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

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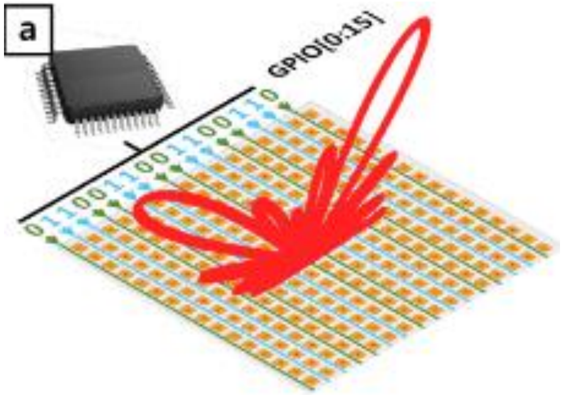
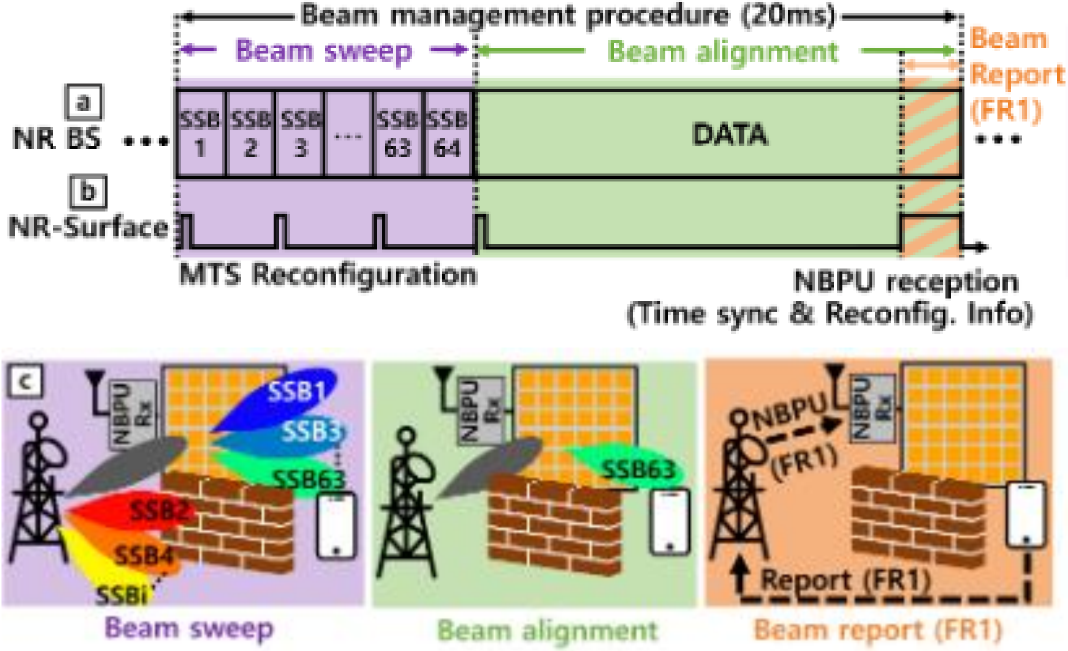
Background

- By the wide bandwidth and advanced modulation techniques, mmWave achieves high data rates and breakthrough the spectrum shortage
- Cost: substantial path loss – limiting the coverage, especially under complex indoor scenarios with significant obstructions
- Reconfigurable metasurface, that can adapt to varying channel and user mobility, has emerged as an economic solution to expand mmWave coverage.



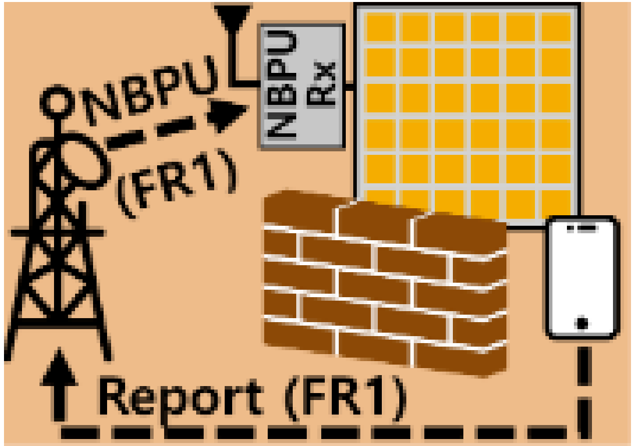
Background - NR beam management

- Beam sweep
  - first 5ms
  - the BS transmits up to 64 Synchronization Signal Blocks (SSB)
- Beam report
  - each UE select one and fed back to the BS via beam report.
- Beam Alignment:
  - the uplink and downlink data is exchanged during data beam alignment through the selected beam patterns.
- Misalignments and blockages
  - To mitigate, NR uses inter-band Carrier Aggregation that integrates the high-rate FR2 data plane with a FR1 control plane



Background - NB IoT

- NB-IoT is an NR protocol for serving IoT devices,
  - FR1 band and occupies only 180KHz bandwidth(BS side)
  - allows NB-IoT to utilize the guardband of the FR1 band
- NarrowBand Packet Unit(NBPU)
  - Embedded in the NB-IoT
  - BS side: 180kHz, Rx side: 15KHz
  - Interpret as On-off-key NBPU symbol at the Rx



