

# Multi-User Augmented Reality with Communication Efficient and Spatially Consistent Virtual Objects

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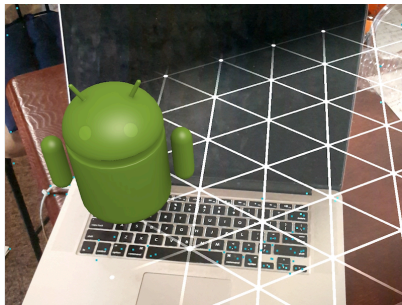
# Multi-user Augmented Reality(AR)



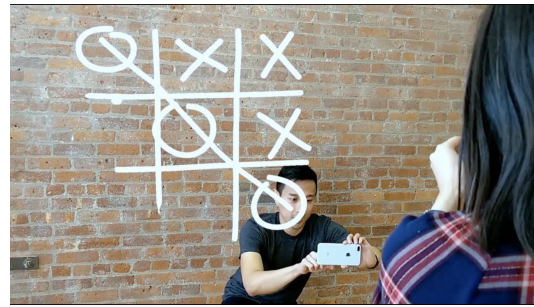
Pokemon Go Buddy Adventure



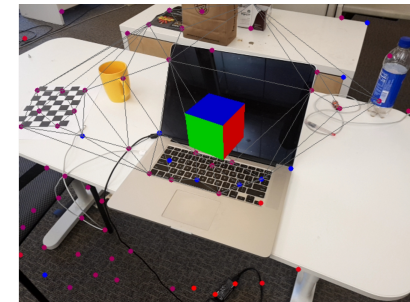
Minecraft



CloudAnchor



Just a Line



VINS-AR\*

\*Li, P., Qin, T., Hu, B., Zhu, F., and Shen, S. Monocular visual-inertial state estimation for mobile augmented reality. ISMAR 2017

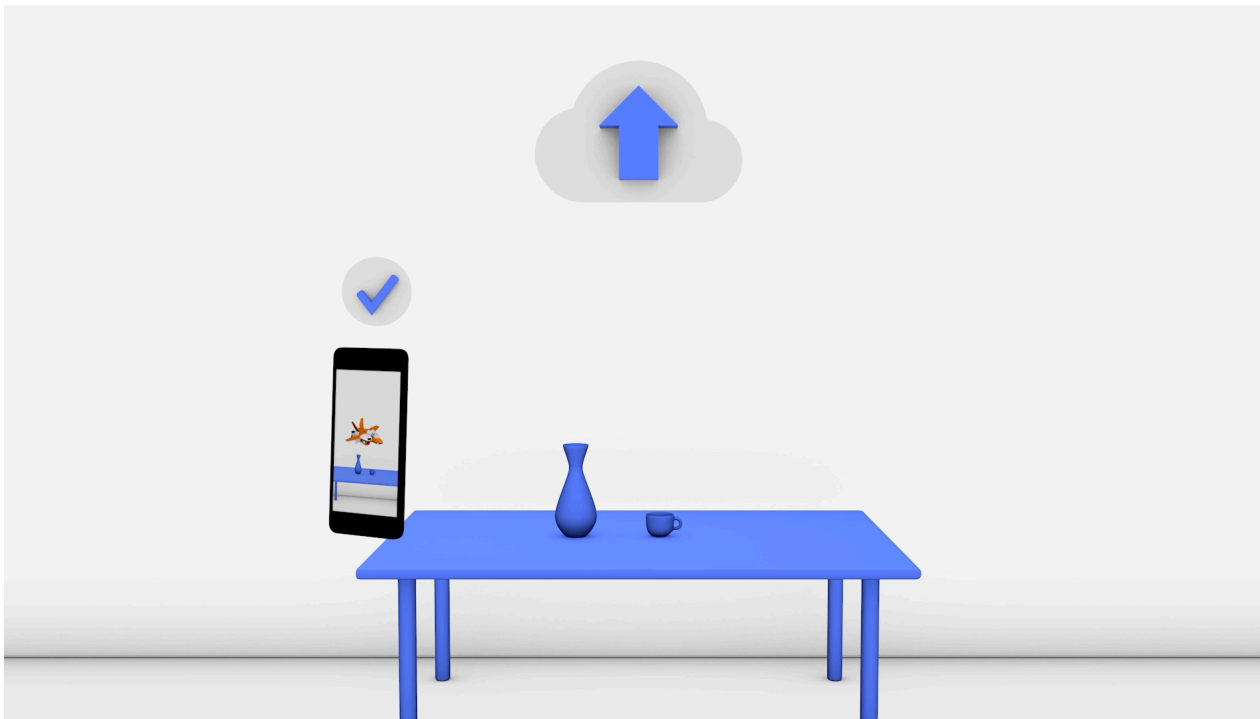
# Multi-user AR Initialization process\*



Current AR platforms such as ARCore, ARKit, and HoloLens rely on simultaneous localization and mapping (SLAM). VINS-AR is also based on SLAM.

