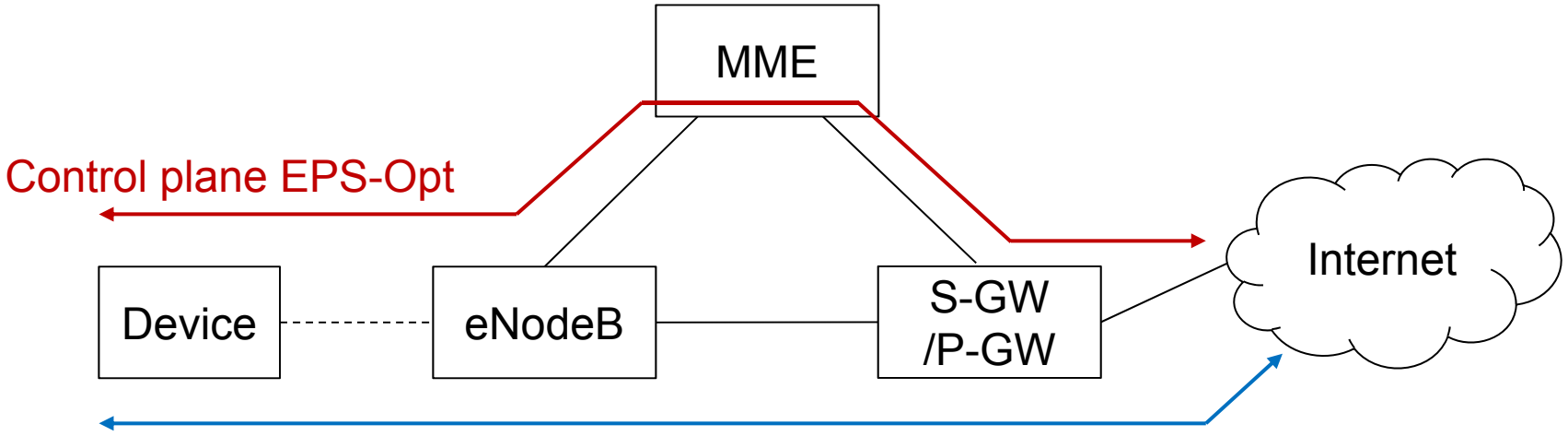
- **MSG3 (e.g. RRC connection request [RRC])**
  - TC-RNTI from RAR
  - If two or more devices transmitted same preamble, collision occurs in this step
    - ➔ backoff, return to preamble transmission
- **MSG4 (e.g. Contention resolution [MAC] + RRC connection setup [RRC])**
  - If collision is not happened
- **MSG5 (e.g. RRC connection setup complete [RRC] + service request [NAS])**
  - ① For control plane EPS optimization, data can be included in service request
  - ② For user plane EPS optimization, data is transmitted after additional resource allocation

Delivery Path

❑ Path by EPS optimization

- ➢ Control plane : data is transmitted through MME
  - ✓ Data is transmitted with non-access stratum (NAS) signaling connection procedure by random access
  - ✓ Additional control plane overhead (data forwarding in MME)

- ➢ User plane : data is transmitted by user plane connection
  - ✓ Require to re-establish / resume access stratum (AS) access stratum context by random access
  - ✓ Reduced control plane overhead



- MME : Mobile Management Entity
- S-GW : Serving gateway
- P-GW : Packet data network gateway

New Radio

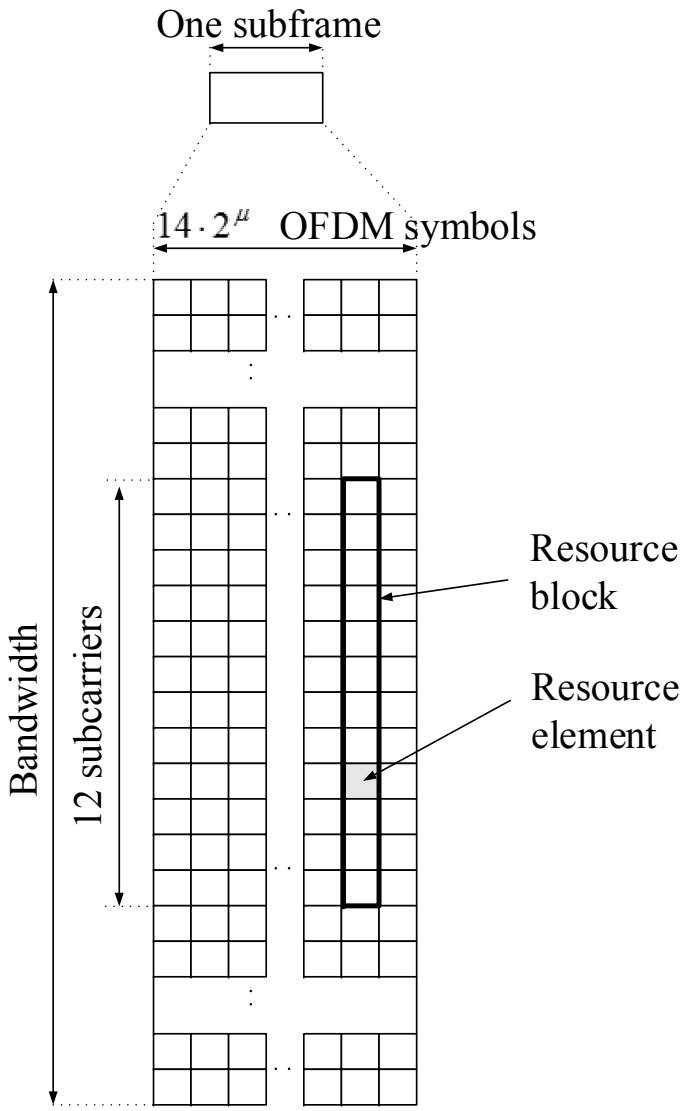
- **Related technical specification numbers**
  - 3GPP TS 38.xxx / 3GPP TR 38.xxx
- **Data transmission procedure**
  - Not fully decided
  - Non-orthogonal multiple access is studied [1] but not included yet
- **Frame structure**
  - More dense time usage
- **RRC state**
  - RRC_INACTIVE state is introduced

[1] 3GPP TR 38.802 v14.1.0, “3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on New Radio Access Technology Physical Layer Aspects (Release 14)”, June 2017.

New Radio

❑ Frame structure

- Frame (10 ms) and subframe length (1 ms) are equal to conventional LTE
- Slots
  - ✓ 1~32 slots per subframe
  - ✓ (Conventional LTE : 2 slots)
  - ✓ 7 or 12 or 14 symbols per slot
- Subcarrier spacing
  - ✓ 15 x 2^n kHz (n=0,1,...)
  - ✓ (Conventional LTE : 15 kHz)
- Resource block (= unit for scheduling)
  - ✓ 12 subcarriers x 1 symbol
  - ✓ (Conventional LTE : 12 subcarriers x 1 slot)