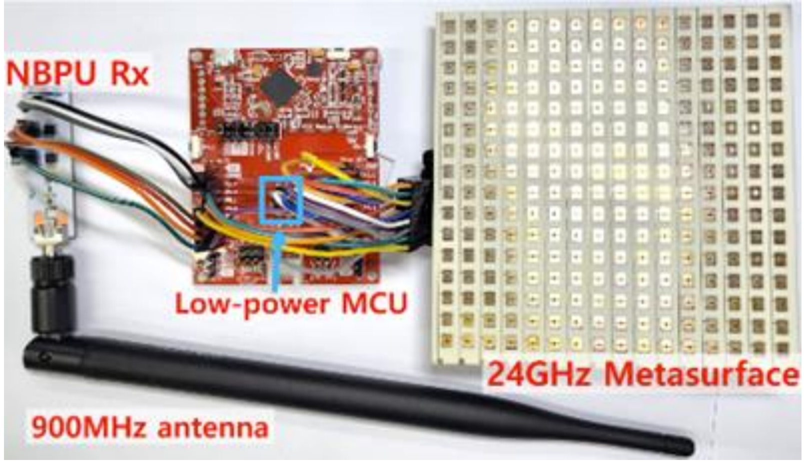
Beam report (FR1)

Synchronization between the metasurface and BS for real-time reconfiguration

NR-Surface

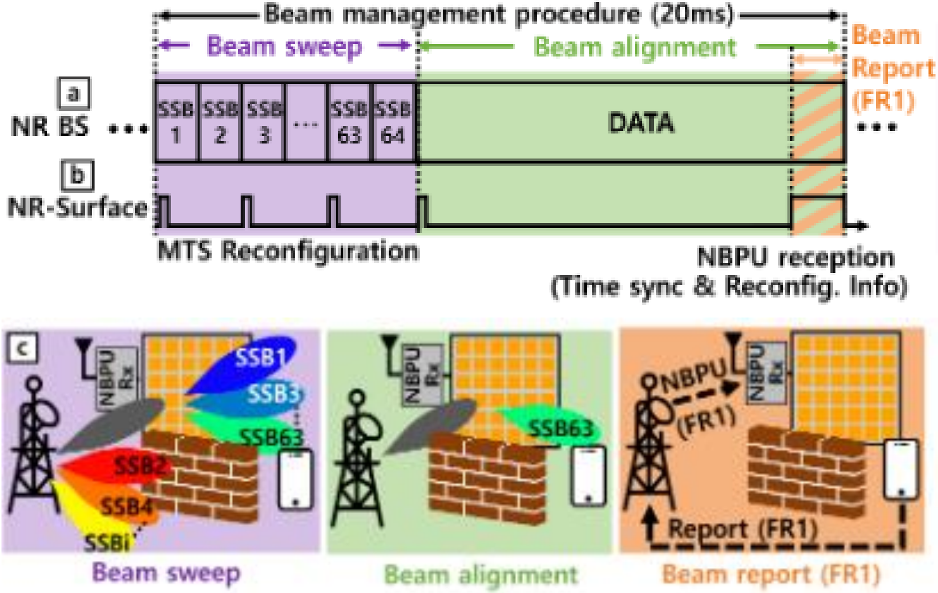
Overall Design

- The 900MHz antenna captures the NR-Surface’s control channel, NBPU, embedded in the NR FR1
- NBPU Rx synchronizes with the NBPU and decodes the reconfiguration info
- MCU reconfigures the metasurface via GPIO to steer the received beam based on the decoded info



Overall Design continued

- During the beam sweep, the metasurface is already reconfigured at the allocated SSBs, sweeping the beams beyond the blockages.
- In the beam alignment, the metasurface steers the beam toward UE’s direction as reported in the previous procedure.
- NBPU Rx acquires reconfiguration info and timing for the next beam management cycle, based on the UE’s beam report.



Metasurface

Ns-reconfigurable metasurface

- 16 by 16 array of unit-cells
- 1-bit digital output(GPIO) control
- Forms narrow beam patterns towards various directions for a wide-area coverage(±70°)
- Unit cell
  - two metal plates and a varactor diode
  - capacitance ranges from 0.22pF (0V) to 0.04pF (15V)
  - 1-bit phase shifter of 180° (π radians) phase shift
  - rise/fall time of <7ns
- All 256 unit-cells consume only ~3nJ

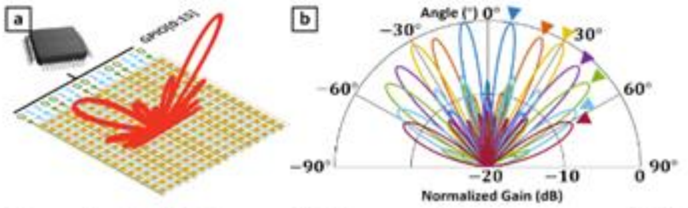


Figure 9: (a) GPIO-controlled metasurface structure and (b) example beam patterns. The main lobes are marked with triangles.

