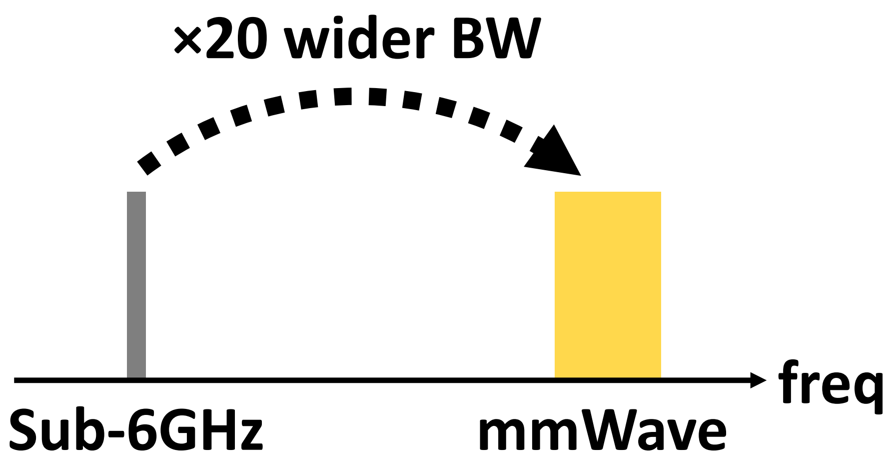
# **NR-Surface:** NextG-ready µW-reconfigurable mmWave Metasurface

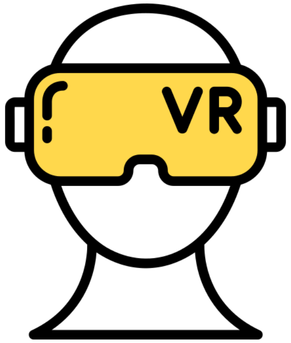
Minseok Kim*, Namjo Ahn*, and Song Min Kim