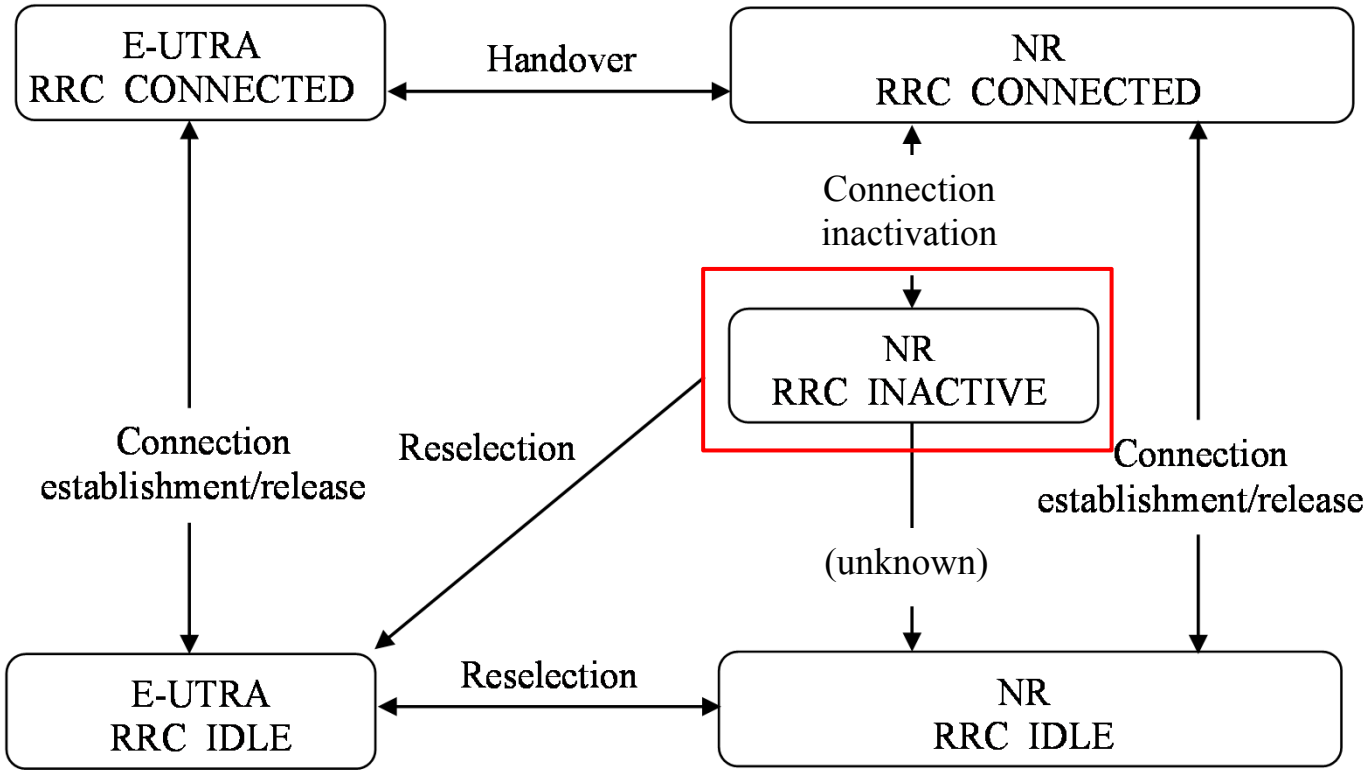


- 3GPP TS 38.211 V0.1.0, "3GPP; TSG Radio Access Network; NR; Physical channels and modulation (Release 15), June 2017.

New Radio

❑ New RRC state : RRC_INACTIVE

- ➢ UE stores access stratum (AS) context in this state
- ➢ Reduce/remove ambiguity
  - ✓ Conventional LTE : RRC_IDLE state with rrc-Suspend ➔ ambiguous



- 3GPP TS 38.331 V0.0.4, "3GPP; TSG Radio Access Network; NR; Radio Resource Control (RRC); Protocol specification (Release 15), June 2017.

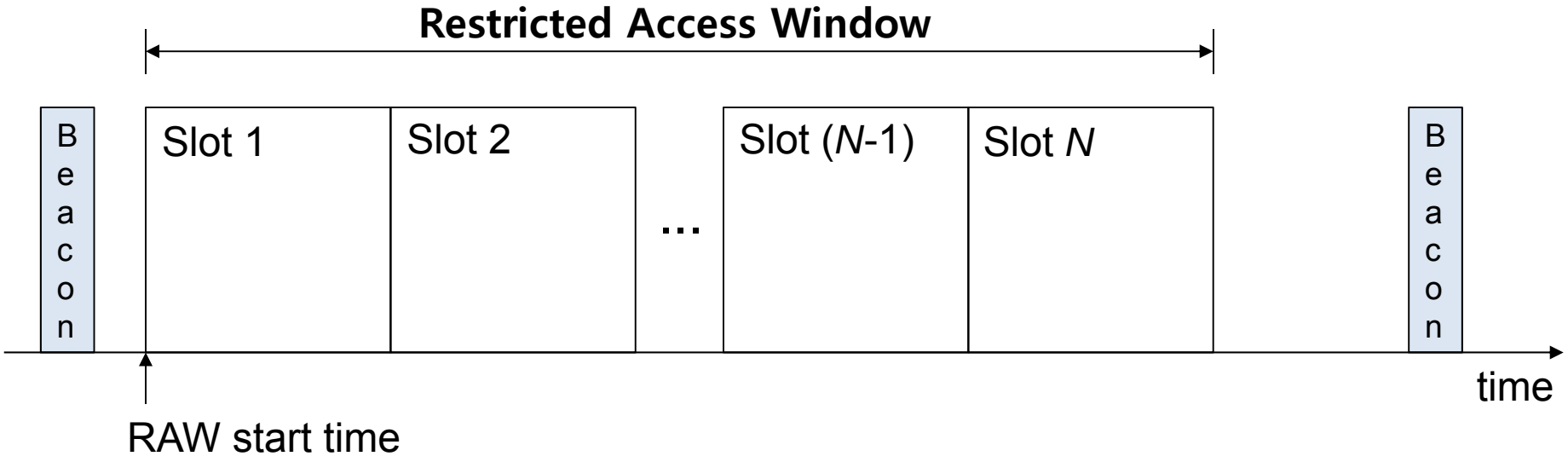
2) IEEE 802.11ah

- **Operating on sub 1 GHz license exempt bands**
  - Extended coverage

- **Target for power saving and congestion control**
  - Target wake time : reduce energy consumption
  - Bi-directional TXOP : reduce the number of contention-based channel accesses
  - **Restricted access window (RAW)** : restricting channel access only to stations belonging to a given group at given time period
    - ✓ Extend the number of devices per AP : ~4,000 devices per AP [2]

[1] IEEE Std 802.11ah-2016, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Sub 1 GHz License Exempt Operation," December 2016.
[2] Chul Wan Park, Duckdong Hwang, and Tae-Jin Lee, "Enhancement of IEEE 802.11ah MAC for M2M Communications," IEEE Communications Letters, vol. 18, no. 7, July 2014.

Restricted Access Window



- **RAW slot assignment in IEEE 802.11ah**
  - $S_i = (A_i + N_{offset}) \bmod N$
  - S_i : Assigned slot for device i
  - A_i : Association ID of device i
  - N_{offset} : Offset
  - N : Number of slots in RAW

➔ equalize the number of devices per slot

- IEEE Std 802.11ah-2016, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Sub 1 GHz License Exempt Operation," December 2016.