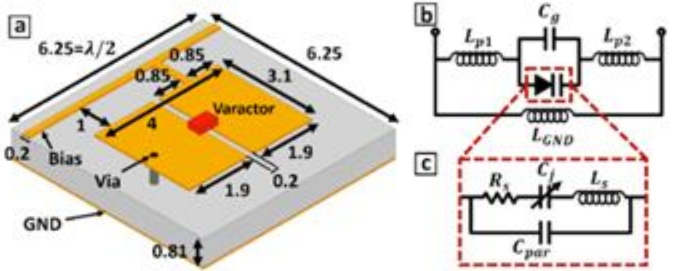


Figure 10: `NR-Surface` (a) unit-cell design and equivalent circuit models for (b) unit-cell and (c) varactor diode. Dimensions are in mm.

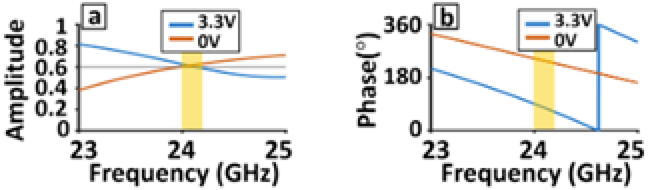


Figure 11: (a) Amplitude and (b) phase of the reflection coefficient when 0V and 3.3V are applied.

Duty-cycling

- Synchronization and reconfiguration only take ~10% of the time, so for the rest the NR-Surface is kept idle
- Because the 20ms beam management cycle is fixed and known, the NR-Surface can precisely schedule when to be in idle (low-power) mode and when to wake up.
  - Even though the MCU (Microcontroller Unit) has a slow wake-up time (10μs), it can still be ready in time because it knows exactly when it needs to be active.

Energy-efficiency perspective

- Synchronization and decoding: 119.3μW
- Reconfiguration: 117μW
- Idle period(during beam alignment): 6.4μW to maintain the configuration
- 2.1-year battery lifetime with a AA

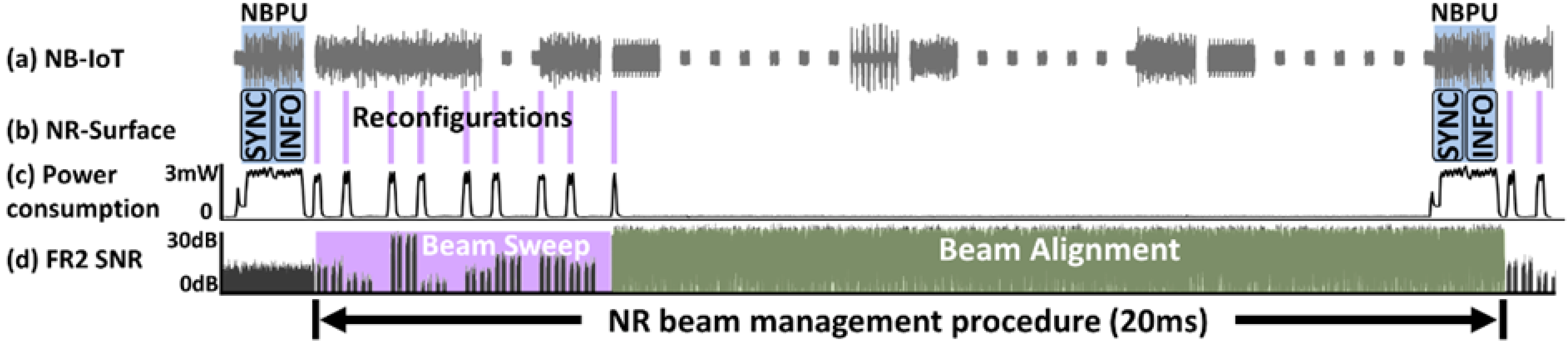
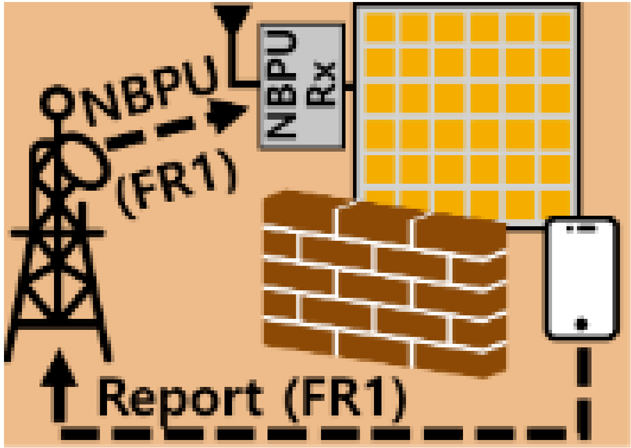


Figure 12: Overall operation of `NR-Surface`. (a) NB-IoT containing the NBPU frame, (b) `NR-Surface` duty-cycled operation synchronized with NR BS, (c) Measured power consumption, and (d) FR2 signal with improved SNR from aligned beams.