* Co-primary authors

# mmWave Communication

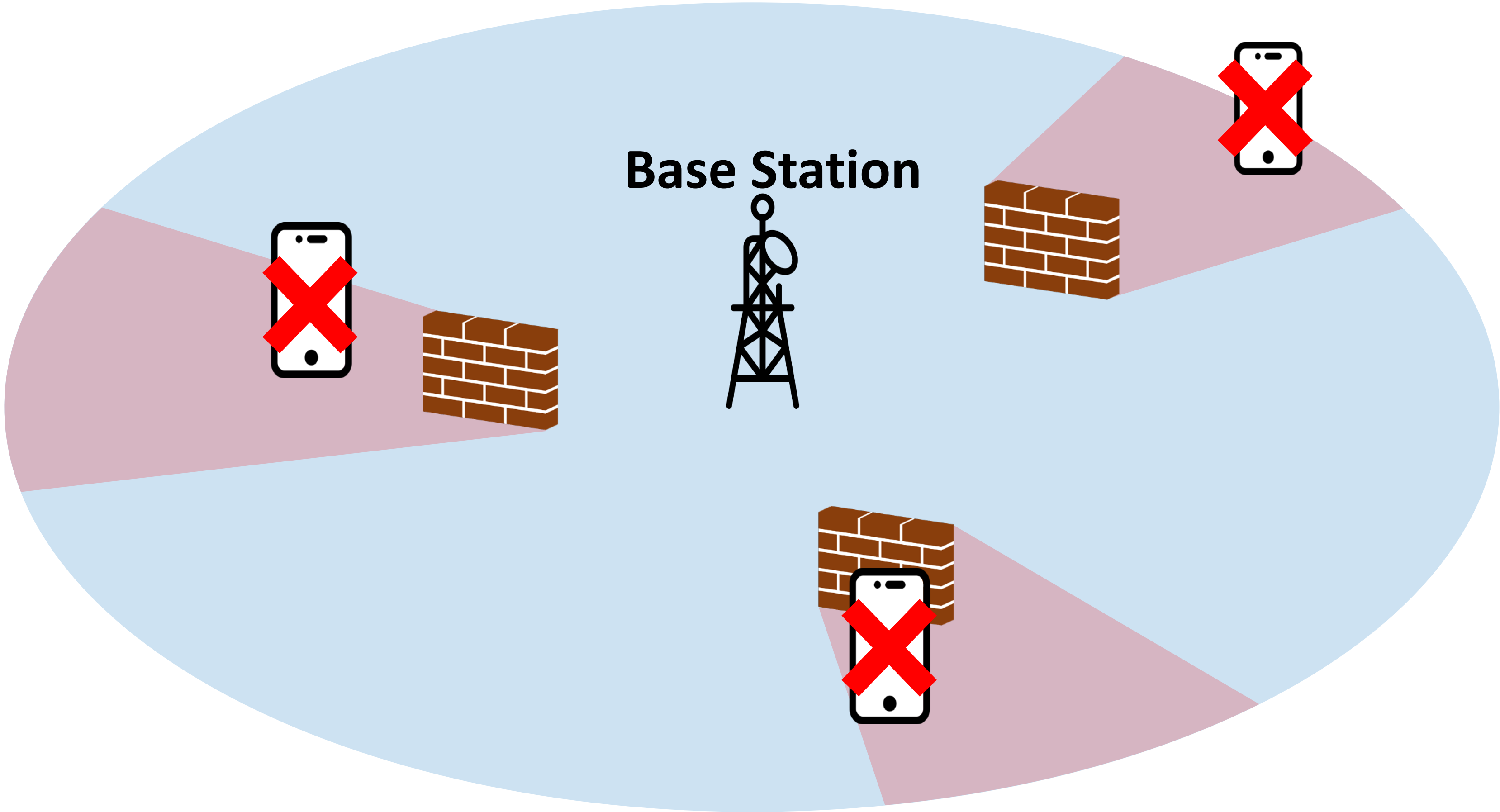



Multi-GHz Wide Bandwidth



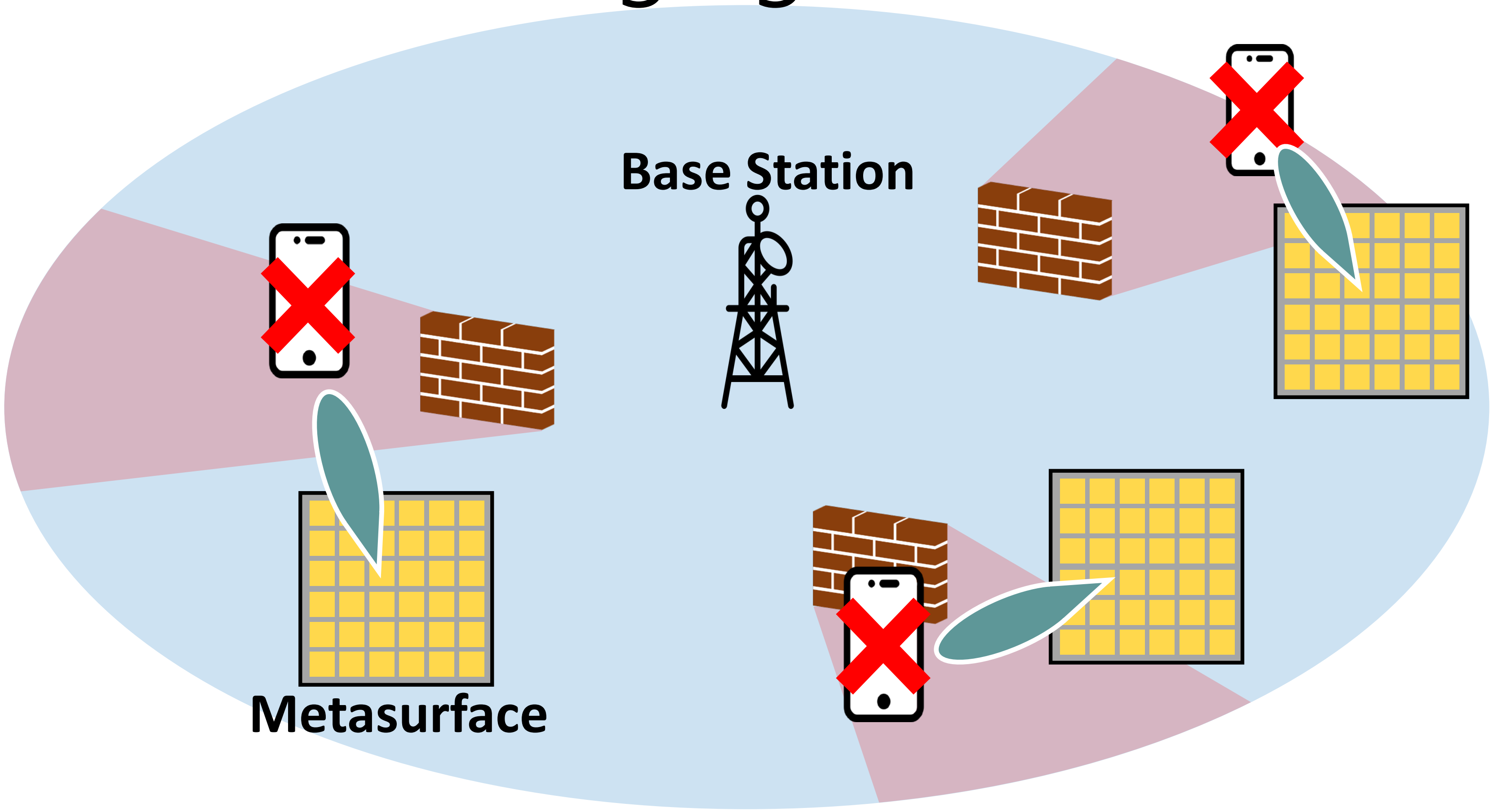

High throughput application

# **mmWave:** Drawback



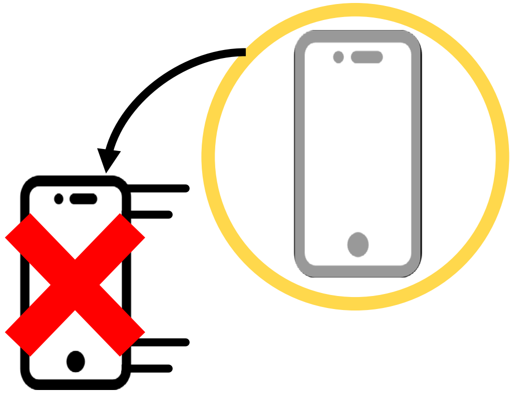

**mmWave suffers from the limited coverage**

# **Metasurface:** emerging solution of mmWave

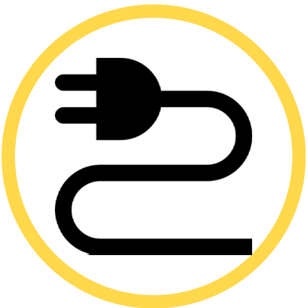



**Metasurface can reconfigure beam to cover the blind spot.**

# **Metasurface,** Are we there yet?



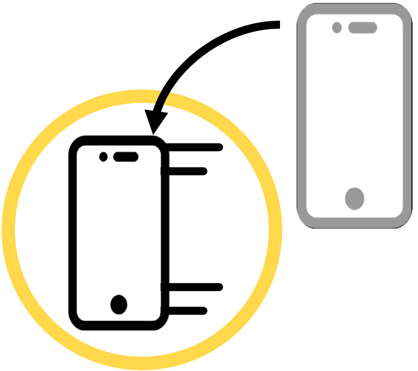
**Non NR-Compliant**
**(Non Real-time)**



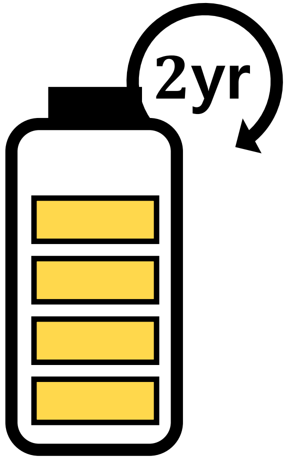
**Need Wall-plug**

[1] Lee, W., Jo, S., Lee, K. et al. Single-layer phase gradient mmWave metasurface for incident angle independent focusing. Sci Rep 11, 12671 (2021)
[2] Xiaocha Liu, Xiaoyi Wang, Guo-Min Yang, Dang Xiang, and Li-Rong Zheng, "Dual-band frequency reconfigurable metasurface antenna for millimeter wave joint communication and radar sensing systems," Opt. Express 32, 13851-13863 (2024)
[3] Yasir Saifullah, Qinzhuo Chen, Guo-Min Yang, Abu Bakar Waqas, and Feng Xu, "Dual-band multi-bit programmable reflective metasurface unit cell: design and experiment," Opt. Express 29, 2658-2668 (2021)