- 1, Extract features from keyframes and construct a point cloud
- 2, Estimate camera location and orientation (pose)
- 3, Project virtual object and draw it on the screen

# Multi-user AR Initialization process\*



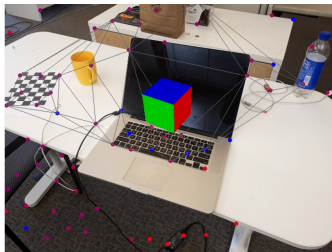
Receive point cloud from Host

Compute transformation from Host's world to Resolver's world.

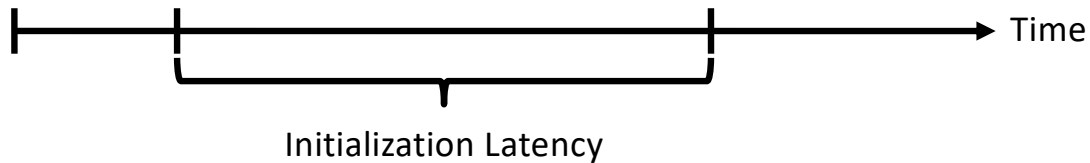
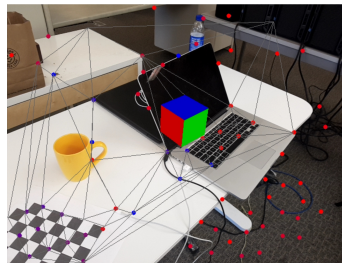
# Background: Initialization Latency

- We define the time from the host start sharing the virtual object to the other user(s) finish relocating the virtual object as the initialization latency.

1. Alice places virtual object

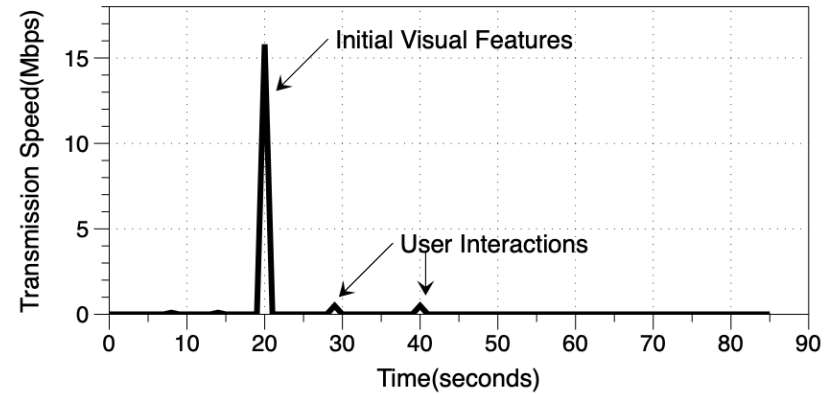
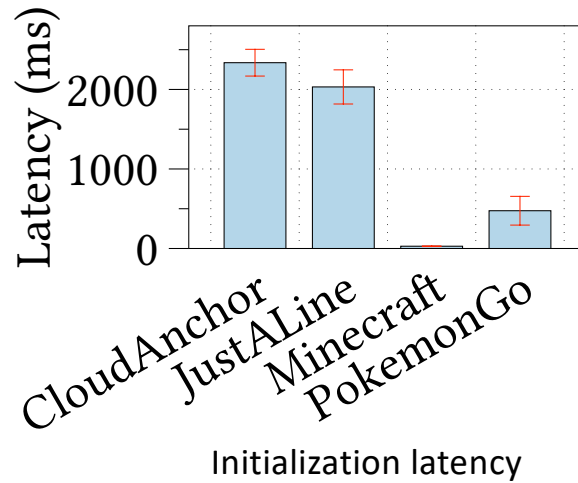