Synchronization

Background - NB IoT (Revisit)

- NB-IoT is an NR protocol for serving IoT devices,
  - FR1 band and occupies only 180KHz bandwidth(BS side)
  - allows NB-IoT to utilize the guardband of the FR1 band
- NarrowBand Packet Unit(NBPU)
  - Embedded in the NB-IoT
  - BS side: 180kHz, Rx side: 15KHz
  - Interpret as On-off-key NBPU symbol at the Rx



Beam report (FR1)

NBPU Symbol

- Use the FR1 guardband as the control channel to minimize disruption from the NR traffic
    - Downlink-only control channel
- 12 subcarrier 4QAM OFDM(4 possible phases) with 15KHz spacing
- Envelope detector
    - “zero-power downconversion”
    - Produce signal based on the overall shape of NB-IoT signal

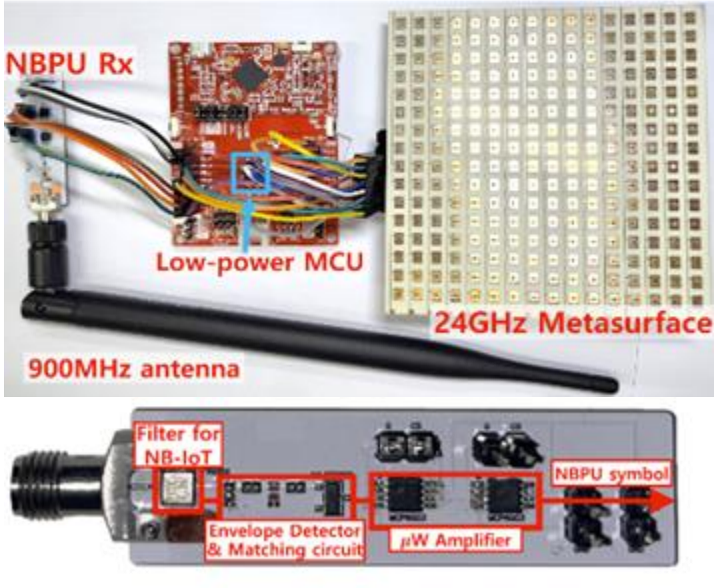


Figure 3: NBPU Rx to yield NBPU symbol from NB-IoT, comprising a filter for NR guardband operation, envelop detector for zero-power downconversion, and μW amplifiers to boost SNR.

NBPU Symbol - Cont.

- Envelope detector produces harmonics at frequencies that are the differences between pairs of subcarrier frequencies.

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

  - kΔf : frequency where k: subcarrier separation and Δf is the spacing(15kHz), (φi −φi−k): phase difference between ith and i-kth subcarriers
- Goal: create an NBPU symbol with max power(max SNR) for best detection.
  - Choose NB-IoT subcarrier phases to make the envelope (NBPU symbol) as strong as possible
  - Align the 1st harmonics in phase for constructive interference

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

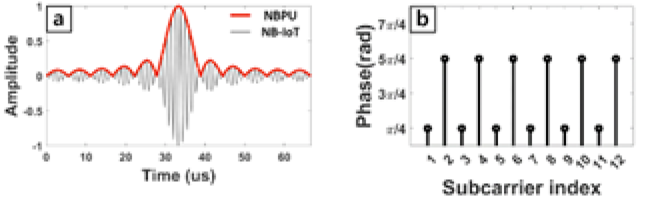


Figure 4: (a) The selected NBPU symbol with the maximum SNR and the corresponding (b) NB-IoT symbol (4QAM OFDM with 12 subcarriers).

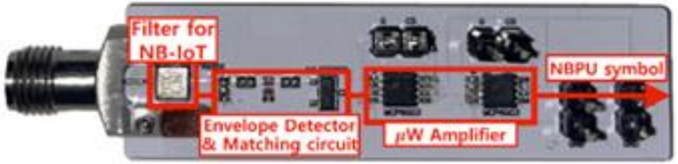


Figure 3: NBPU Rx to yield NBPU symbol from NB-IoT, comprising a filter for NR guardband operation, envelop detector for zero-power downconversion, and μW amplifiers to boost SNR.

NBPU Frame

- Each frame contains 5 symbols for synchronization and 5 for reconfiguration information
- Columns in the middle is the mandatory Narrowband Reference Signal for channel sounding
- Inserted every 20 NV IoT subframes

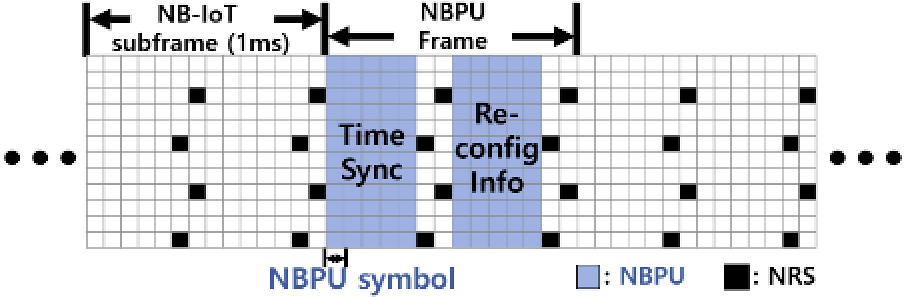


Figure 5: An NBPU Frame fits into one NB-IoT subframe. It has sync and reconfiguration info. (i.e., timing and phase).

ns-synchronization

- Goal: ~260ns, sampling rate of 3.84Msps
    - Sampling rate is too high: consumes too much power
- Equivalent-Time Sampling
    - Sampled at 14Ksps, but takes sample from 5 consecutive symbols with spacing of 260ns by MCU clock. And these five samples collectively to mimic a 3.84Msps sampling
    - Matched filtering on the samples for optimal detection and synchronization - ensure the signal power is concentrated in the central portion of the symbol