[4] Xu, G., Overvig, A., Kasahara, Y. et al. Arbitrary aperture synthesis with nonlocal leaky-wave metasurface antennas. Nat Commun 14, 4380 (2023). https://doi.org/10.1038/s41467-023-39818-2
[5] Bai, Xudong, et al. "Dynamic millimeter-wave OAM beam generation through programmable metasurface." Nanophotonics 11.7 (2022): 1389-1399.
[6] Lili Chen et al.,Towards Seamless Wireless Link Connection, MobiSys'23
[7] Kun Qian et al., MilliMirror: 3D Printed Reflecting Surface for Millimeter-Wave Coverage Expansion, MobiCom'22
[8] Kun Woo Cho et al., mmWall: A Steerable, Transflective Metamaterial Surface for NextG mmWave Networks, NSDI 23

# We present: **NR-Surface**



**Real-time NR-compliant**




**Multi-year Battery lifetime**

# Challenges

**Challenge 1**

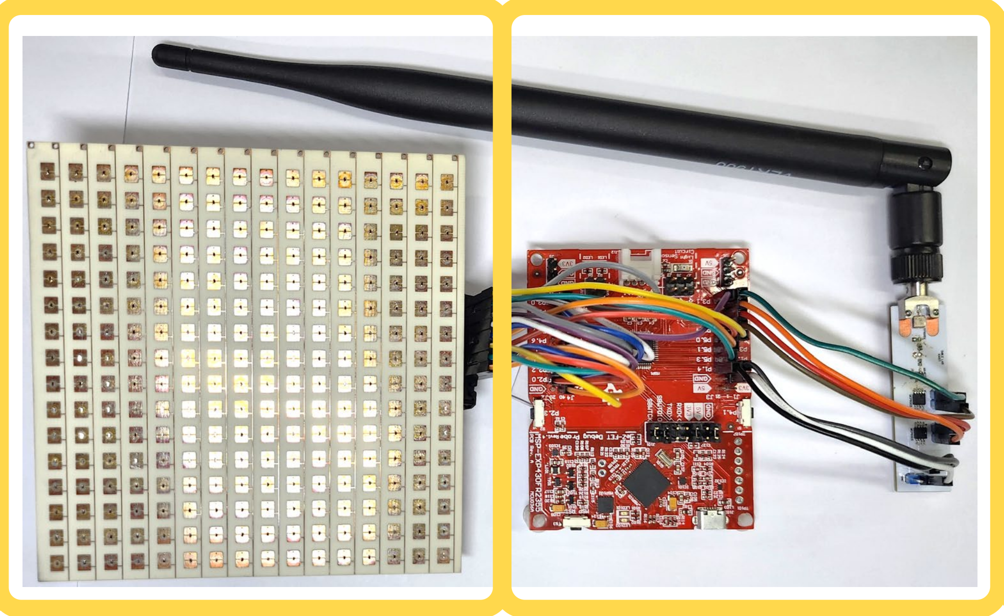
Real-time reconfiguration

**Challenge 2**

Symbol-level synchronization to BS

All at uW-regime power consumption

# Key Design



**Design 1**

**Design 2**

**Low duty-cycled metasurface within NR beam management procedure**

**Multi-symbol synchronization over low-bandwidth asymmetric communication**

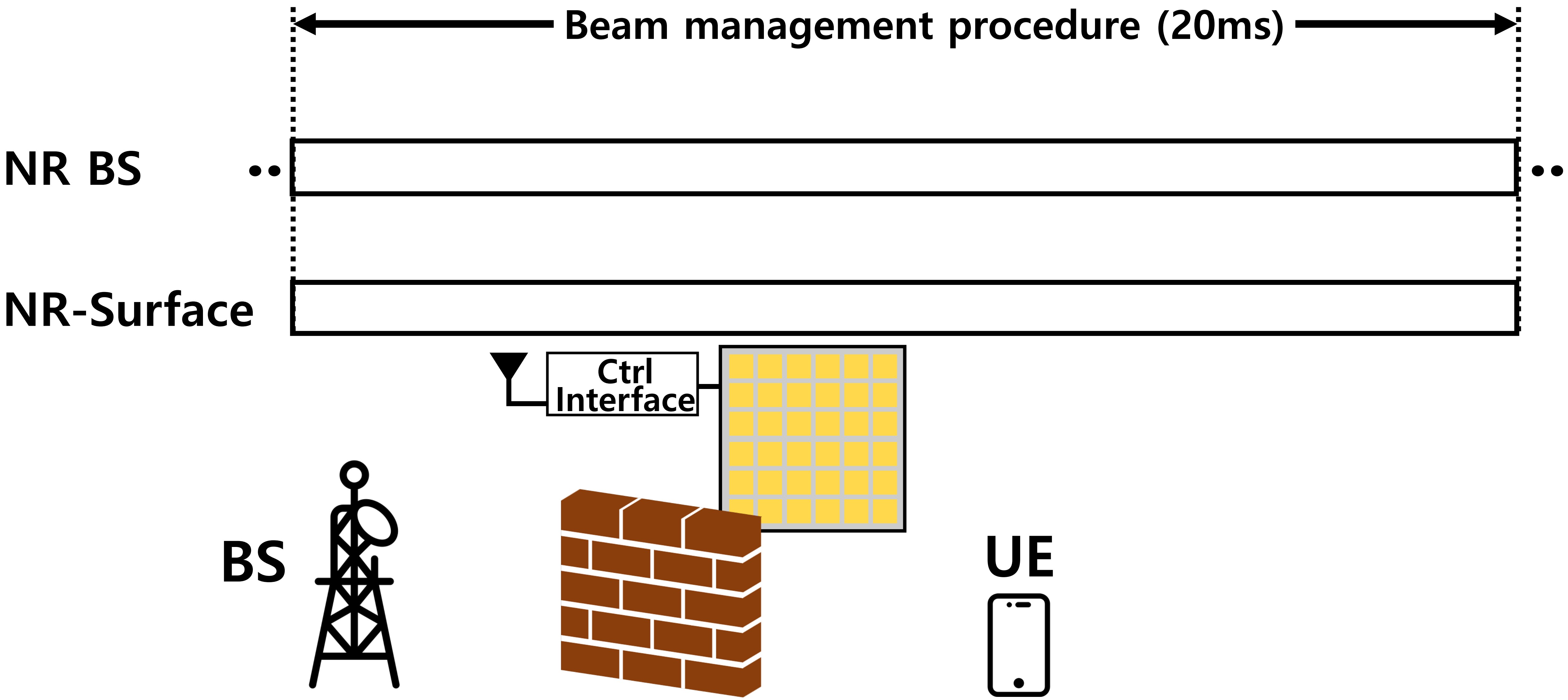
**https://youtu.be/2mouM2IWdzc?si=kNtmlATFHwk_11Ai**