2. Bob sees virtual object



# Measurements: Initialization Latency

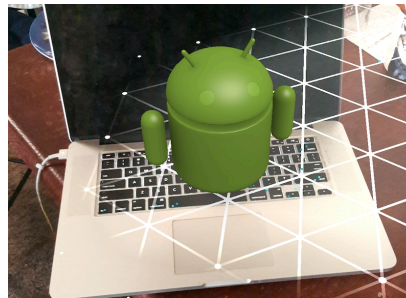
- We measured the initialization latency of popular multi-user AR apps on Android
- 2 Pixel 4 over a WiFi connection with 10 Mbps up/down



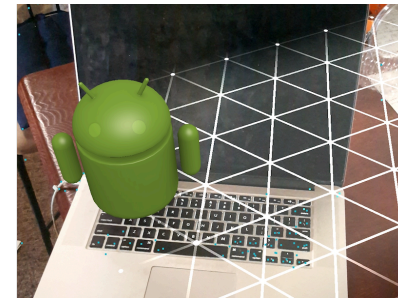
What has been sent? Can we speed up this process?

# Background: Spatial drift/inconsistency

We measured VINS-AR and ARCore and found spatial drift(across time) and inconsistency(across users) problems

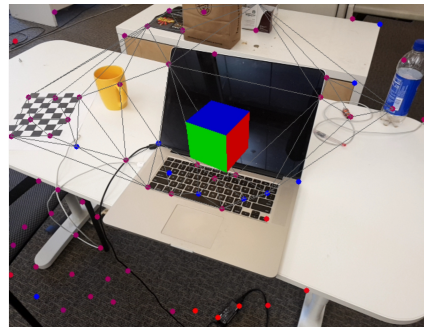


Time=T1

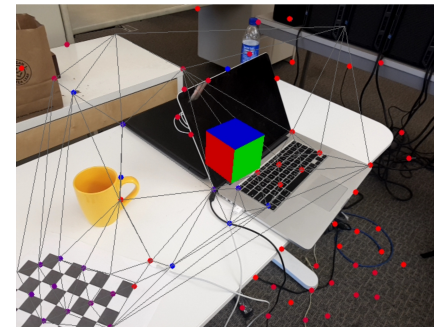


Time=T2

Drift over time



Phone1



Phone2

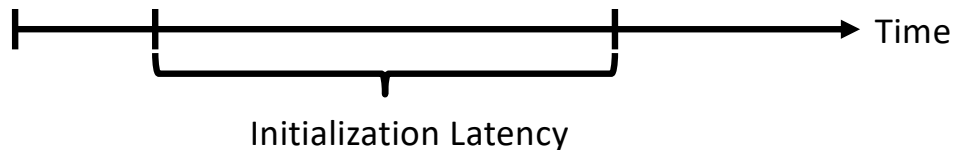
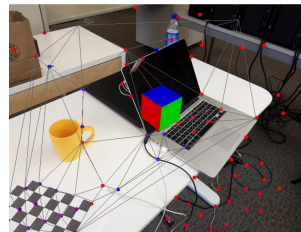
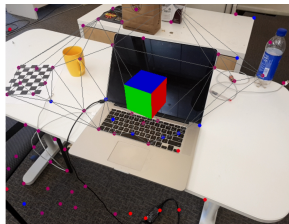
Location difference across different devices

The data sent during initialization have what impact on the spatial inconsistency?

# Problem Statement

- Problem: multi-user AR apps exhibit long initialization latency (up to 2 seconds) and high spatial inconsistency (up to 30cm) due to large "spike" of data being uploaded and joint computations being performed on that data
- Goal: reduce the initialization latency while maintaining low spatial inconsistency