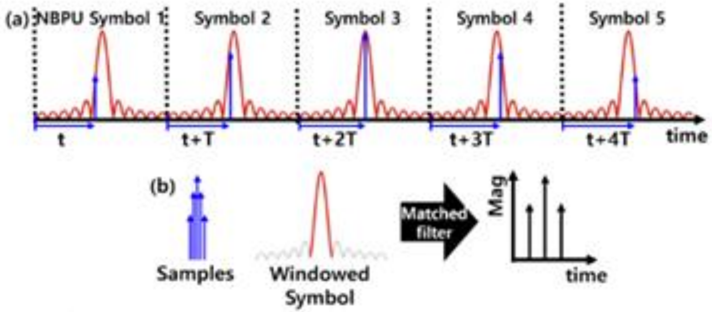


Figure 6: (a) Equivalent time sampling utilizes the accumulated sampling time offset T where t is common offset for all five symbols. (b) The windowed symbol makes the computationally complex matched-filtering light.

Evaluation

Hardware configutation

- Metasurface
    - 16x16 unit-cells on RO4003C substrate (32mil thickness ~0.8128mm)
    - Each column connected to a single bias line
    - Configured by MCU GPIO interface
    - MAVR011020-1411 varactor mounted on each unit-cell center
- NBPU Rx
    - TFR915X Surface-Acoustic-Wave filter (915MHz center, 320KHz bandwidt
    - MA4E2200 Schottky diode for envelope detection
    - Two-stage MCP6G03 amplifiers (+68dB total gain, adjustable to +40dB)
    - 22nH parallel and 48nH series inductors
    - Achieves +14dB SNR in typical scenarios
- Power Consumption
    - Max consumption during synchronization and decoding: 2.4mW, Reduced to 119.3µW (20.4x reduction) through duty-cycling
    - Reconfiguration power: 1.67mW, reduced to 117µW with duty-cycling
    - Low-power mode: 6.4µW
    - Total average consumption: 242.7µW
    - Estimated 2.1-year lifetime on a single AA batter

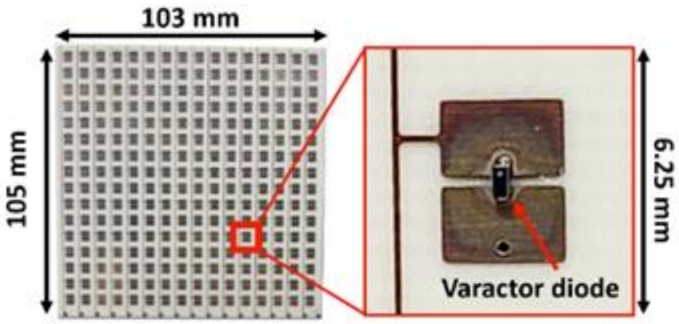
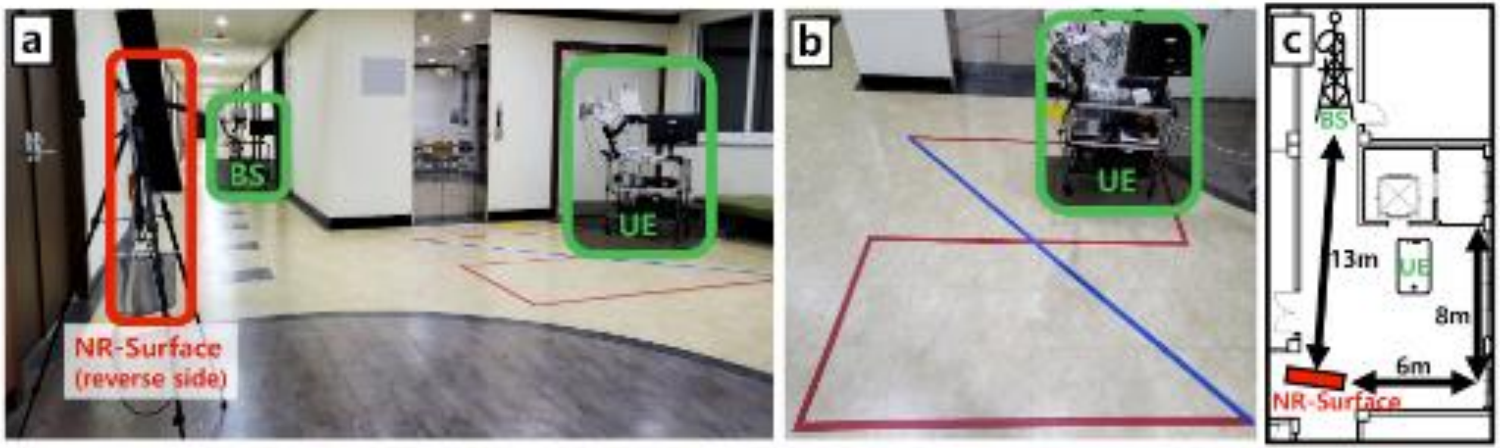


Figure 13: Metasurface and a unit-cell.