# NR-Surface

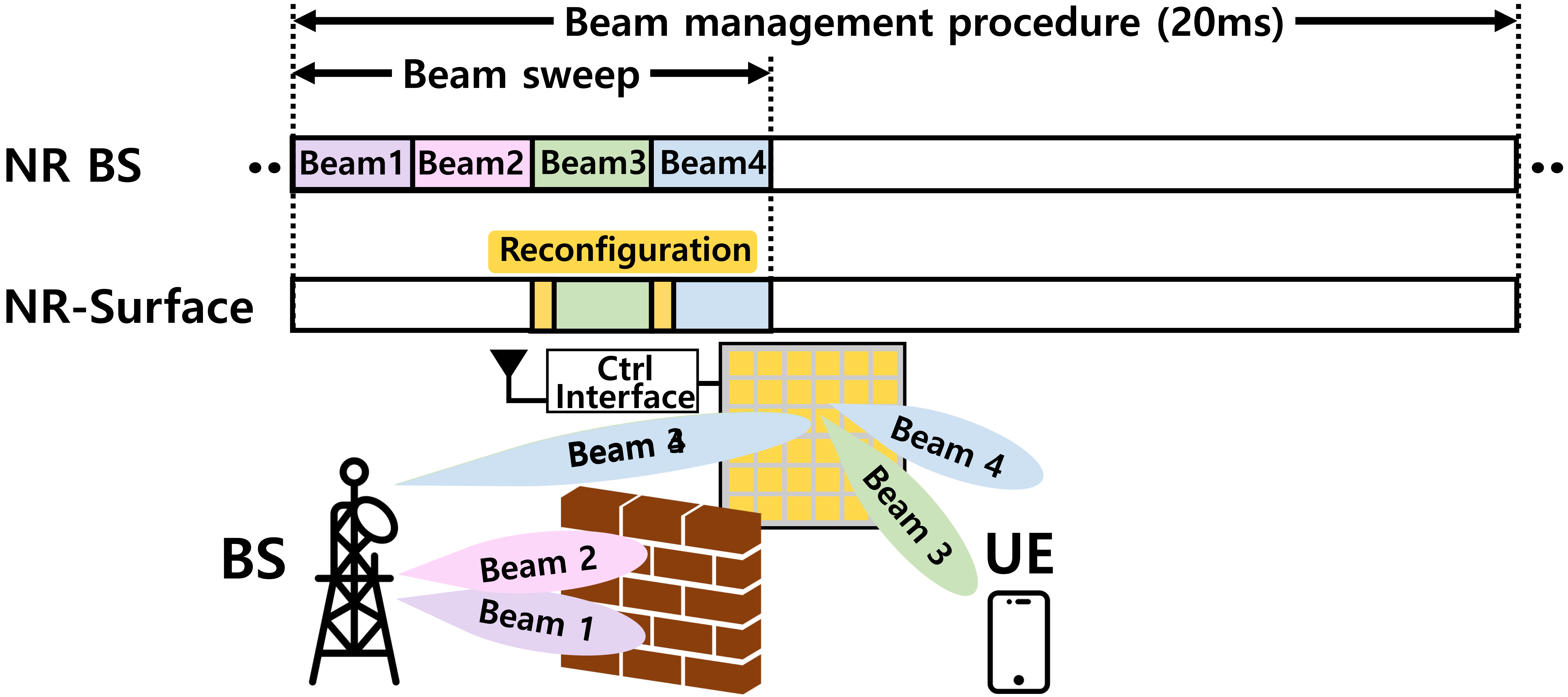
## Real-Time Reconfiguration Demo

Smile LAB

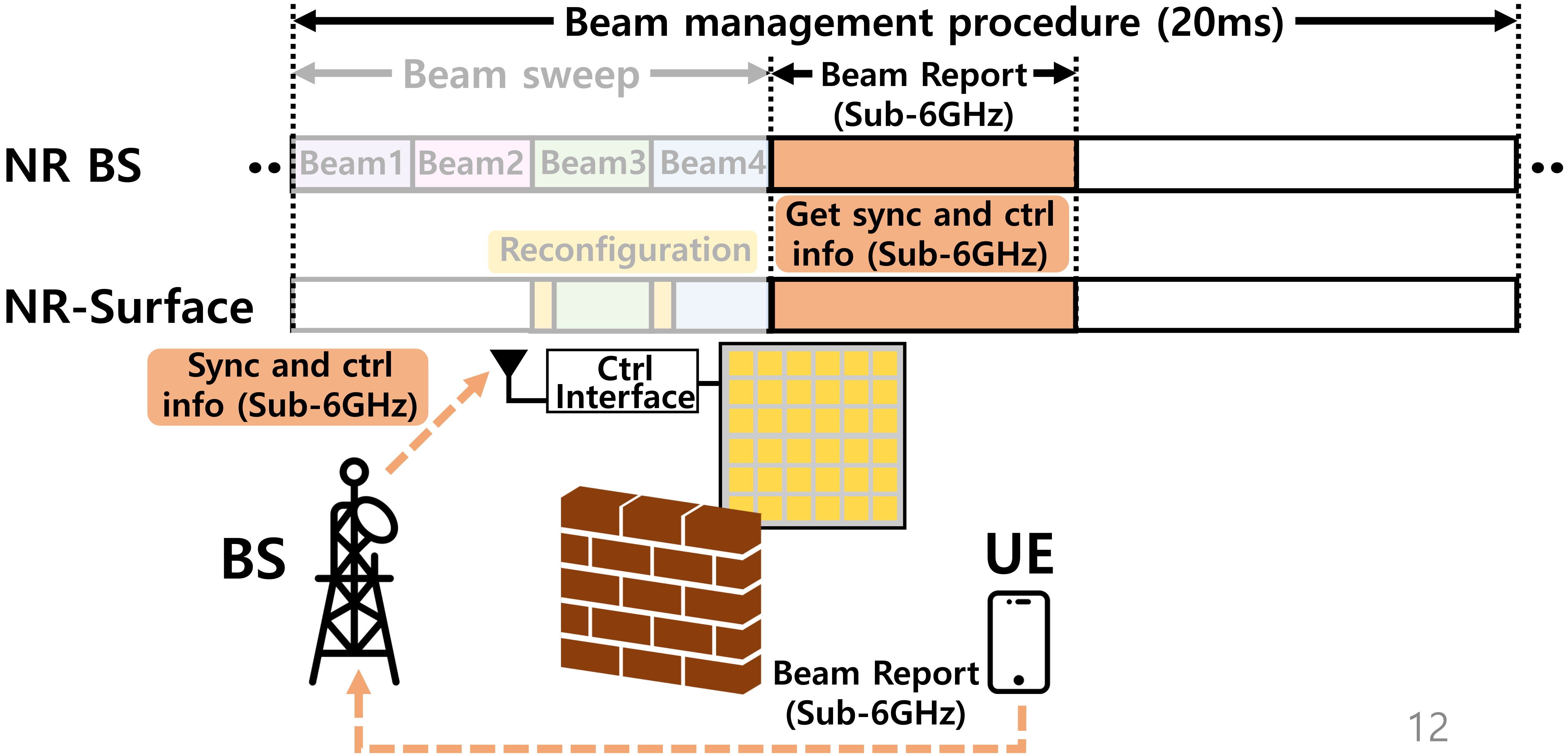
# NR-Surface Operation Overview



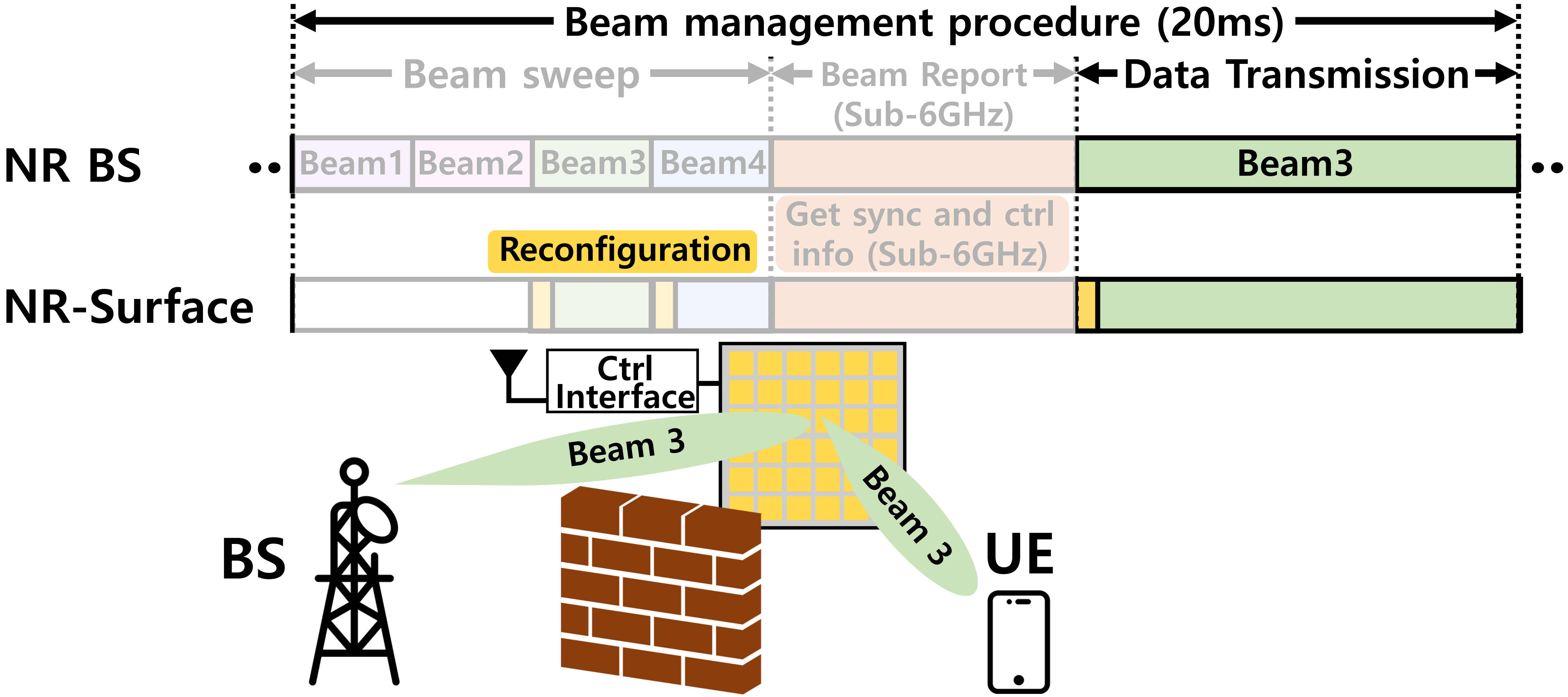
# Beam Sweep


Beam management procedure (20ms)
Beam sweep
NR BS
Beam1
Beam2
Beam3
Beam4
Reconfiguration
NR-Surface
Ctrl Interface
Beam 4
Beam 3
Beam 2
Beam 1
BS
UE

# Beam Report


Beam management procedure (20ms)
Beam sweep
Beam Report (Sub-6GHz)
NR BS
Beam1
Beam2
Beam3
Beam4
Get sync and ctrl info (Sub-6GHz)
Reconfiguration
NR-Surface
Sync and ctrl info (Sub-6GHz)
Ctrl Interface
BS
UE
Beam Report (Sub-6GHz)

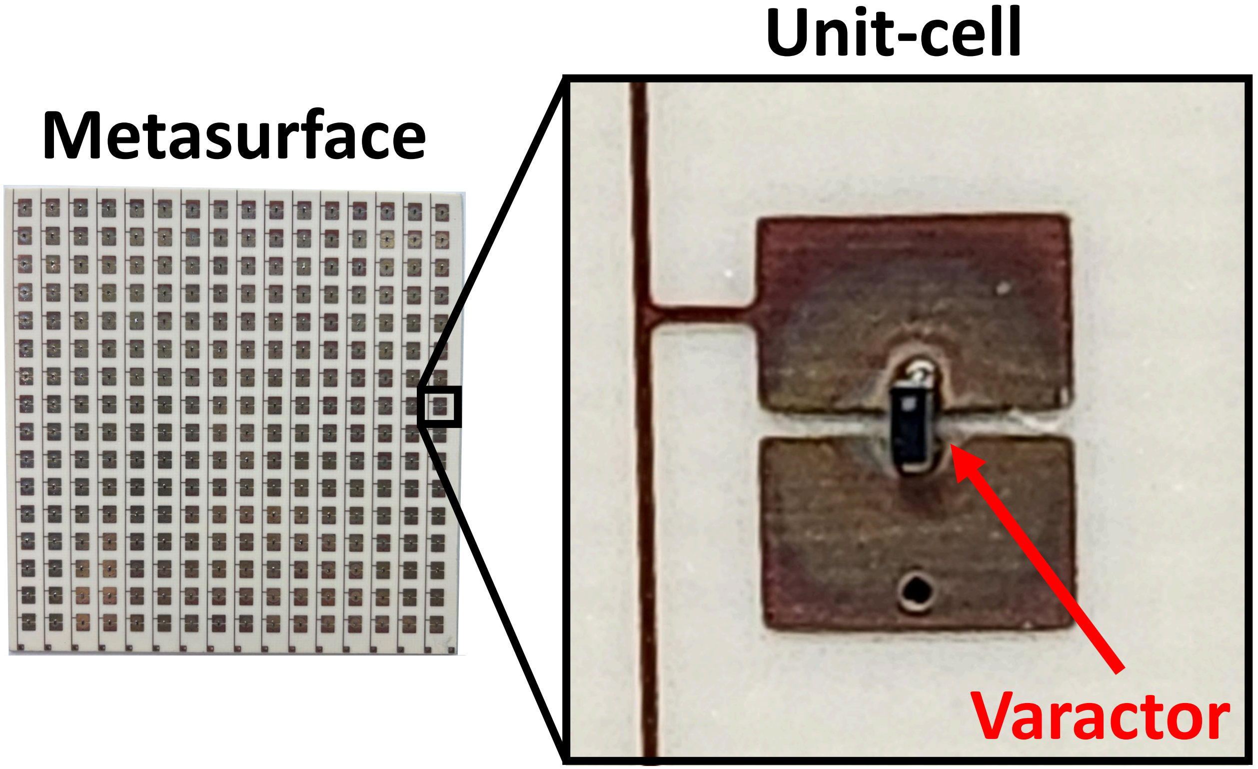
# Data Transmission



# Design 1: **Low Duty-Cycle**


**Opportunity** **Hold beam patterns for the majority (>90%) of period**

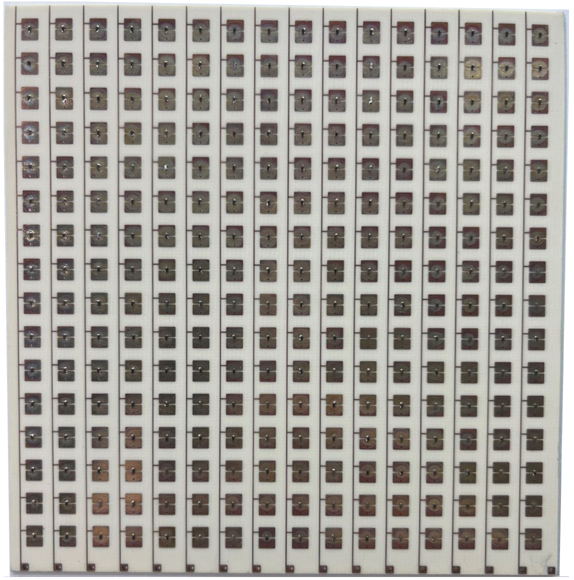
# Varactor-based Metasurface Design




- Zero power consumption at varactor to hold beam pattern
- MCU enters sleep mode while beam patterns are held