1. Alice places virtual object
2. Bob sees virtual object

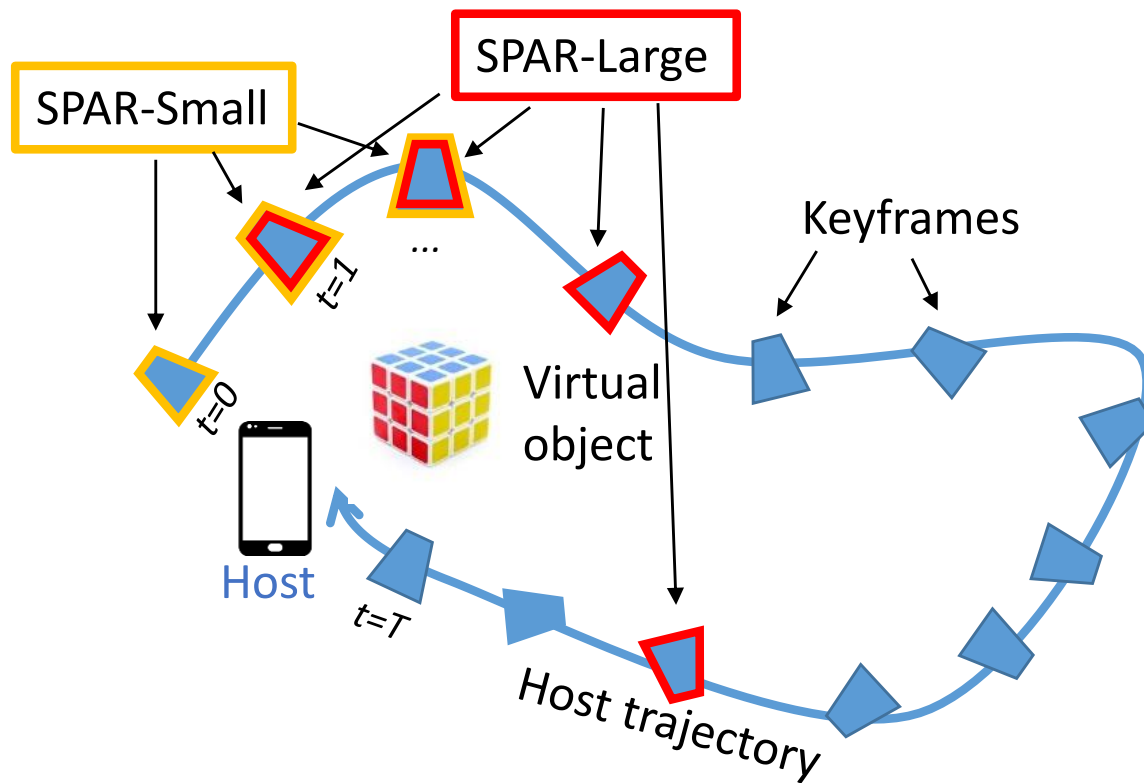


# Proposed approach: SPAR

Proposed approach: main system modules of SPAR (Spatially Consistent AR)

1. adapt the AR data being uploaded based on virtual object visibility and distance --> reduced latency
2. synchronize and update the coordinate systems of the AR devices --> low spatial inconsistency
3. tool to automatically quantify spatial inconsistency