NR Evaluation Setup

- FR2 (mmWave) Transmissions
  - Base Station (BS):
    - USRP X300 series SDR
    - 50MHz channel bandwidth, 64 SSBs for beam sweeping
    - ADMV1013 for upconversion to 24.125GHz
    - 24GHz microstrip patch array antenna (+22dBi directivity)
    - +5dBm transmit power
  - User Equipment (UE):
    - ADMV1014 for downconversion
    - USRP X300 series with custom GNURadio block
    - Measures SSB SNRs and reports via 905MHz ISM band
- FR1 (Sub-6GHz) Transmissions
  - Base Station:
    - USRP running srsRAN (O-RAN compliant)
    - 915MHz center frequency, 180KHz bandwidth for NB-IoT
    - VERT900 antenna (+3dBi gain)
    - Receives beam reports on 905MHz
    - NB-IoT payload contains NBPU (Narrowband Positioning Unit) data
    - Best SSB index reflected in subsequent NBPU transmissions



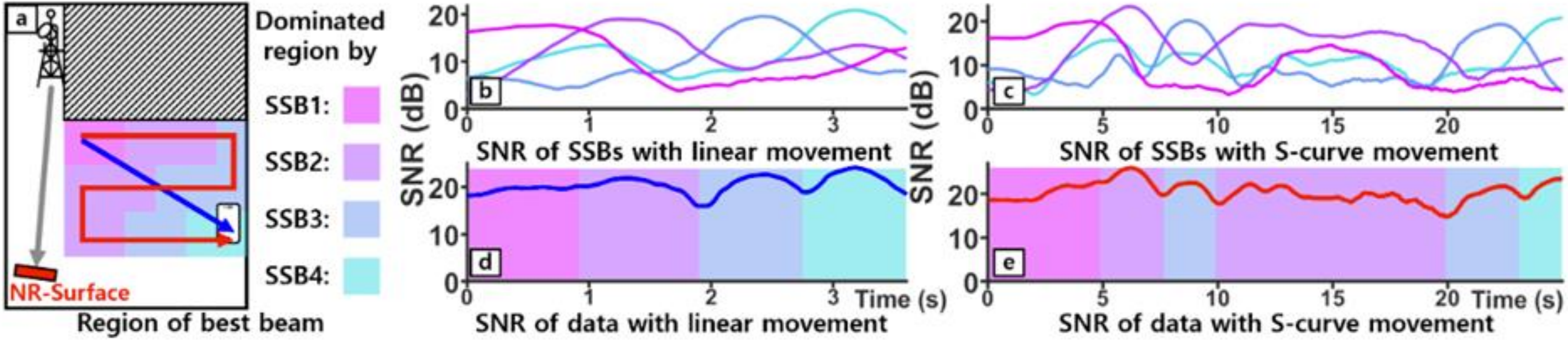


Figure 14: `NR-Surface`'s real-time reconfiguration performance under mobile UE scenario. (a) In the indoor experiment setting, `NR-Surface` can increase coverage with multiple beams. Under various UE movements (e.g., linear & S-curve), the best beam is changed by the location (b,c) and `NR-Surface` reflects it in real time (d,e).

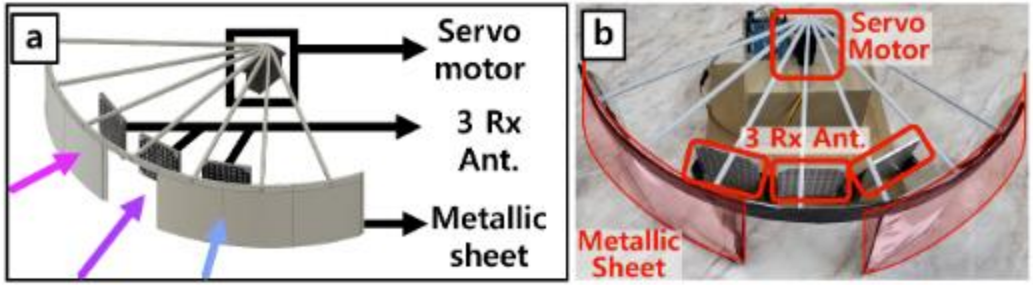


Figure 17: (a) outline of both blockage and UE design and (b) its implementation.

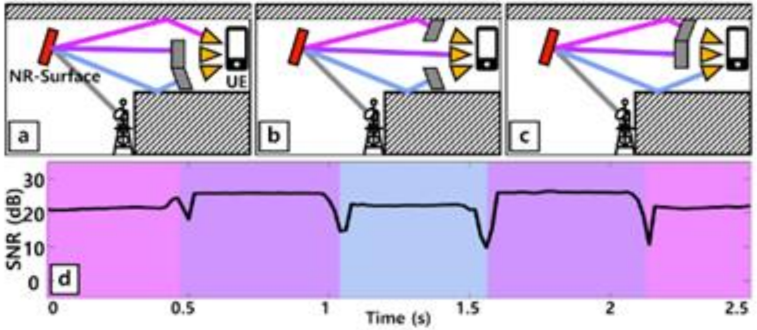


Figure 18: (a) - (c) show a scenario that only one antenna among 3 is not blocked. (d) shows the achieved SNR by the blockage environment change.