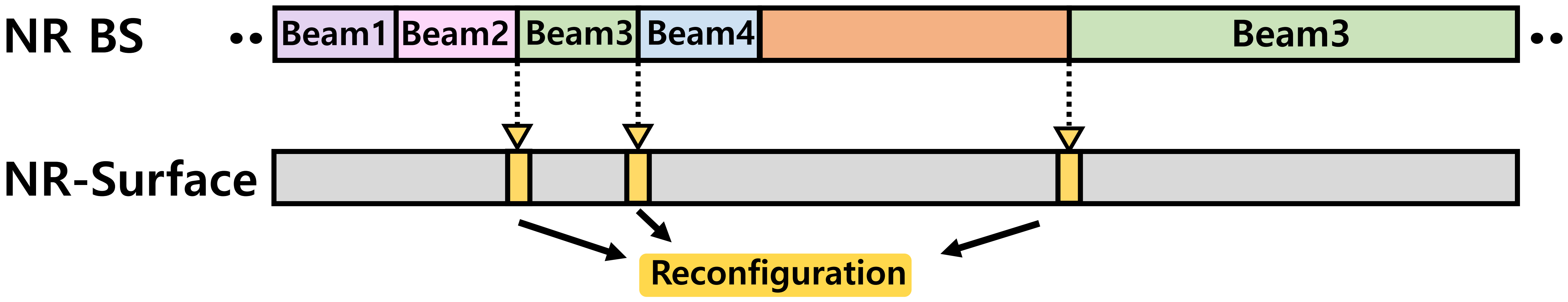
# Low-power Reconfigurable Metasurface

16x16 Array



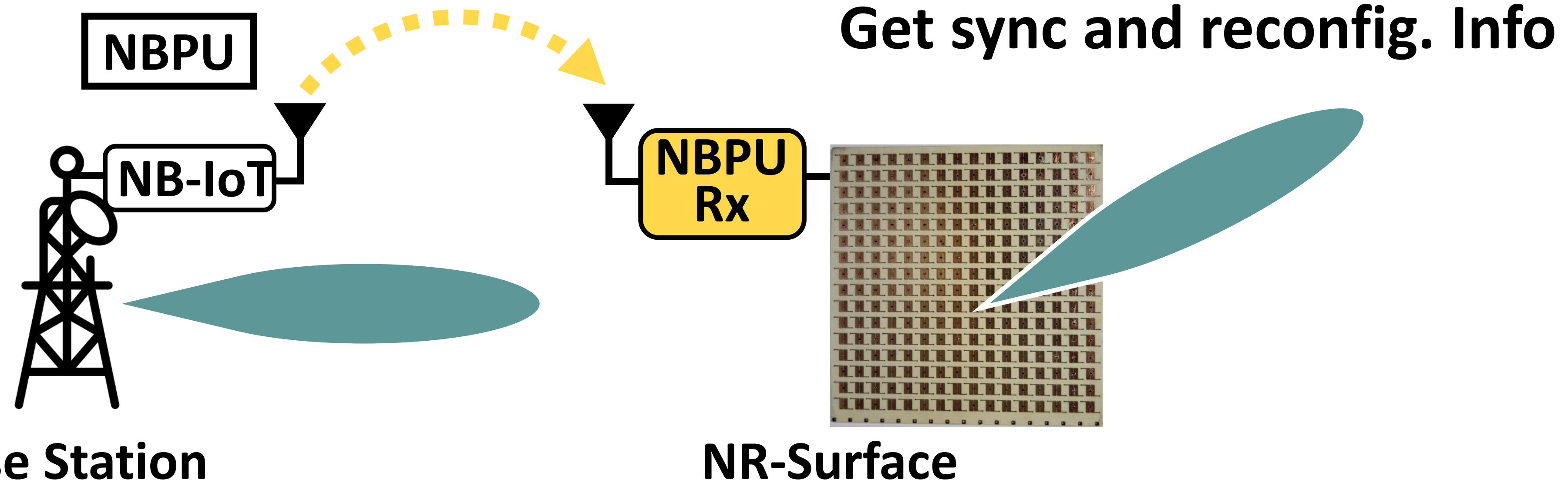
- Metasurface(256-cell) hold beam pattern at < 72nW (2.1 year lifetime with an AA battery)
- Narrow beam-width of 6.3°

# Design 2: Symbol-level Sync with BS




**For real-time NR-compliant reconfiguration, NR-Surface needs symbol-level synchronization (<260ns).**

# Narrow Band Packet Unit (NBPU)

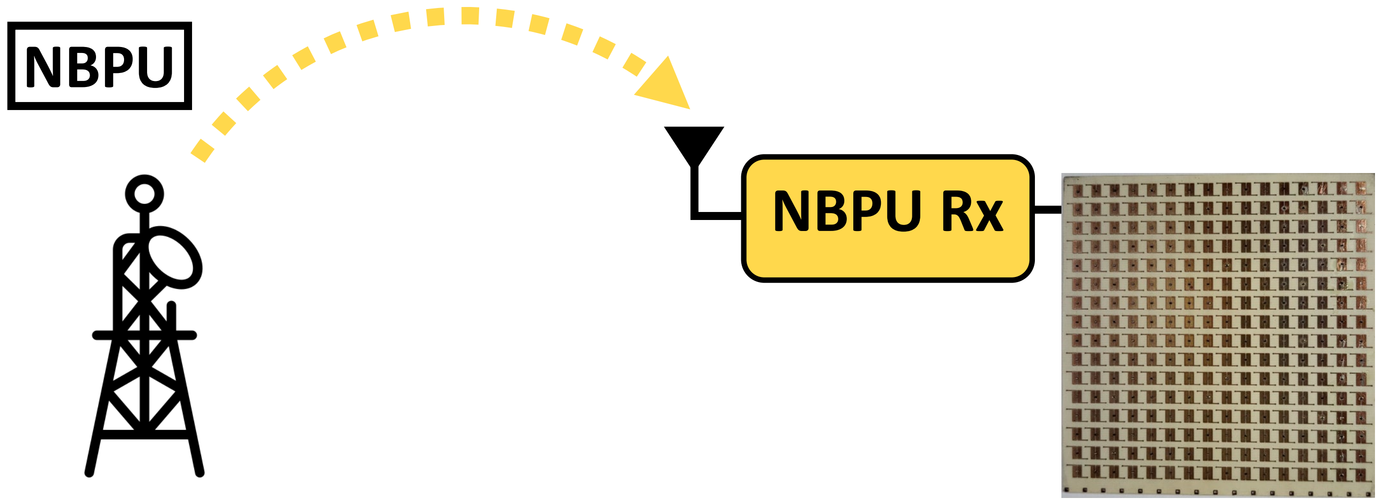



NBPU is embedded in NB-IoT → No BS hardware change required

# NBPU: Asymmetric Communication

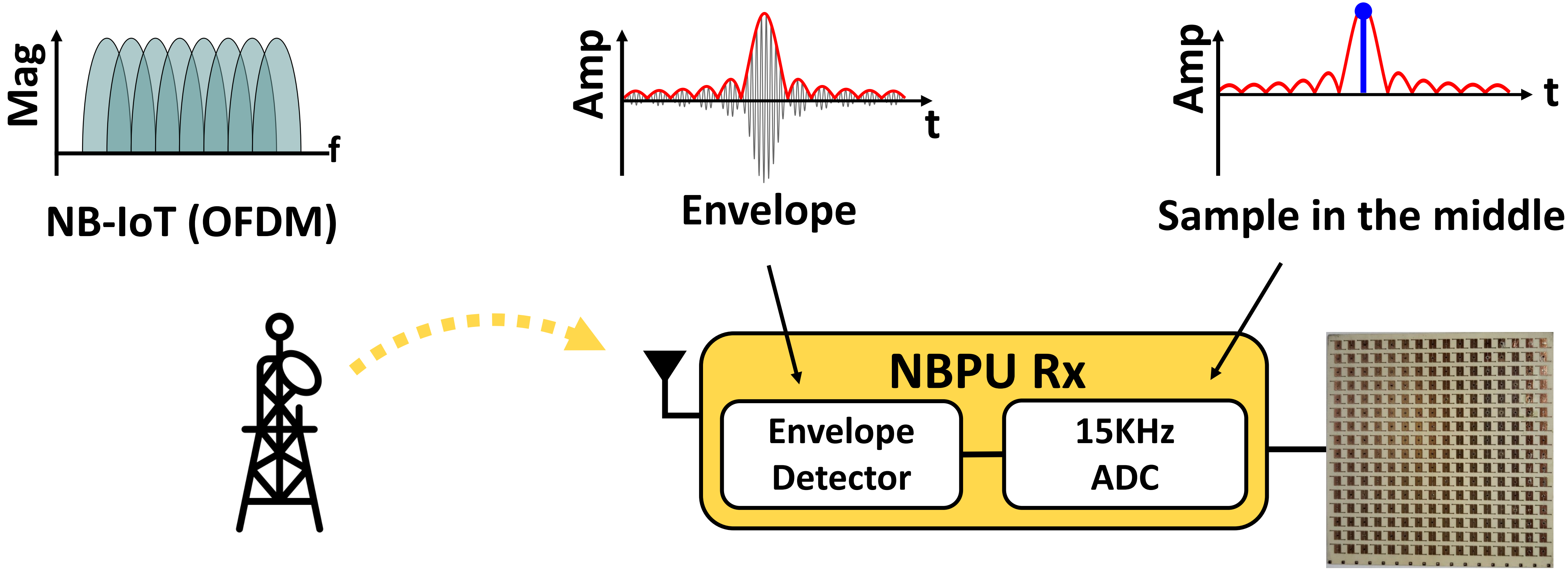
NBPU embedded
in 180KHz NB-IoT

Interpret as it is
15KHz BW signal




**Asymmetric communication for ×12 narrower BW than NB-IoT**

# NBPU Overview




**Select NB-IoT symbol to maximize NBPU SNR**

# NBPU Symbol design

- NB-IoT uses OFDM with 12 subcarrier.