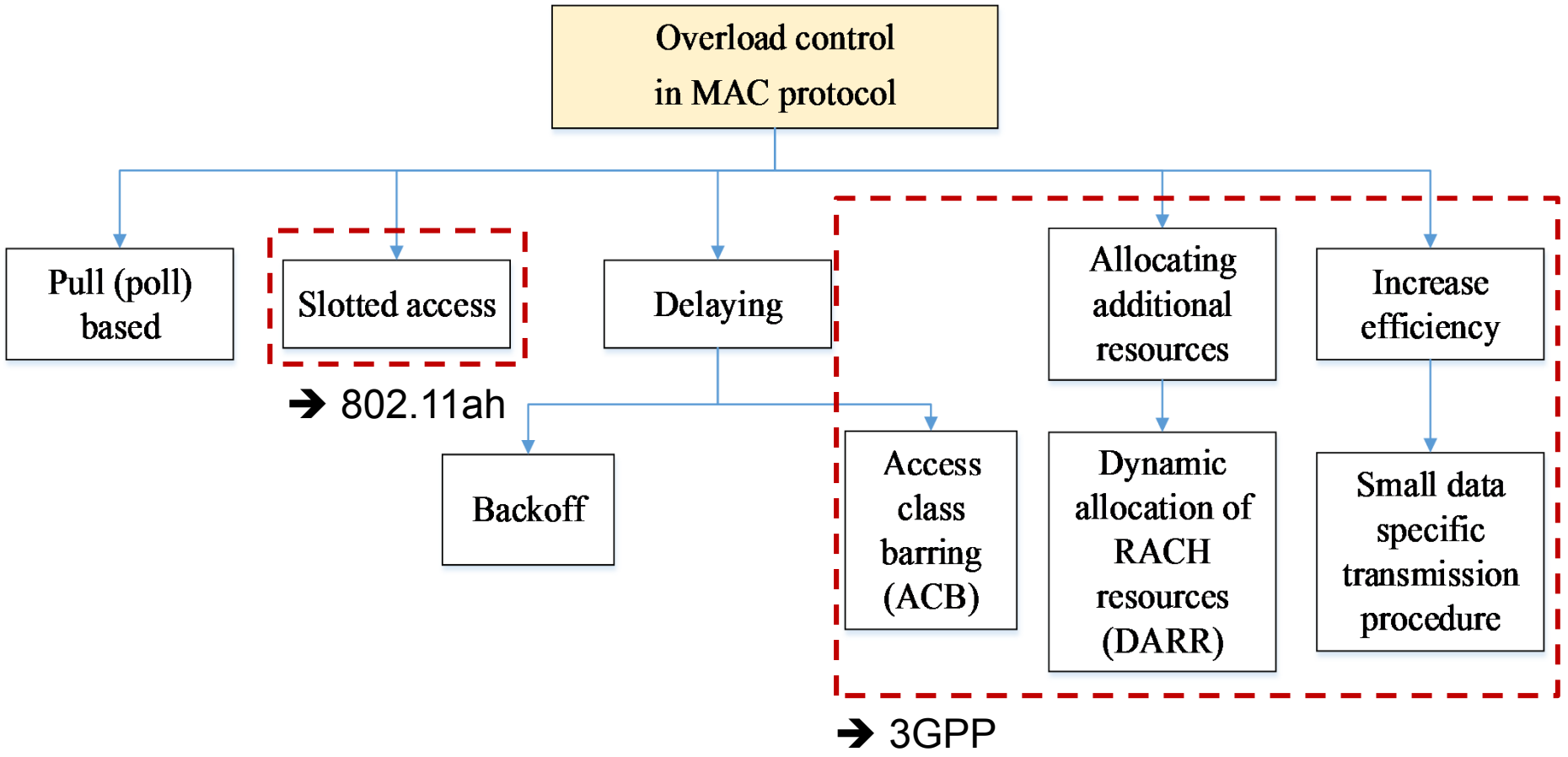
Operations of 802.11ah MAC Protocol



[1] Chul Wan Park, Duckdong Hwang, and Tae-Jin Lee, "Enhancement of IEEE 802.11ah MAC for M2M Communications," IEEE Communications Letters, vol. 18, no. 7, July 2014.

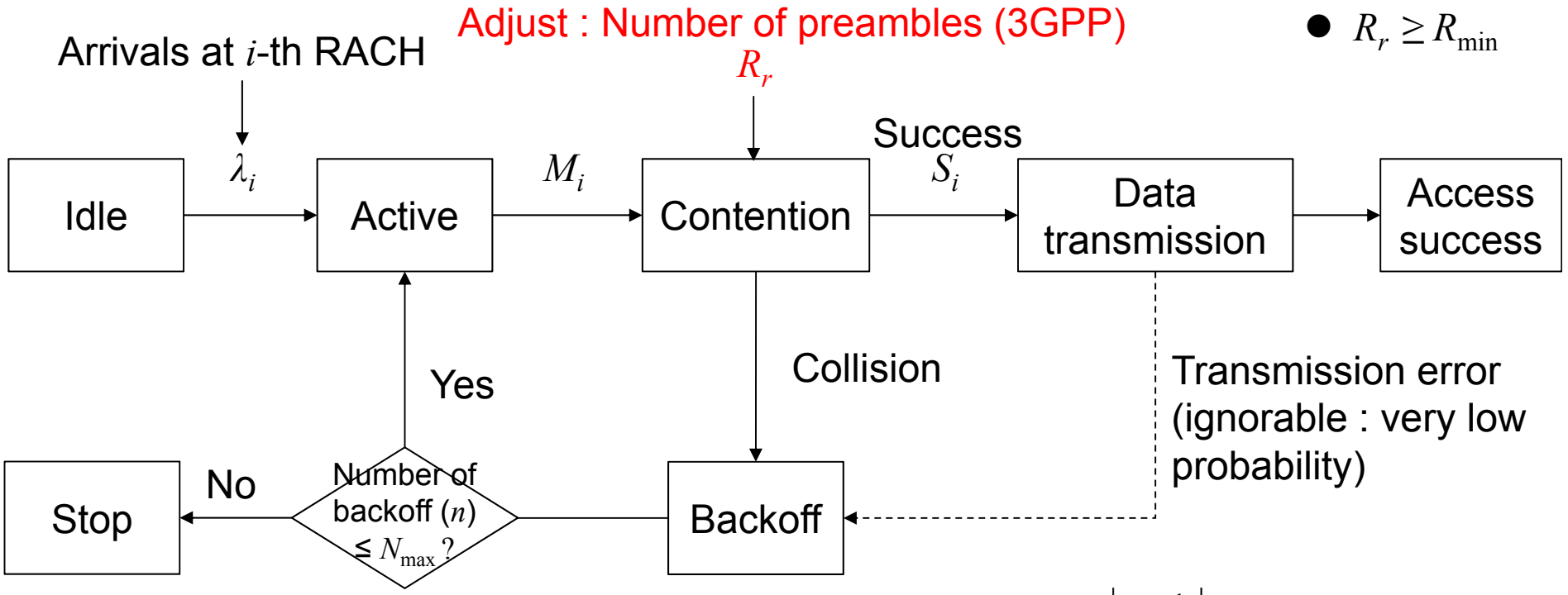
Overload Control for Massive IoT Devices

Overload control



[1] 3GPP TR 45.820 v13.2.0, “Cellular System Support for Ultra-low Complexity and Low Throughput Internet of Things (CIoT),” November 2015.
[2] 3GPP TR 37.868 v11.0.0, “RAN Improvements for Machine-type Communications,” October 2011.

1) Dynamic allocation of RACH resources



$$r = \left\lfloor \frac{i-1}{K} \right\rfloor + 1$$

when SIB2 is broadcasted for every K RACHs

❑ Metrics

- Throughput = S_i / R_r
- Access success ratio = $\sum_i S_i \Big/ \sum_i \lambda_i$

[1] 3GPP TR 37.868 v11.0.0, “RAN Improvements for Machine-type Communications,” October 2011.
[2] J. Choi, “On the Adaptive Determination of the Number of Preambles in RACH for MTC,” IEEE Communications Letters, vol. 20, no. 7, pp. 1385-1388, July 2016.
[3] 3GPP TR 36.321 v12.6.0, “3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification (Release 14),” March 2017.