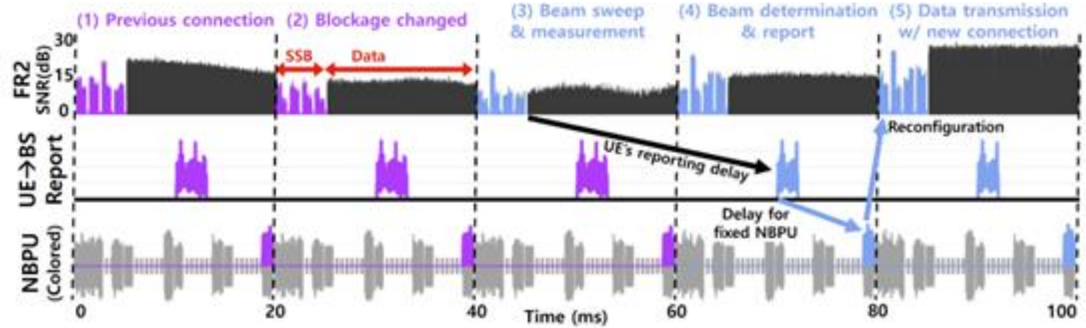


Figure 16: Real-world measurements of transmitted signals at the moment of blockage change. (1)-(3) Due to the dynamic blockage, the data SNR drops and the best SSB changes during the beam sweep. (4) The best SSB is determined and reported to the BS, which is also delivered to `NR-Surface` within 20ms. (5) `NR-Surface` is reconfigured to recover data SNR gain.

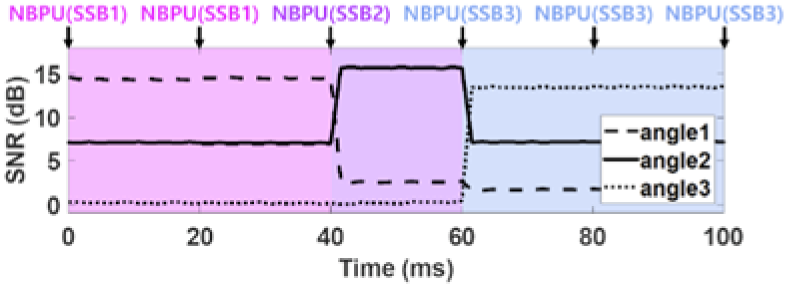


Figure 19: SNR of three beam patterns when `NR-Surface` is reconfigured in real-time. `NR-Surface` continuously receives NBPU and reconfigures beam patterns every 20ms.

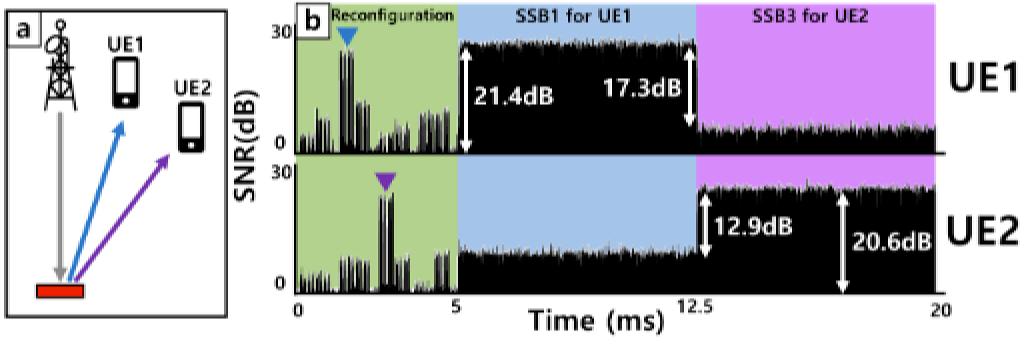


Figure 20: (a) `NR-Surface` operation scenario with multiple UEs (b) SNR fluctuation of the received FR2 per each UE.

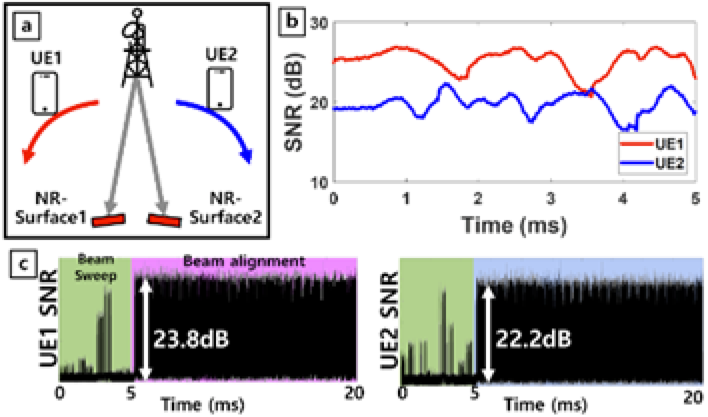


Figure 21: (a) Multiple `NR-Surface` scenario with multiple moving UEs (b) SNR fluctuation of the received FR2 per each UE (c) Received SNR of each UE, while both users moved during 5 sec.