- 12 subcarriers makes lots of harmonics when go through envelope detector.

$$\Sigma_{k=1}^{11}\Sigma_{i=k+1}^{12}\cos(2\pi k\Delta f t + \phi_i - \phi_{i-k})$$

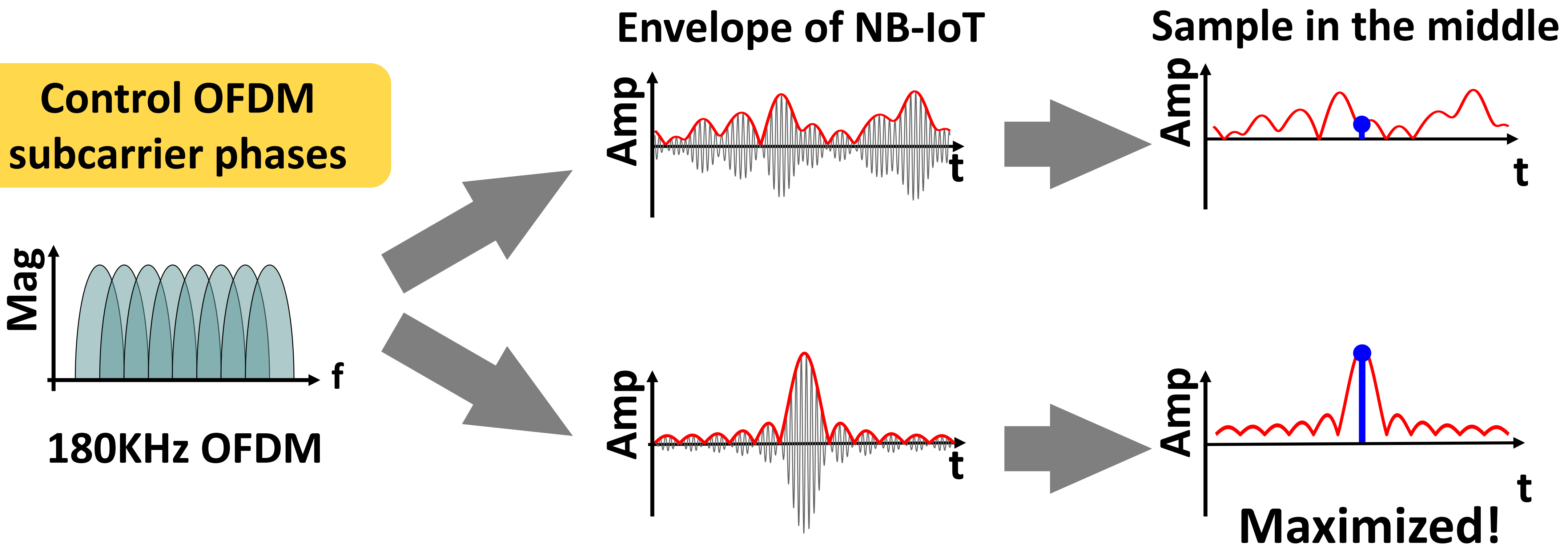
BS control subcarrier phase

- Max SNR signal:

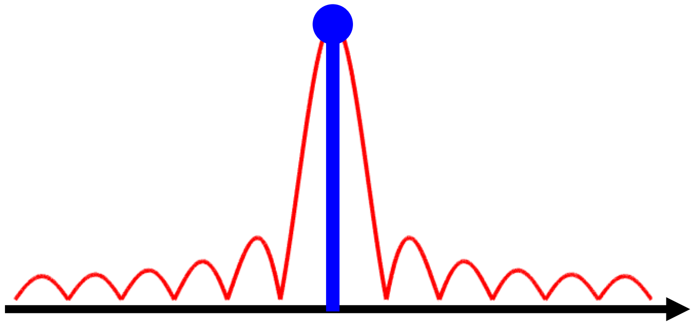
$$\rightarrow \Sigma_{k=1}^{11}(12-k)\cos(2\pi k\Delta f t)$$

# NBPU Symbol design

Control OFDM subcarrier phases



# NBPU Rx VS NB-IoT

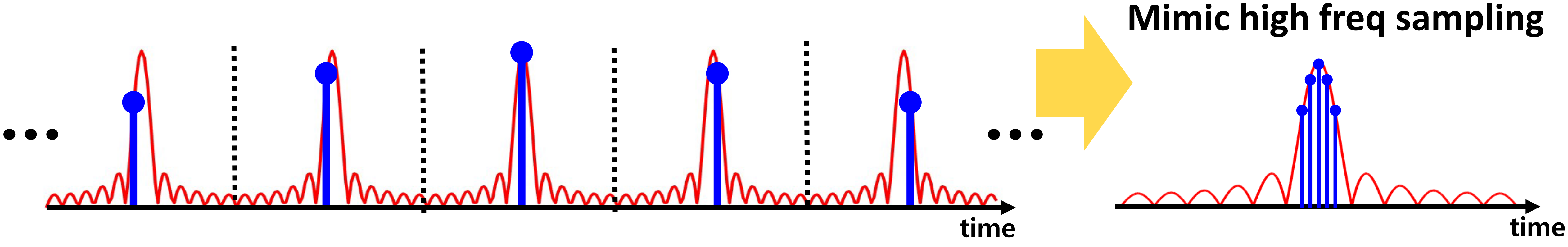



Sampling at 15KHz
(1 sample per symbol)

- ×300 power saving than commercial NB-IoT
- However, sampling every 66.7us limits the time synchronization accuracy

For 260ns synchronization, fine-grained samples (×256) are needed.

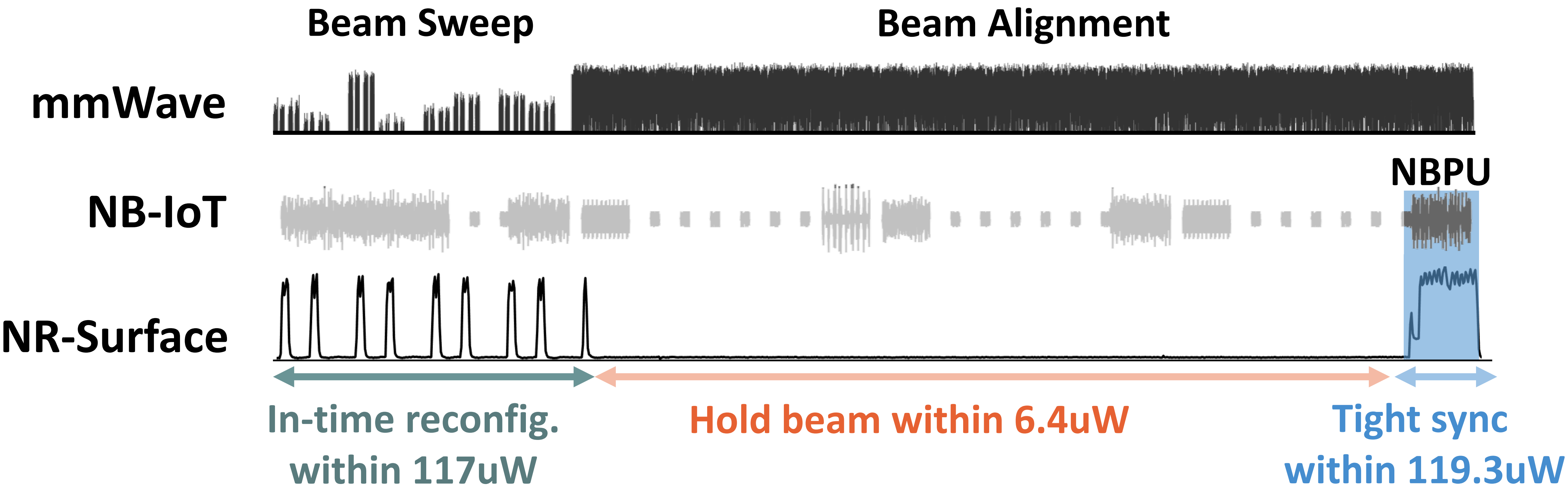
# Equivalent Time Sampling for Sync




- Control clock drift induce high freq sample over multiple symbols
- NBPU Rx shifts 1 tic of clock (223ns) every symbol, which becomes mimicked sampling speed.