# 1) Adaptive AR communications: Sending strategies



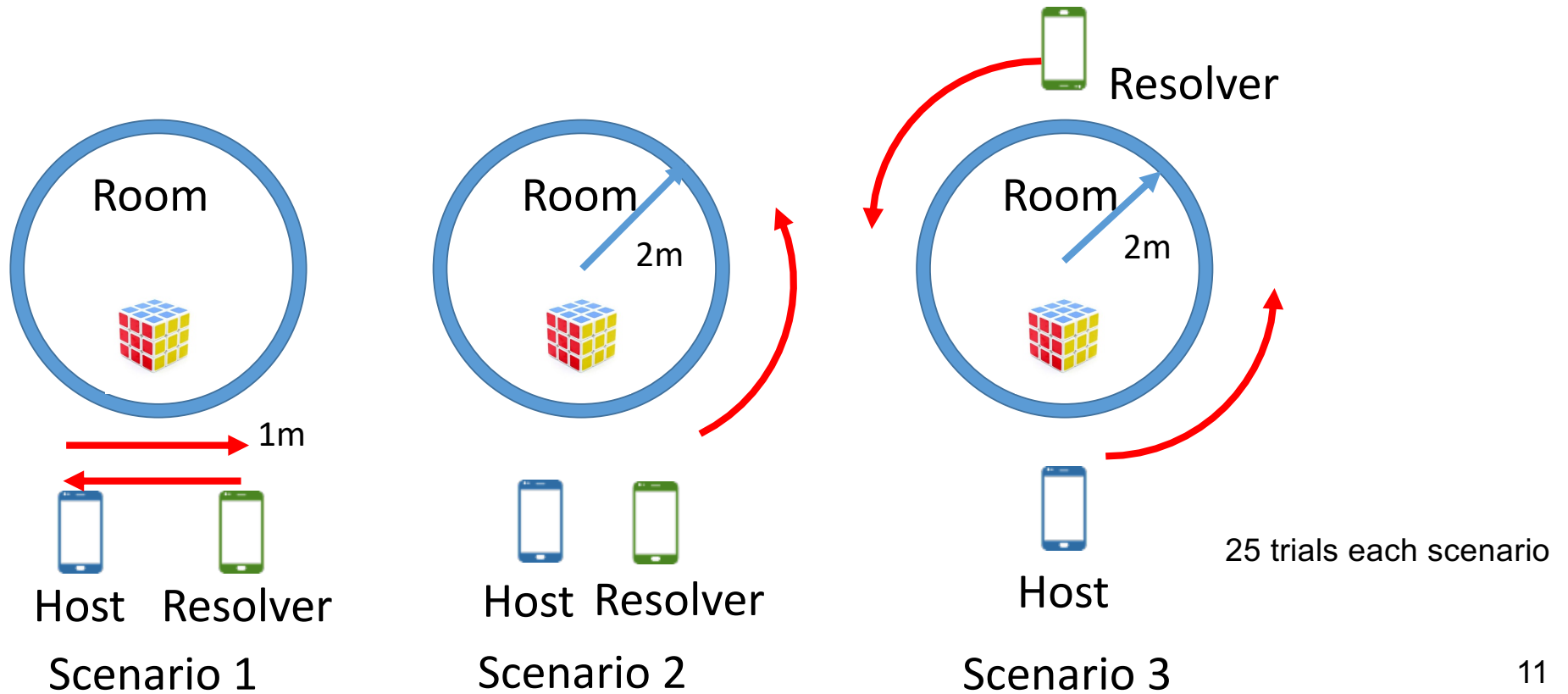
Host needs to send keyframes to Resolver during initialization process.

SPAR-Small: Only send frames that are less than 1m away from the virtual object

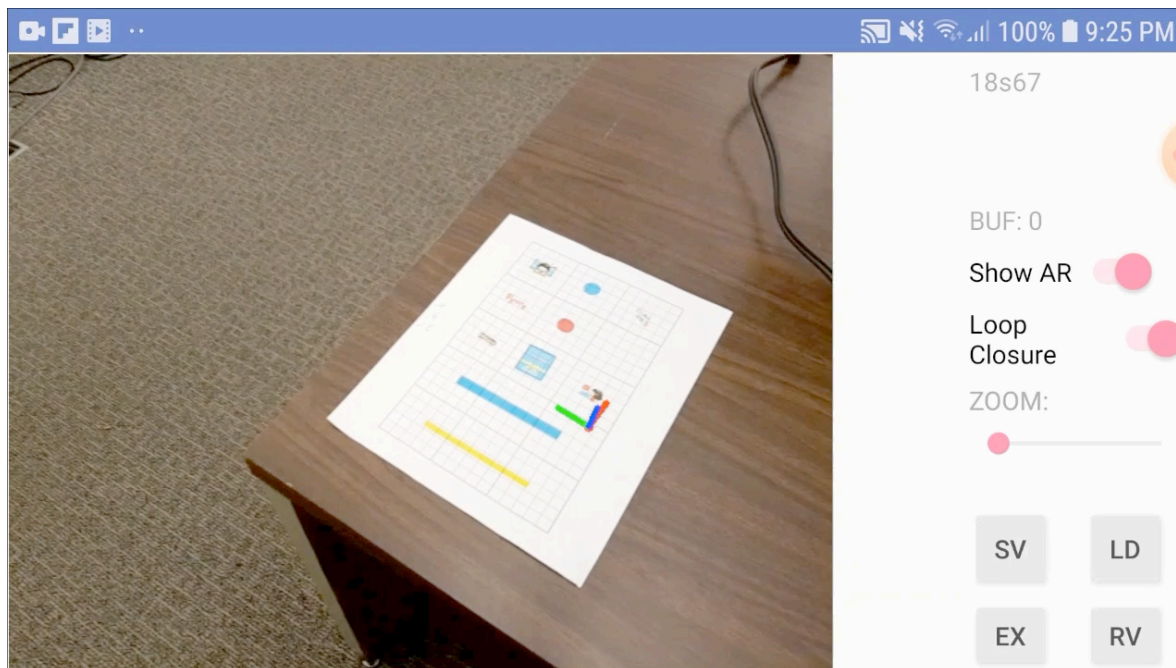
SPAR-Large: Only send frames when virtual object is shown on the frame.