Dynamic allocation of RACH resources : LTE

Expectation of the number of successful devices

- when M_i devices contending with R_r preambles

$$\mathbf{E}[S_i \mid M_i, R_r] = M_i P_s = M_i \left(1 - \frac{1}{R_r}\right)^{M_i - 1}$$

Throughput

$$\mathbf{E}[T_i \mid M_i, R_r] = \frac{\mathbf{E}[S_i \mid M_i, R_r]}{R_r} = \frac{M_i}{R_r}\left(1 - \frac{1}{R_r}\right)^{M_i - 1}$$

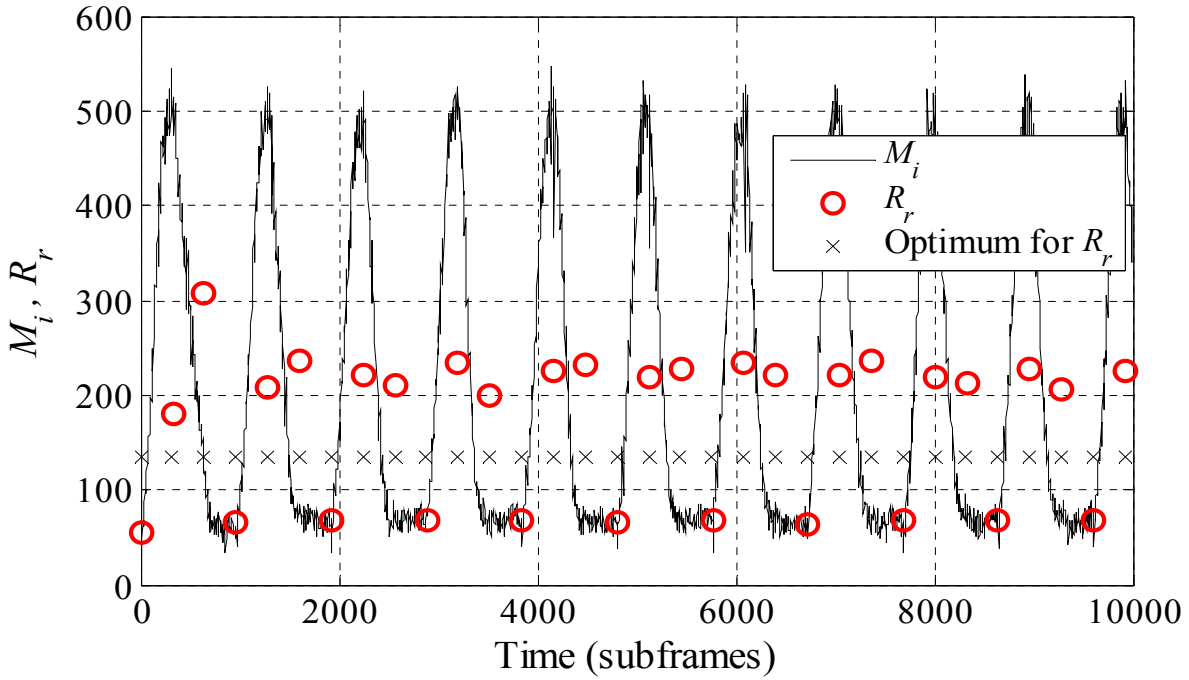
Optimal throughput

$$\frac{\partial \mathbf{E}[T_i \mid M_i, R_r]}{\partial M_i} = 0 \quad \Rightarrow \quad \mathbf{E}[T_i \mid M_i, R_r] \approx \mathrm{e}^{-1} \quad \text{when} \quad (M_i = R_r)$$

Previous studies

- $R_r \leftarrow M_{i-1}$ with the assumption of K=1

Throughput degradation problem from update interval



$$r = \left\lfloor \frac{i-1}{K} \right\rfloor + 1$$

- Environment : 3GPP TR 37.868
- Number of devices : 100,000
- Arrival : uniform distribution
- RACH interval = 5 subframes
- Update interval = 320 subframes

❑ Existence of update interval (=Si-periodicity) in 3GPP

- ➢ BS **cannot control the number of preambles** (thus, number of active devices) during multiple RACHs
- ➢ However the **number of active devices continuously changed** during multiple RACHs

➔ **"fluctuation"** happens ➔ Difference between M_i and R_r

➔ Throughput degrades since throughput is maximized when $M_i = R_r$

- Sung-Hyung Lee, So-Yi Jung, Jae-Hyun Kim, "Dynamic Resource Allocation of the Random Access for MTC Devices," ETRI Journal, vol.39, no.4, Aug. 2017.

Optimal number of preambles

- **eNodeB can set the number of preambles as that when optimal condition continues**

- **If the optimal condition continues, the number of preambles becomes**

$$B^*(i) = \sum_{n=1}^{N_{\max}} \overline{\lambda} T_{RAREP} (1 - e^{-1})^{n-1}$$

- n : number of backoff experienced by a device
- $\overline{\lambda}$: average arrival rate per time slot
- T_{RAREP} : RACH periodicity with n

- **For a sufficiently large N_{th},**

$$B^*(i) = B_N^*(i) + B_D^*(i) \approx B_N^*(i)$$ ➔ unknown

$$B_N^*(i) = \sum_{n=1}^{N_{th}} \overline{\lambda} T_{RAREP} (1 - e^{-1})^{n-1}$$

$$B_D^*(i) = \sum_{n=N_{th}+1}^{N_{\max}} \overline{\lambda} T_{RAREP} (1 - e^{-1})^{n-1}$$

- N_{th} : a threshold for n

How to find R_r which is close to the optimum for R_r

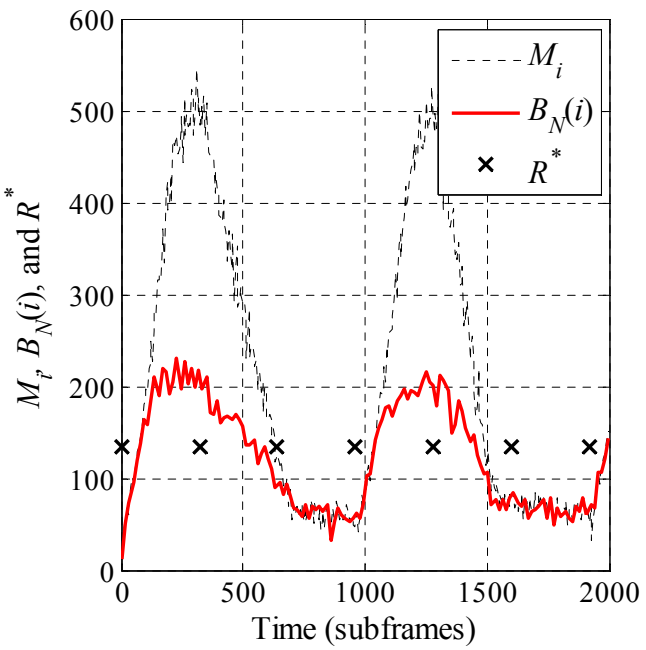
- **The actual number of devices with sufficiently small *n* can be similar to that in optimal case**
  - i.e.

$$B_N^*(i) = \sum_{n=1}^{N_{th}} \bar{\lambda} T_{RAREP} (1 - e^{-1})^{n-1} \approx B_N(i) = \sum_{n=1}^{N_{th}} M_i[n]$$

$$B_N^*(i) + B_D^*(i) \approx B_N^*(i) \approx B_N(i)$$

required obtainable

- $M_i[n]$: actual number of contending devices with n



- **To acquire $B_N(i)$ in eNodeB**
  - Preambles can be divided into two groups
    - ✓ One is for devices with $n \le N_{th}$
    - ✓ The other is for devices with $n > N_{th}$
  - The BS can estimate $B_N(i)$ by estimating the number of devices contending in each group

- Sung-Hyung Lee, So-Yi Jung, Jae-Hyun Kim, "Dynamic Resource Allocation of the Random Access for MTC Devices," ETRI Journal, vol.39, no.4, Aug. 2017.