**NR-Surface achieve < 234ns synchronization accuracy**

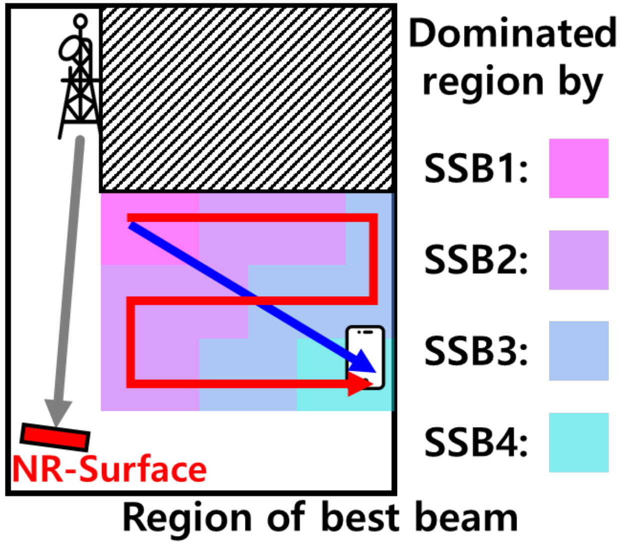
# End-to-End Operation



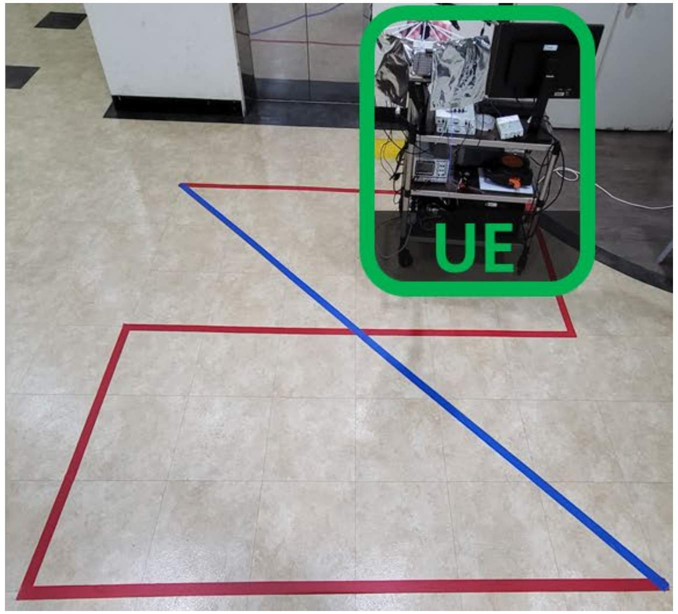

**NR-Surface operates NR-compliantly within 242.7uW.**
**→ 2.1 year lifetime with one AA battery**

# Evaluation: NR-Surface under Mobility

## Scenario 1: User moves in the blind spots.

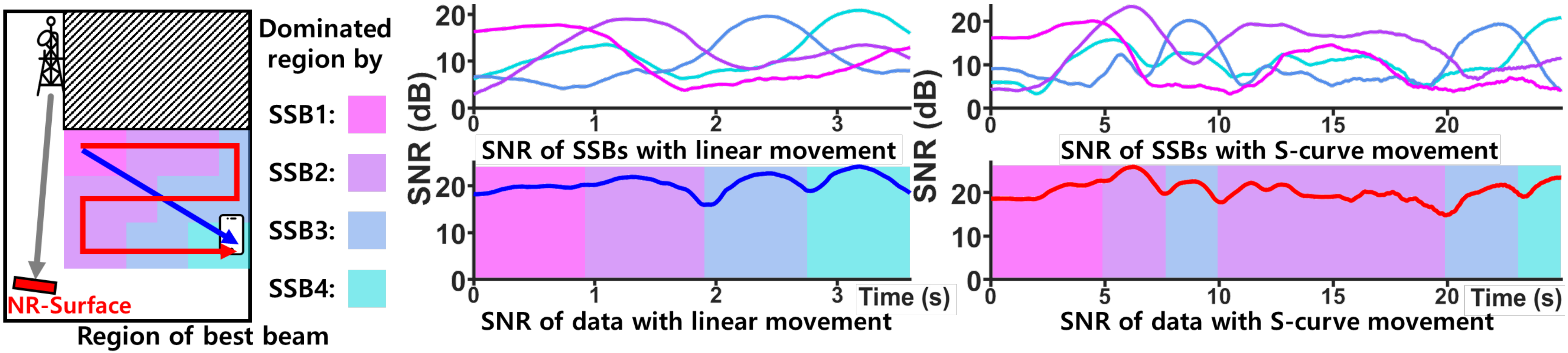






# Evaluation: NR-Surface under Mobility

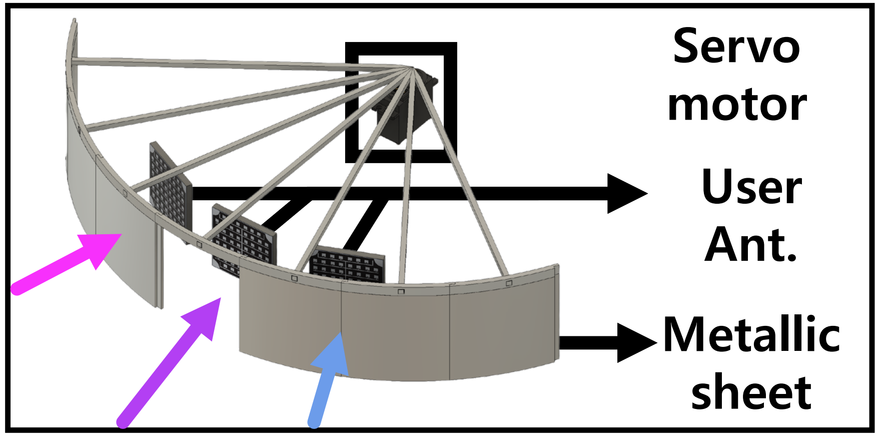
## Scenario 1: User moves in the blind spots.