ALL: send all keyframes.

# 1) Adaptive AR communications: User mobility pattern



# 1) Adaptive AR communications: User mobility patten example

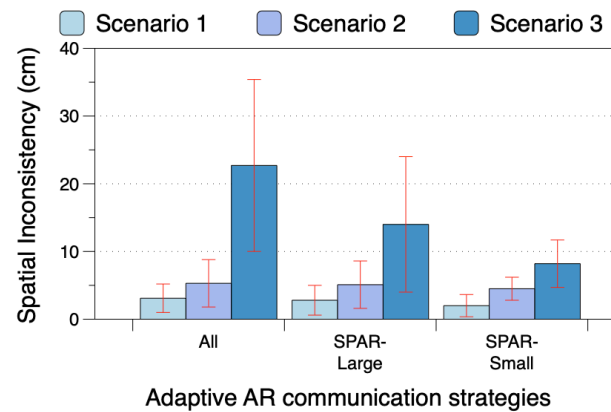
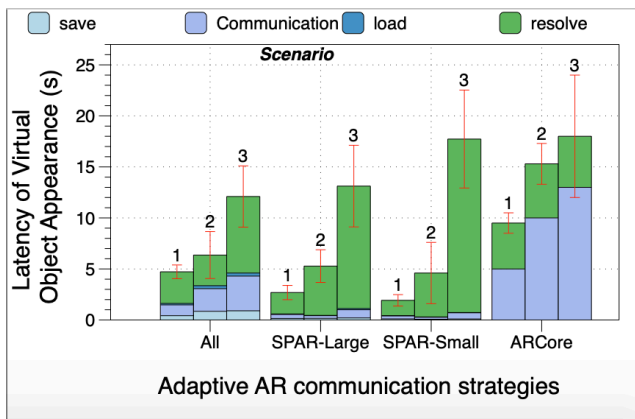


Host walks around the room.

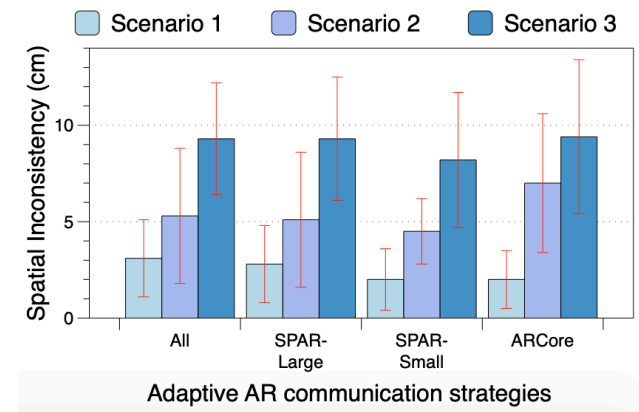
Resolver is not shown. It can start from the same place(scenario 2) or a different place(scenario 3)

Video speed 1.5x

# 1) Adaptive AR communications: Results



First resolve

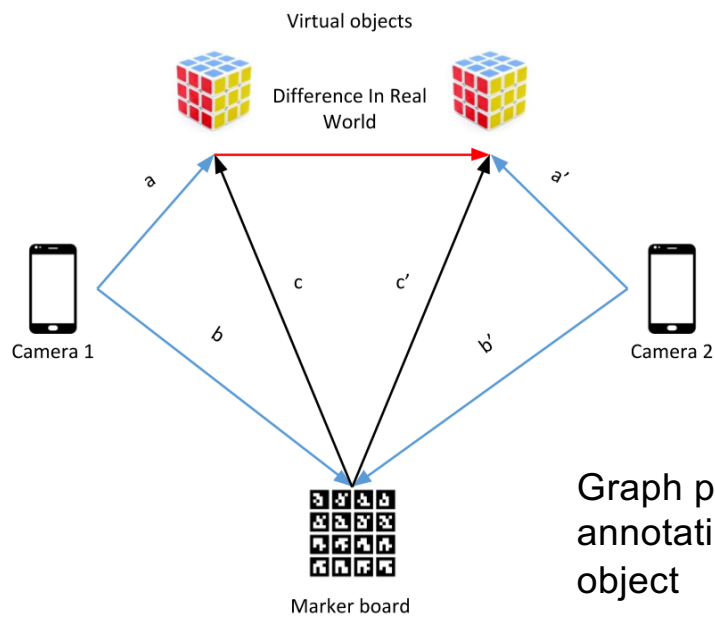


Lowest spatial inconsistency

**SPAR can reduce initialization latency up to 55% in scenario 1 and 2  
Spatial inconsistency can be reduced by up to 60%.**

