Enabling High-Quality Untethered Virtual Reality (MoVR)

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Motivation/Introuction

- Streaming Virtual Reality (VR) systems
  - Multi-Gbit/s data rates from game console to wearable headset
  - 100 frames per second frame rate to make it realistic, avoid nausea
- Replace cable from console to headset with RF link
  - mmWave: only practical RF technology that supports those rates
    - > 24 GHz, 24 GHz in this paper
    - Highly directional, like light
    - **Problem:** Blocked by hand, head, obstacles, like light
  - **Challenge:** User is mobile, creates dynamic blockages
- Interest from Google, many other smaller companies

Design (§3)

- Overview shown in Figure 2: wall-mounted mmWave relay module (referred to as the "*mirror*" throughout)
  - AP chooses to send direct (above), or thru relay if direct path blocked
- **Quantifying blockage** (Figure 4)
  - Hand: -14 dB, head: -20 dB, body: -25 dB
  - **Status quo:** AP finds a "bounce" path off a wall or object (best case of *that* is **-15 dB**, since longer distance and bounce scattering)

MoVR Mirror Design (§4.2)

- Overall design (Figure 6): receive antenna to amplifier to transmit antenna

- Phased array antennas for both transmit & receive
  - Create narrow transmit, receive beams
- No radio, just a relay
- **Problem:** Some signal transmitted from mirror is received by mirror, resulting in **feedback loop** that saturates the amplifier, generates garbage (Fig. 6b, right)
- So set the amplifier so that forward *gain* minus *leakage* is negative, so the feedback loop dies away
  - So need forward gain **less than** leakage
  - **But leakage varies** with angles of antennas (Figure 7)
  - So need **adaptive algorithm** to set the forward amplifier gain
- **Challenge:** No radio to measure signal levels on the mirror
- **MoVR approach:** Monitor current draw of the amp, increase gain continuously until **high current draw** indicates saturation, then back off the gain. Repeat continuously.

Alignment and Tracking (§§5.1, 5.2)

- Very sensitive to alignment (-20 dB for 10 degrees misalignment as shown in Figure 9), so need precise alignment
  - *For Direct Mode:* Need AP to headset alignment
  - *For Relay Mode:* Need AP to mirror, **and** mirror to headset alignment
- **b) AP to headset** alignment:
  - Just leverage VR laser tracker: gives location *and* orientation
- **a) AP to mirror** alignment:
  - Challenge: The mirror can't receive, just relay
  - AP transmits on some frequency, mirror reflects **back to the AP** on a neighboring frequency, AP measures power of the reflection
    - Frequency shift overcomes problems with listening and transmitting on the same frequency
    - **Need two angles:** Angle at AP θ_1 , angle at mirror θ_2
      - Exhaustive two-dimensional search in those two angles to maximize power
- **c) Mirror to headset** alignment:
  - Leverage AP to headset alignment from VR laser tracker, from step (a) above
  - Then, translate coordinates from AP to mirror: **have angle** from step (b) above, **need distance** as

well to translate coordinates
    - Approach: **Triangulate mirror location** as shown in **Figure 10**
        - ϕ_{AP} is θ_1 from previous step
        - ϕ_H is found by a similar two-dimensional exhaustive search with AP sending to mirror, searching over mirror and headset angles

Evaluation (§7)

- HTC VIVE VR system hardware with custom mirror hardware in a 5 meter by 5 meter room
- LoS blocked 20 times over 5 minutes while playing a game (**Fig. 12** shows blockage durations, 245 milliseconds median, *i.e.* 25 frames, so would cause a noticeable glitch)
- Mirror Performance (no blockage = 0 dB reference level in Fig. 13)
    - Compare no blockage versus blockage without MoVR
        - Fig. 13: -27 dB loss from bouncing off a wall
    - Compare no blockage versus blockage **with** MoVR
        - Fig. 13: Improvement in SNR from amplification, shorter paths
    - Why sometimes 3 dB worse? No explanation, possibly amplifier saturation, beam alignment problems
- Beam Alignment and Tracking Performance (§7.3)
    - Two degree accuracy for AP to mirror beam alignment (Fig. 14), ground truth coming from laser distance measurement tool
    - Whole system (Fig. 15) versus exhaustive search in **all three angles:** MoVR 4 dB worse sometimes about the same number of times to possibly explain Fig. 13
- Beam Alignment Latency
    - **Important:** needs to be fast to track – claimed 0.9 μs to align, 1.7 μs to reconfigure phase shifters, compared to 1 ms delay in the VR tracker so MoVR is much faster
- System Performance (§7.4)
    - Compare no mirror (bounce off walls), fixed gain mirror, MoVR with **LoS path blocked by hand**
    - Where's the AP in Fig. 16?
    - Better with MoVR's adaptive gain control