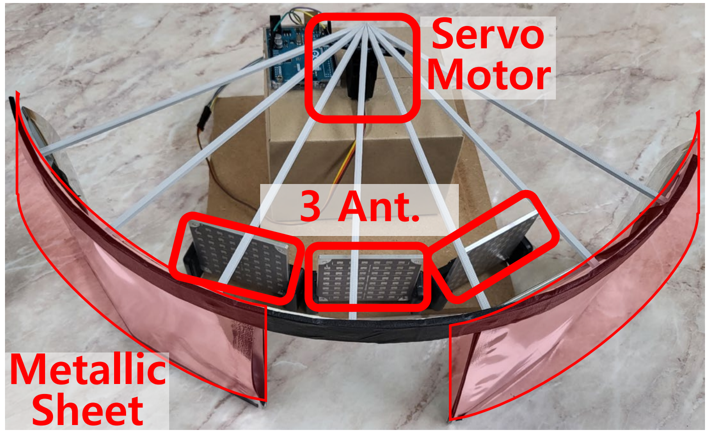



**NR-Surface provides 19.3dB average gain to mobile users.**

# Evaluation: NR-Surface in dynamic Env.

## Scenario 2: Blockage around user is dynamically changed.

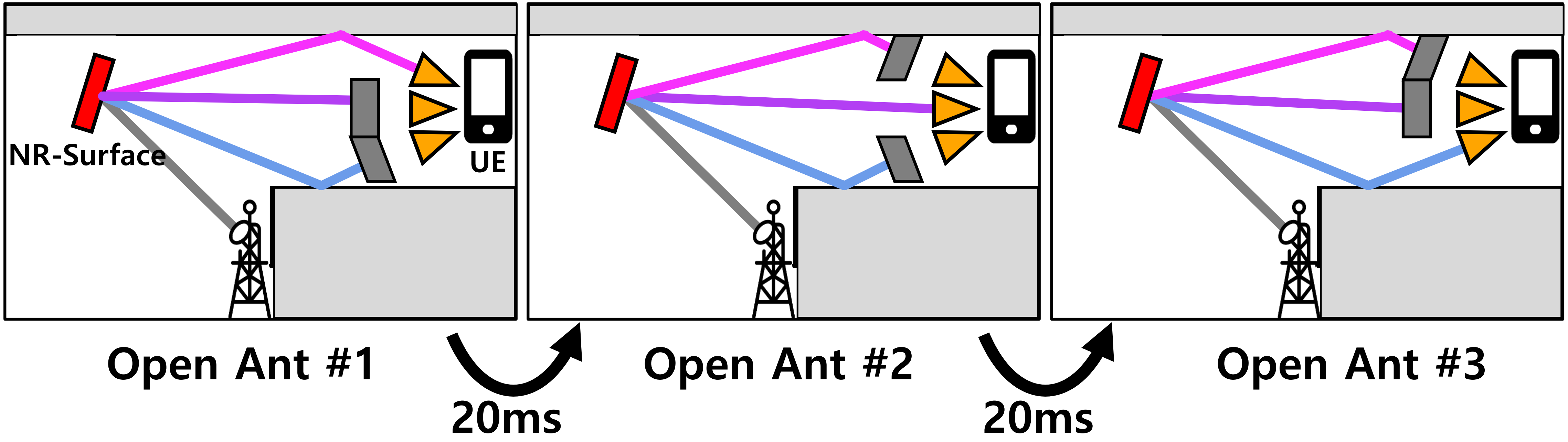



**Install rotatable metallic sheet with a slit in front of a user's antenna.**

# Evaluation: NR-Surface in dynamic Env.

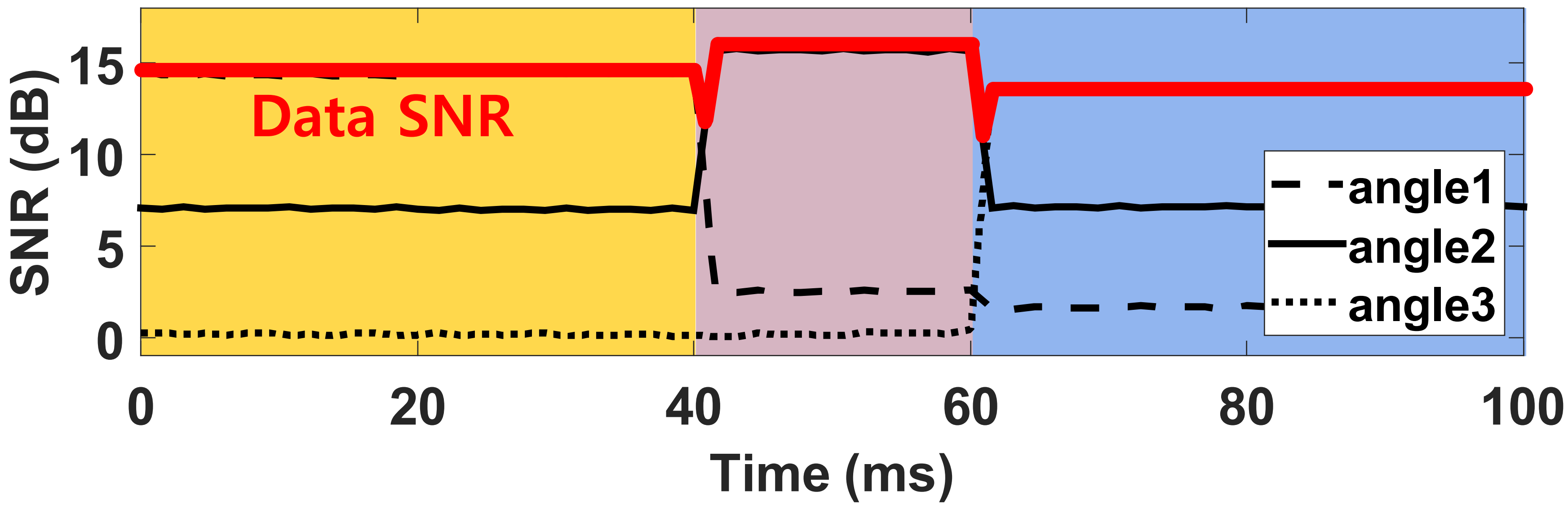
Scenario 2: Blockage around user is dynamically changed.



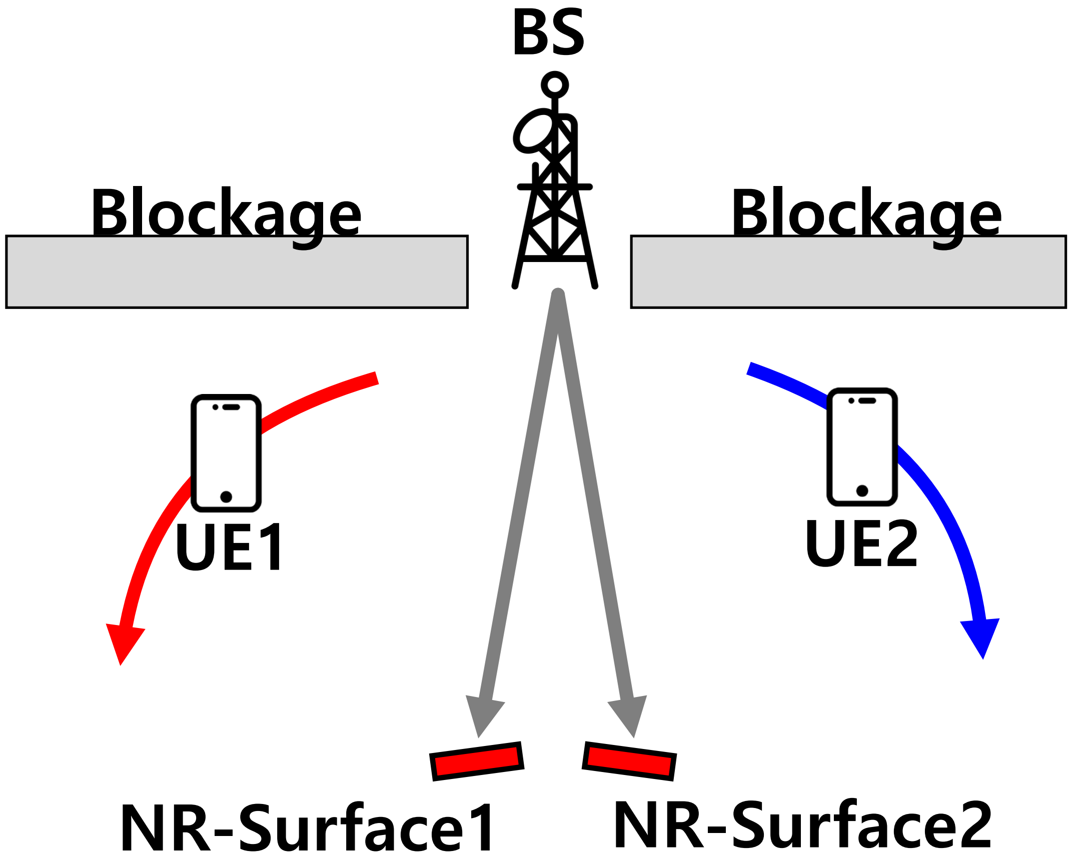

Servo motor rotates metallic sheets to change blockage environment in every 20ms

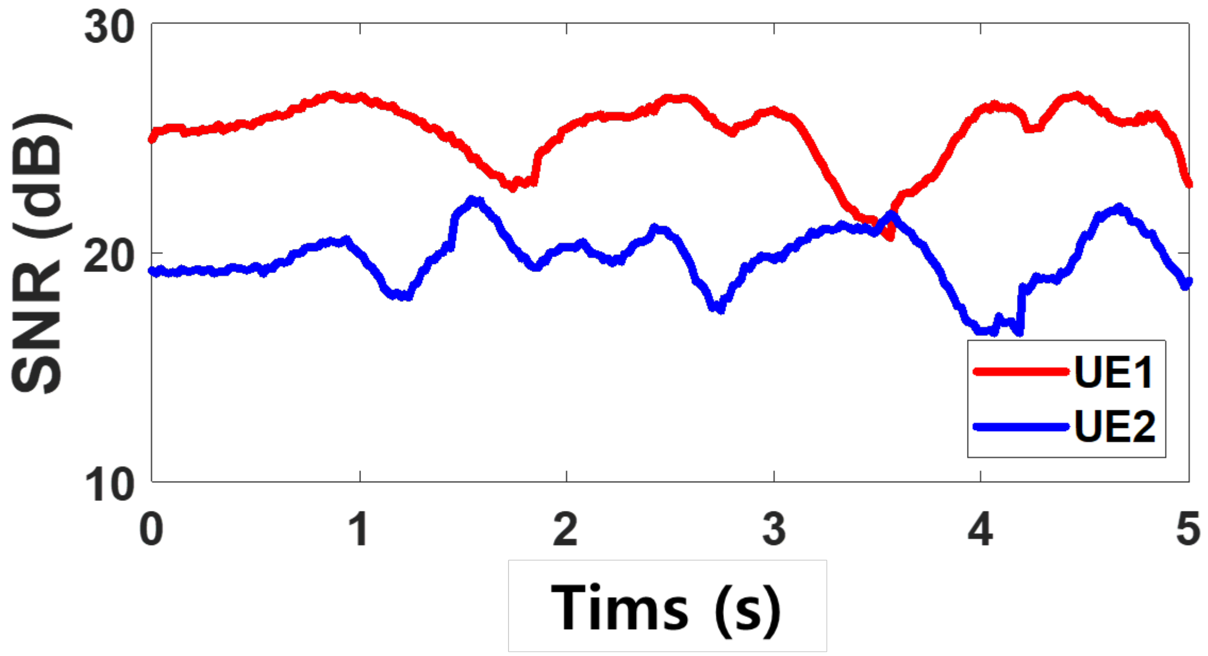
# Evaluation: NR-Surface in dynamic Env.

## Scenario 2: Blockage around user is dynamically changed.



# Evaluation: Multi NR-Surface & Multi UE




**Supports multi NR-Surface and multi-user**

# Conclusion

- We introduce **NR-Surface**, a new metasurface:
- **2.1 year lifetime on a single AA battery**
- **Real-time operation with NR beam management procedure**

# Thank you!

https://smile.kaist.ac.kr/