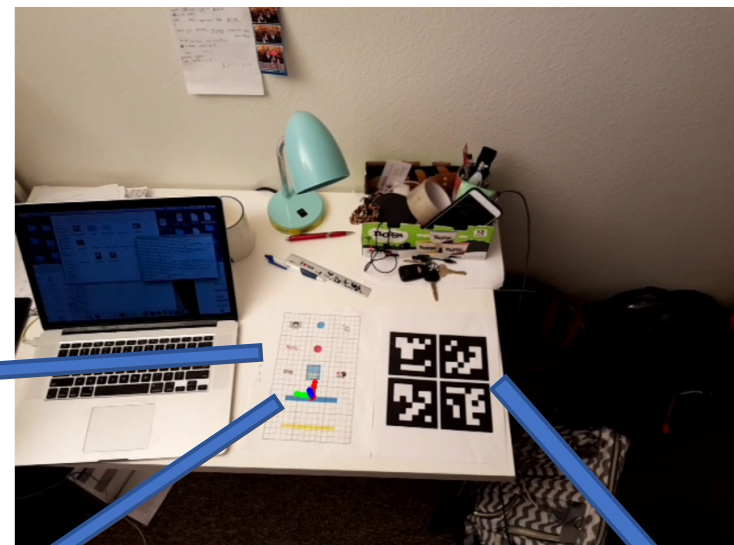
### 3) A tool for spatial drift/inconsistency measurement

Hand annotating frame by frame is time-consuming  
we developed a methodology to estimate the spatial drift/inconsistency that only requires paper printouts



Graph paper for  
annotating virtual  
object

Virtual object

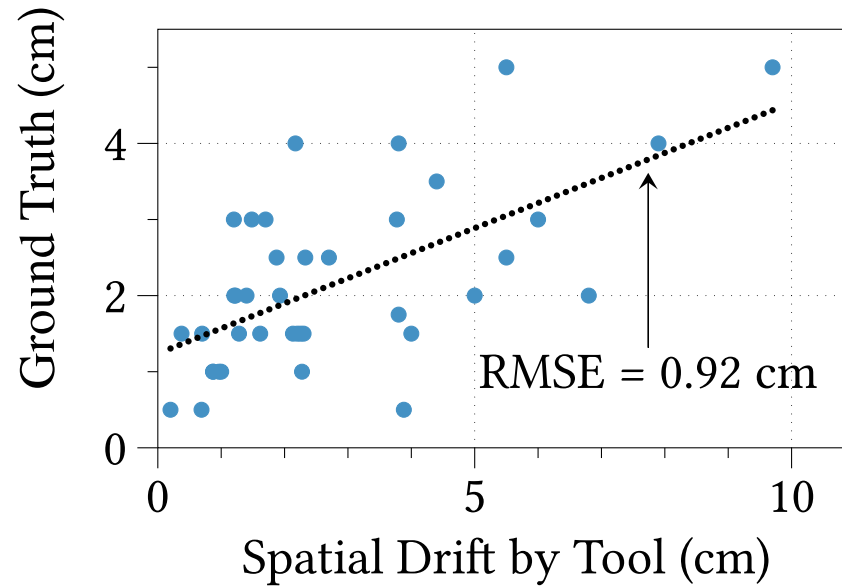


Environment setup

markerboard

### 3) A tool for spatial drift/inconsistency measurement

we measured the ground truth by hand-annotating the frames over 10 videos.



**The tool accurately estimates the spatial drift with an RMSE of < 1 cm**

# Key Take-Aways

multi-user AR apps exhibit high initialization latency and high spatial drift/inconsistency

SPAR adapts the uploaded data and performs coordinate system alignment to address these problems

SPAR can reduce the latency by up to 55%, while decreasing the spatial inconsistency by up to 60%, compared to baseline methods.