Proposed preamble partition based DARR Protocol

- **Preamble partition protocol (device)**
  - Obtain the announced number of preambles and N_{th}
  - If $n \leq N_{th}$ then the device selects a preamble in first group
  - Otherwise, the device selects a preamble in second group
  - Other procedures are equal as conventional procedures

Algorithm 3.1. Algorithm for the devices with the preamble partition protocol

1: On receiving SIB2 from BS:
2: obtain and update $\mathbf{C_1}$, $\mathbf{C_2}$ and N_{th}.
3: On receiving the request for RA procedure from upper layer:
...
8: if $n \leq N_{th}$
9: randomly selects a preamble in $\mathbf{C_1}$
10: else
11: randomly selects a preamble in $\mathbf{C_2}$
12: end
...

• Sung-Hyung Lee, So-Yi Jung, Jae-Hyun Kim, “Dynamic Resource Allocation of the Random Access for MTC Devices,” ETRI Journal, vol.39, no.4, Aug. 2017.

Proposed preamble partition based DARR Protocol

- **Preamble partition protocol (base station)**
  - Estimate the number of devices contending in each group
  - Based on the estimated number, assign the number of preambles in each group
  - Announce two number of preambles and N_{th}

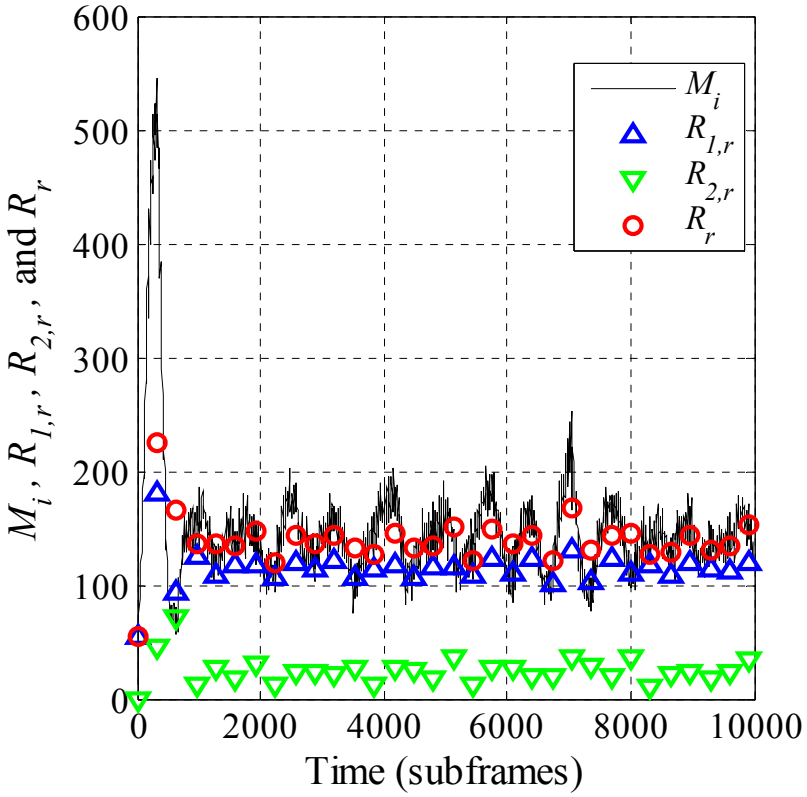
Algorithm 3.2 Algorithm for the BS with the preamble partition protocol

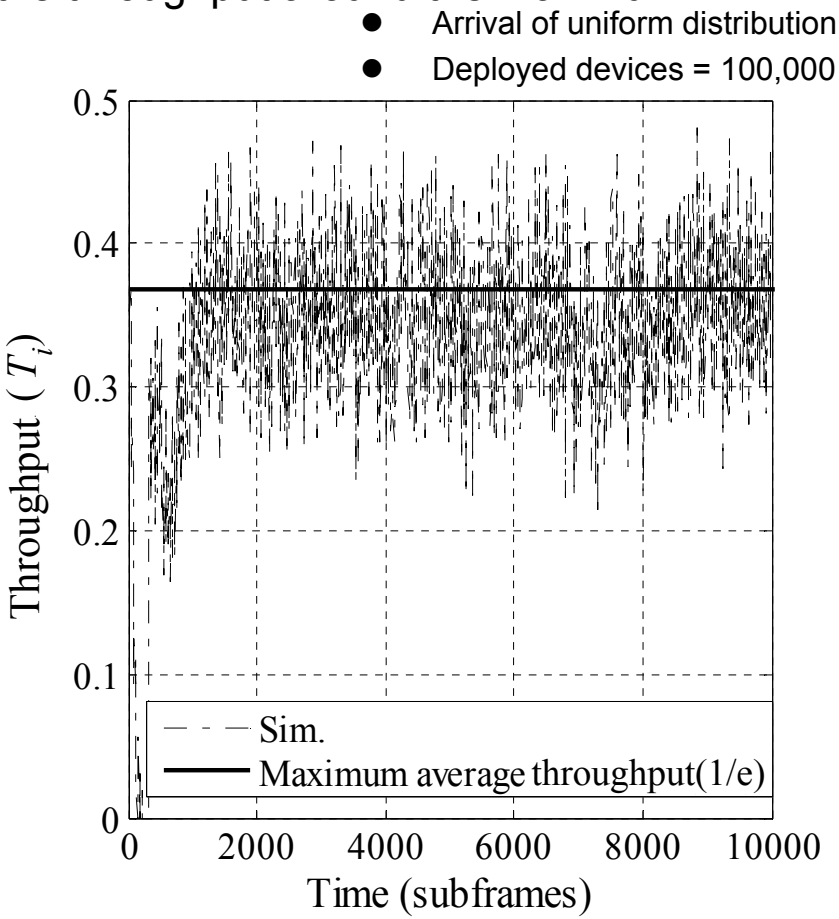
On completing time slot i:
  obtain $\hat{M}_{m,i}$ using (3.26).
On completing r-th si-period:
  obtain $\bar{M}_{1,r}$ and $\bar{M}_{2,r}$ using (3.27).
  $R_{1,r+1} = \max(\lceil \bar{M}_{1,r} \rceil, R_{min})$
  if $R_{2,r} = 0$
    $R_{2,r+1} = \lceil \gamma \bar{M}_{1,r} \rceil$
  else
    $R_{2,r+1} = \lceil \bar{M}_{2,r} \rceil$
  end if
  construct the pools for each group, $\mathbf{C}_1$ and $\mathbf{C}_2$.
  transmit SIB2 including information for $\mathbf{C}_1$, $\mathbf{C}_2$, and N_{th} .

• Sung-Hyung Lee, So-Yi Jung, Jae-Hyun Kim, “Dynamic Resource Allocation of the Random Access for MTC Devices,” ETRI Journal, vol.39, no.4, Aug. 2017.