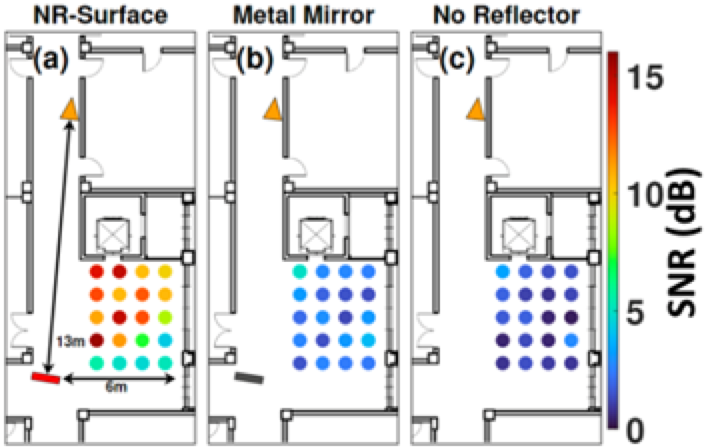


Figure 22: Comparison of SNR at various Rx locations (do between (a) `NR-Surface` placed at red rectangle (b) me mirror of the same size with `NR-Surface` (c) no reflect placed. The Tx is placed at orange triangle steered towar `NR-Surface`.

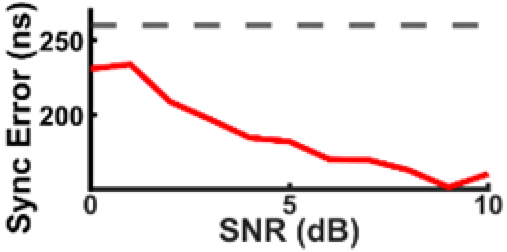


Figure 23: NBPU Synchronization error versus SNR.

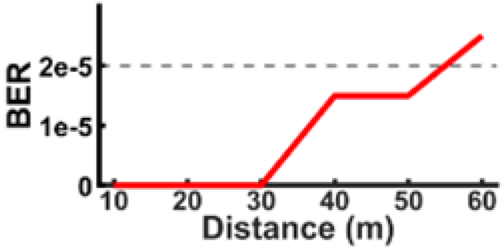
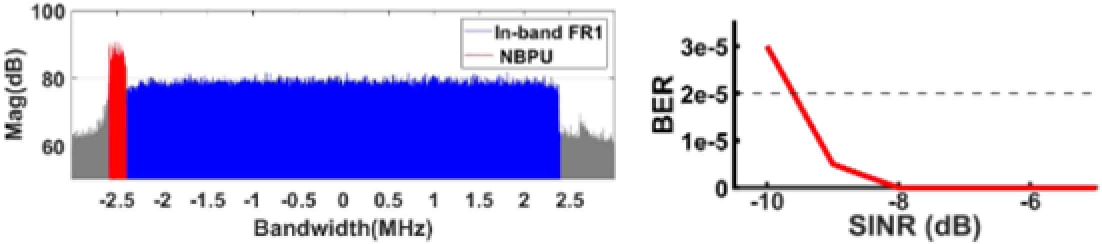


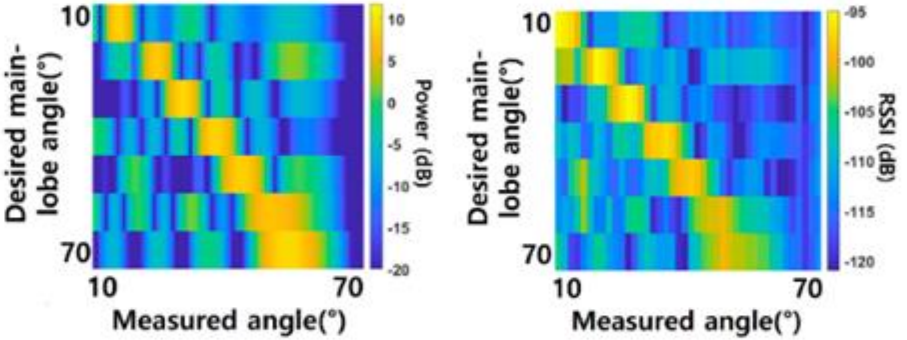
Figure 24: `NR-Surface` BER versus distance to the BS.



(a) Coexistence of NBPU and in-band FR1.

(b) BER versus SINR in NR guardband

Figure 25: Evaluation setup and BER performance against NR interference.



(a) Simulated beam pattern (b) Measured beam pattern

Figure 26: Beam patterns with desired main-lobe angles from 10° to 70°

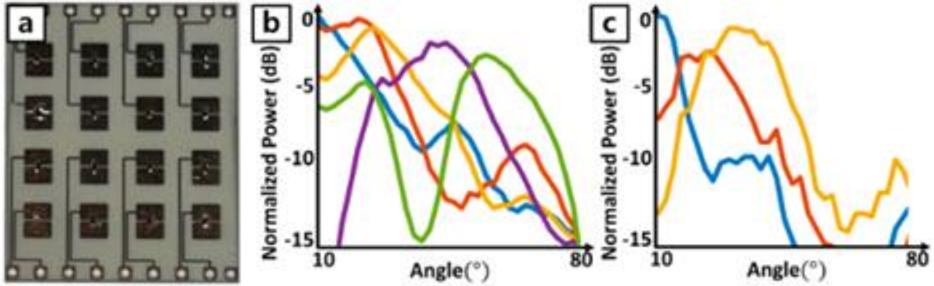


Figure 27: (a) Fabricated 3D metasurface and (b) measured 3D Beam pattern of `NR-Surface` steered towards different azimuth angles and (c) different elevation angles direction (smoothed with window=10°).

Opinions

1. Paper structure is not quite clear
2. The explanation is not that clear to me
3. Limited functionality I guess?
4. Novelty of utilizing guardband for the NBPU design

Discussion