Performance evaluations : Arrival and throughput over time

- **Arrival, pool size selection, and throughput over time with proposed protocol**
  - Throughput = (number of successful preambles) / (number of allocated preambles R_r)
  - Pool size selection with $B_N(i)$ can result the throughput around the maximum





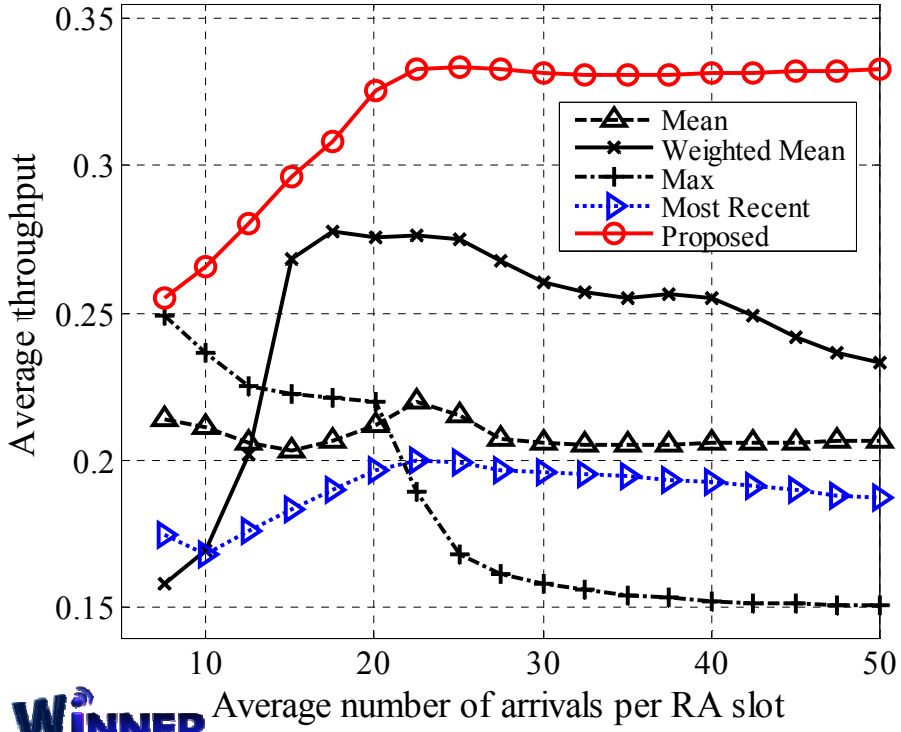
- Sung-Hyung Lee, So-Yi Jung, Jae-Hyun Kim, “Dynamic Resource Allocation of the Random Access for MTC Devices,” ETRI Journal, vol.39, no.4, Aug. 2017.

Performance evaluations : Throughput vs. traffic load

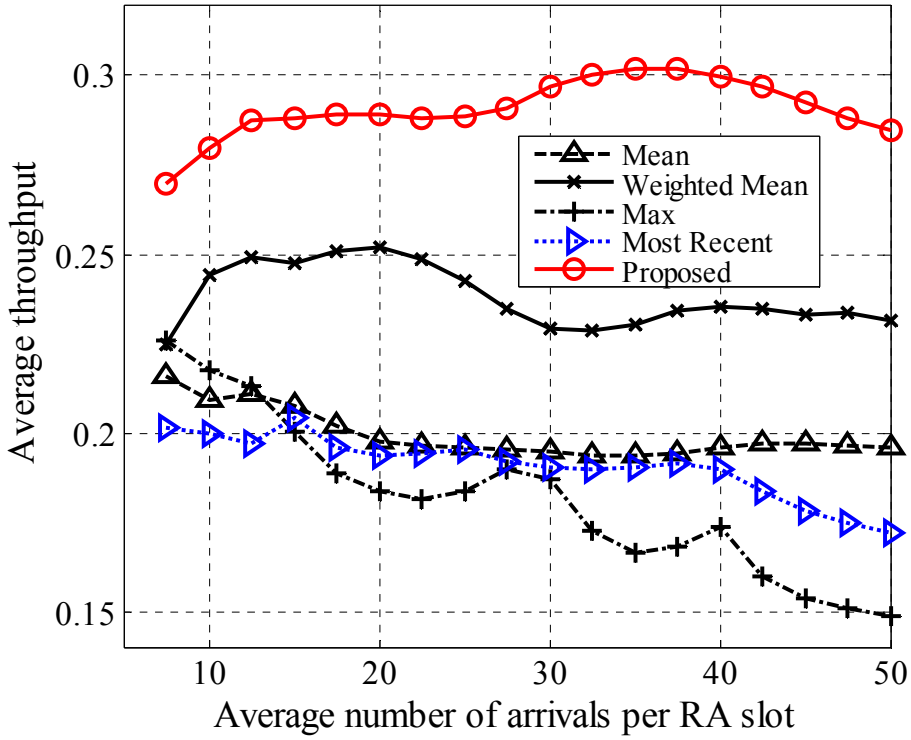
❑ Comparison for the average throughput

- ➢ The preamble partition approach increases throughput
  - ✓ From the reduction of fluctuation problem
  - ✓ Uniform distributed arrival : 29.7 ~ 114.4% ↑ (50 arrivals/slot - 100,000 devices in sector)
  - ✓ Beta distributed arrival : 23.0 ~ 91.3% ↑ (50 arrivals/slot - 100,000 devices in sector)

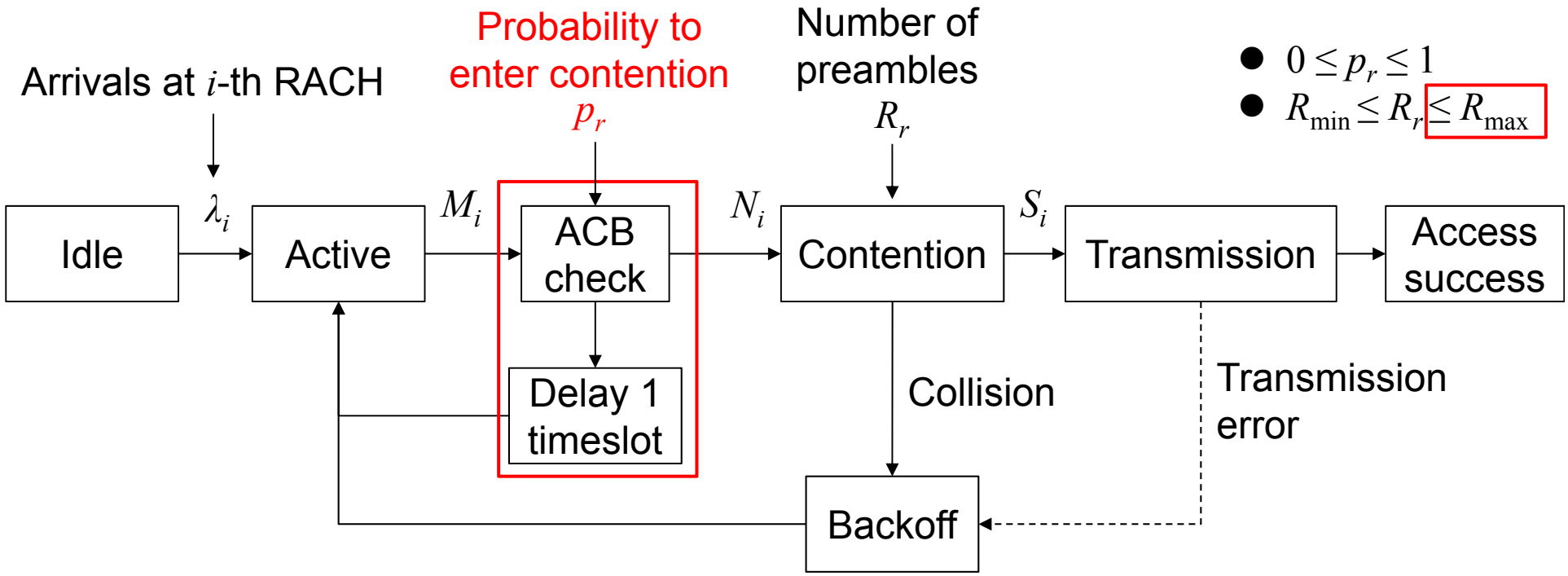
● **Arrival of uniform distribution**



● **Arrival of Beta distribution**



2) Access Class Barring (ACB)



❑ Metric

- Throughput = S_i / R_r

[1] S. Duan, V. Shah-Mansouri, Z. Wang, and V. W. S. Wong, "D-ACB: Adaptive Congestion Control Algorithm for Bursty M2M Traffic in LTE Networks," IEEE Transactions on Vehicular Technology, vol. 65, no. 12, pp. 9847-9861, Dec 2016.

Access Class Barring (ACB)

- **Objective for ACB to maximize throughput**

$$\arg\min_{p_r} \quad \left(\mathbf{E}[N_i \mid M_i, p_r] - R_r\right) \qquad (0 \le p_r \le 1)$$

- **Expected number of contending devices**
  - when M_i devices enters contention with probability p_r

$$\mathbf{E}[N_i \mid M_i, p_r] = M_i p_r$$

- **Optimal throughput**

$$\mathbf{E}[N_i \mid M_i, p_r] = R_r$$

- **Optimal contention probability**

$$p_r = \frac{R_r}{M_i}$$

DARR + ACB

❑ The optimal number of preambles and ACB factor

- $R_r^* = \min[R_{\max}, M_i]$
- $p_r = \min[1, R_r/M_i]$ ➔ Implies that ACB activates when R_r = $R_{\max}$

❑ Update interval and ACB factor

- ACB continues when $M_i > R_r$ continues
  - ✓ M_i increases gradually ➔ (R_r / M_i) is also decreases gradually
  - ✓ $|p_r — (R_r/M_i)|$ (the error between selected ACB factor and optimal ACB factor) is also decreases
  - ➔ Amplitude of fluctuation will decrease

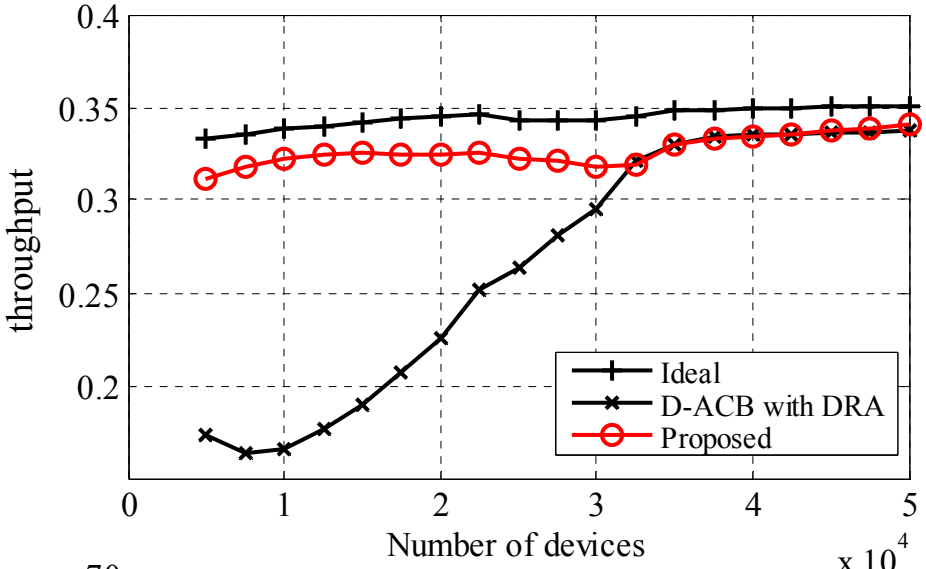
❑ DARR and ACB

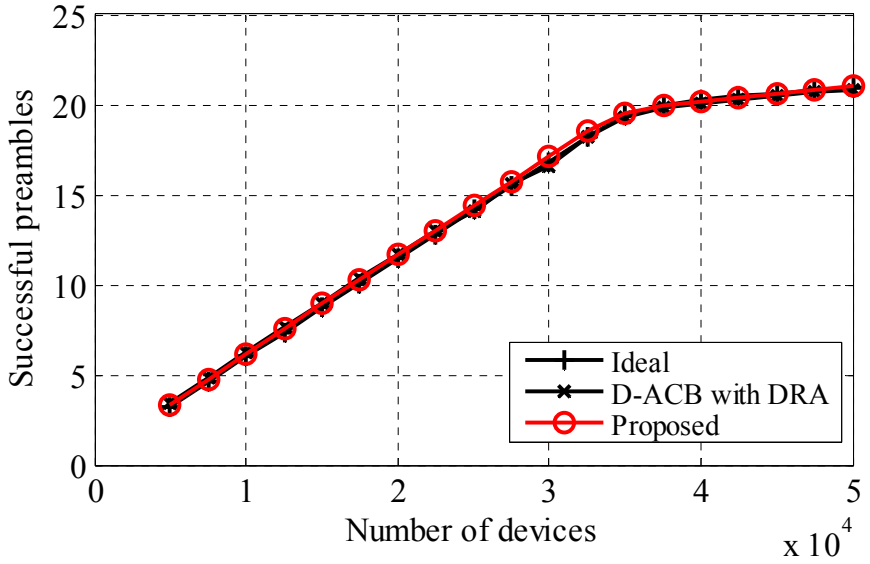
- If the DARR is performed considering fluctuation problem, then the DARR and ACB protocol will work

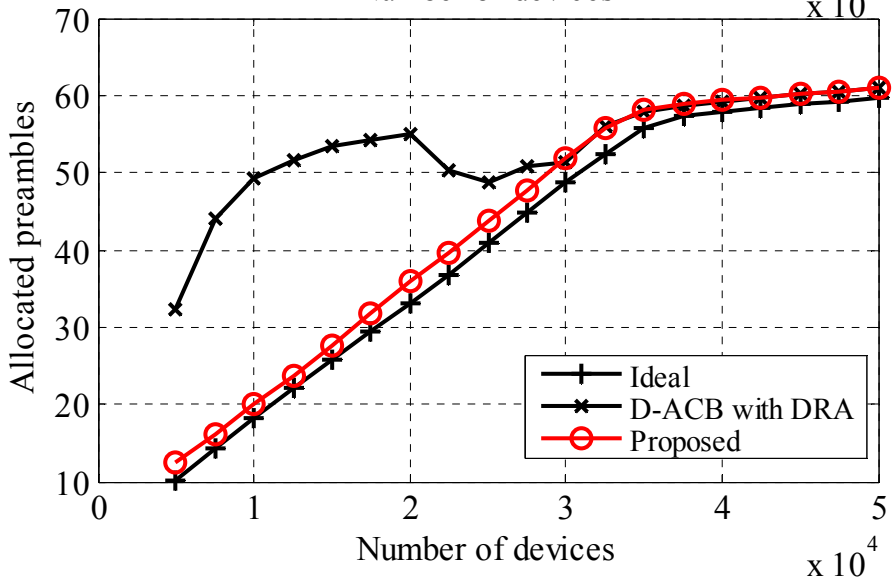
Performance evaluations : Throughput vs. Number of devices

❑ Comparison of throughput

- ➢ Ideal : assume that BS knows the number of arrivals in future RACHs
- ➢ D-ACB with DRA : [1]
- ➢ Fixed update interval : 32 RACHs
- ➢ Proposed protocol shows 92.32 ~ 97.25% of ideal case utilization



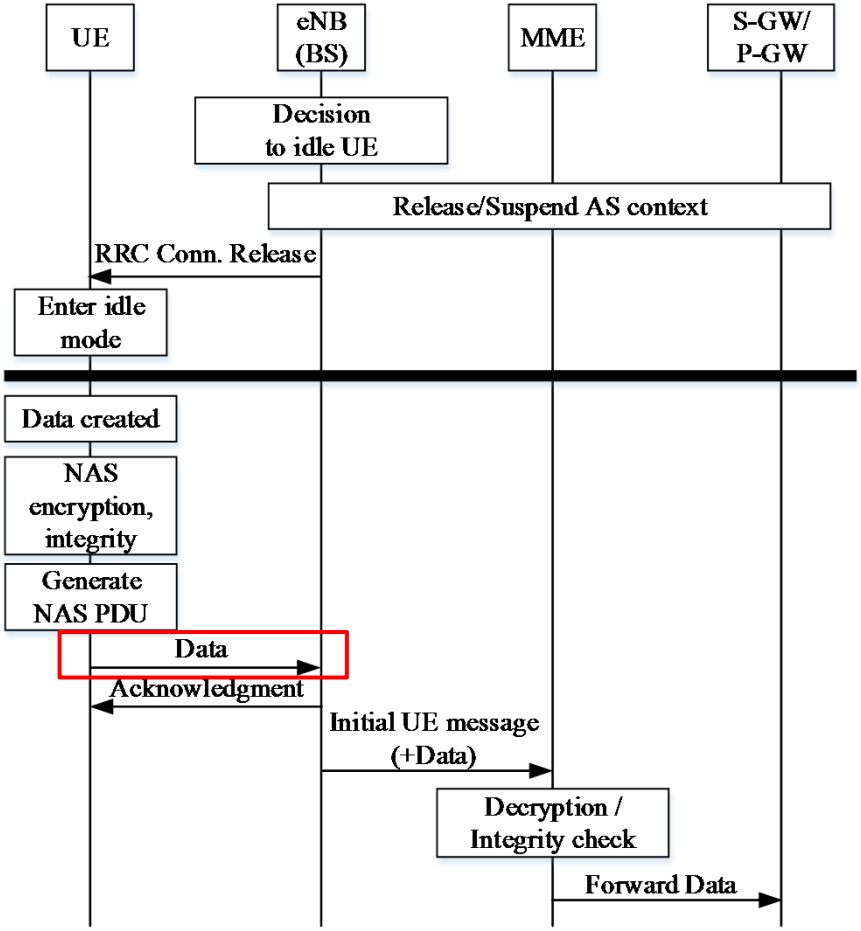




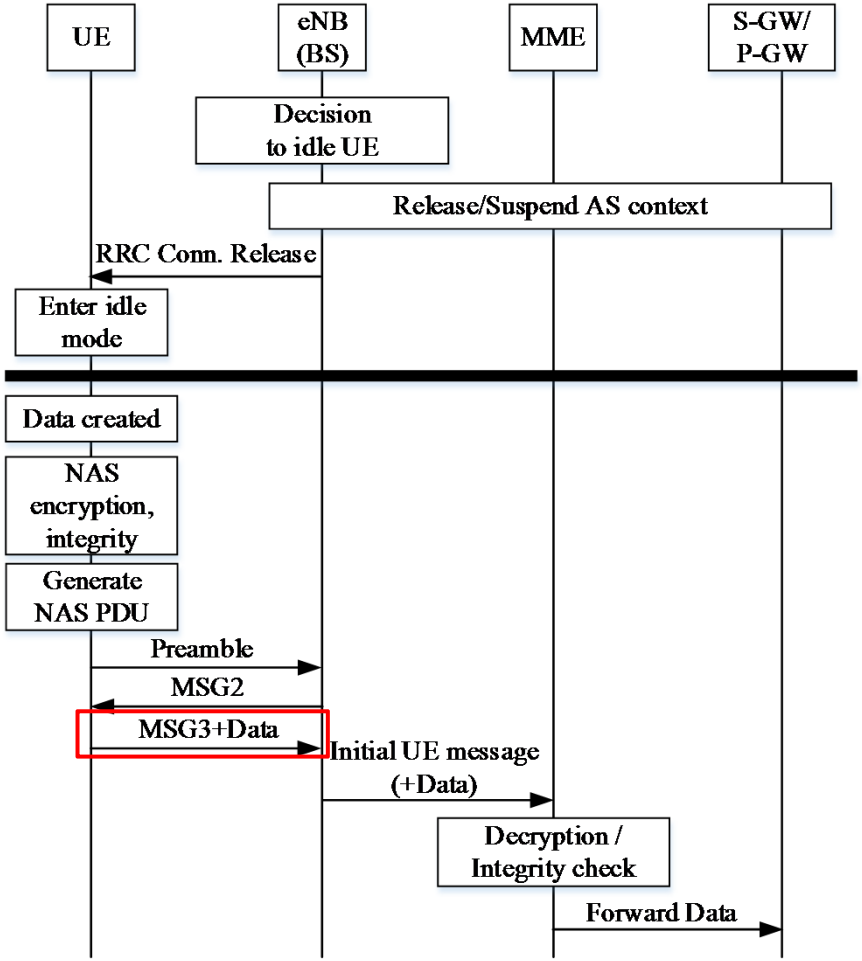
[1] S. Duan, V. Shah-Mansouri, Z. Wang, and V. W. S. Wong, "D-ACB: Adaptive Congestion Control Algorithm for Bursty M2M Traffic in LTE Networks," IEEE Transactions on Vehicular Technology, vol. 65, no. 12, pp. 9847-9861, Dec 2016.

3) Short data transmission procedures in previous studies

❑ Data in MSG1 [1]



❑ Data in MSG3 [2]



❑ Actual resource usage needs to be evaluated

[1] K. D. Lee, S. Kim, and B. Yi, "Throughput comparison of random access methods for M2M service over LTE networks," in 2011 IEEE GLOBECOM Workshops (GC Wkshps), Dec 2011, pp. 373-377.

[2] S. M. Oh and J. Shin, "An Efficient Small Data Transmission Scheme in the 3GPP NB-IoT System," IEEE Communications Letters, vol. 21, no. 3, pp. 660-663, March 2017.

Summary

Summary

❑ MAC Protocols for Massive IoT devices

- ➢ 3GPP
  - ✓ CIoT EPS optimization : reduced signaling than conventional LTE
  - ✓ NB-IoT : Channel structure for narrowband IoT
  - ✓ New radio : Tighter resource block, new RRC state
- ➢ IEEE 802.11ah
  - ✓ Restricted access window

❑ Overload Control for Massive IoT Devices

- ➢ Dynamic allocation of RACH resources (DARR)
  - ✓ Adaptively change the amount of time-frequency resources for random access
- ➢ Access class barring (ACB)
  - ✓ Adaptively change the number of contending devices per the resources for RACH
- ➢ Combination of DARR and ACB
- ➢ Short data transmission procedures

Considerations and future works

- **Overload control with different objectives**
  - Percentile of success ratio
  - Delay

- **Overload control with new MAC protocols**
  - DARR and/or ACB with new channel structure and physical layer modulations (NOMA, etc.)

Thank you !



Q & A