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# A COMMUNITY-DRIVEN APPROACH TO DEMOCRATIZE ACCESS TO SATELLITE GROUND STATIONS

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If you were to launch a small satellite in Low-Earth Orbit (LEO) today, the cost of installing/renting ground stations around the world to maintain global coverage is likely to rival the satellite launch costs. While satellite launch costs for small players have reduced significantly due to the emergence of ride sharing programs operated by both public and private organizations, access to ground station infrastructure is still a luxury due to the immense cost and form factor of the components involved, which need to be installed in a large, elevated area free from any obstructions. Global coverage using specialized ground station infrastructure is necessary in LEO satellites, since these appear over a certain region of the earth only few times a day only for a duration of ~10 minutes and their signals are often attenuated beyond detection. In this work, we try to overcome this barrier by designing a community-driven distributed reception paradigm, in which weak signals received from many tiny handheld receivers are combined to recover the desired signal.

Today, as the number of satellites being launched in the Low-Earth Orbit (LEO) is increasing at an exponential rate [4], the number of ground stations required to receive signals from all these satellites is not increasing at the same rate. LEO satellites [5] orbit the earth between altitudes of 300km - 2000km with orbital periods between 80 – 100 minutes. They don't visit the same region on earth more than 3-4 times in a day with each visit lasting only 10 minutes, after which they go out of view. In fact, many of the nano satellites being launched today last only 3-4 months before they stop transmitting. This problem is exacerbated by the fact that the signals from these small satellites are often very weak due to the tight constraints on the form factor and power budget involved. Therefore, it is necessary to receive all the data one can in the limited time available. In order to be able to talk to the satellite all the time, ideally, one would have to install ground stations all across the globe. However, installing ground stations for satellite reception is not as trivial as using a small handheld radio for terrestrial reception.

This calls for specialized ground station infrastructure composed of huge antennas and bulky radio setup capable of receiving extremely weak signals, which are often installed on roof/hill tops void of any nearby ground obstructions. What makes the satellite ground station different from other terrestrial transceivers is the nature of the signal they are designed to receive. Satellite signals, unlike most terrestrial signals, are heavily attenuated due to the thousands of kilometers' worth of path loss that they incur. As a result, it is desirable to use a large directional antenna pointing towards the satellite to receive the desired signal using a large directional gain (gain of an antenna is directly proportional to its size). However, since the satellite keeps moving constantly, one would need to constantly change the direction in which the antenna points throughout the duration of the satellite's pass over an area. Hence, most of the LEO satellite ground stations are equipped with a rotator setup to constantly track the satellite of interest. Furthermore, this large setup needs to be deployed in an elevated open area in order to avoid attenuation due to

**FIGURE 1.** Today's satellite ground stations are expensive and bulky, requiring deployment in open areas/rooftops void of any obstructions.[6]

terrestrial obstructions to an already weak signal. This specialized infrastructure can often lead to an investment of more than 5000 USD in total, which can be huge for enthusiasts and hobbyists interested in receiving satellite signals.

Recently, there has been an evolution of "ground station as a service" [2], from leading providers like Amazon, Kongsberg, Microsoft, etc., that allow renting ground stations installed at different parts of the world on a subscription model. However, the cost of renting a ground station over a period of time starts to rival and overshoot that involved in the launch and development of the satellite itself. There have also been admirable efforts providing free open source ground station network for small satellites like SatNogs [3] and TinyGS, where multiple interested users can sign up and schedule receptions from their own ground stations using a user-friendly API. However, a problem that still exists across these efforts is the cost and bulkiness of the ground station needed to be installed by each user at optimal pre-surveyed locations void of any obstructions. This is still a major bottleneck for space enthusiasts, which limits its scale and accessibility.

In this work, we present *Quasar*, where we take the first step towards solving this problem of bulky and expensive ground stations' access by dividing the task of reception across multiple tiny receivers, each costing less than 50 dollars, that could fit in the palm of one's hand and be deployed anywhere (even indoors). In particular, we use a 10 cm long terrestrial radio antenna hooked onto an RTL-SDR radio, which can be plugged into a Raspberry Pi or a laptop through the USB interface. At first blush, it would appear that this would defeat the purpose since tiny receivers would degrade the received signal quality further. While this is indeed true, we try to trade off individual received signal quality for cost and ease of use, and later boost the signal quality in the cloud by combining weak signals received from a multiple of these tiny receivers after appropriately synchronizing them to each other (see Figure 2). While distributed reception and antenna array techniques have been used in the past, in cellular and WiFi domains, LEO satellite signals pose some interesting new challenges that require rethinking some of the older techniques.

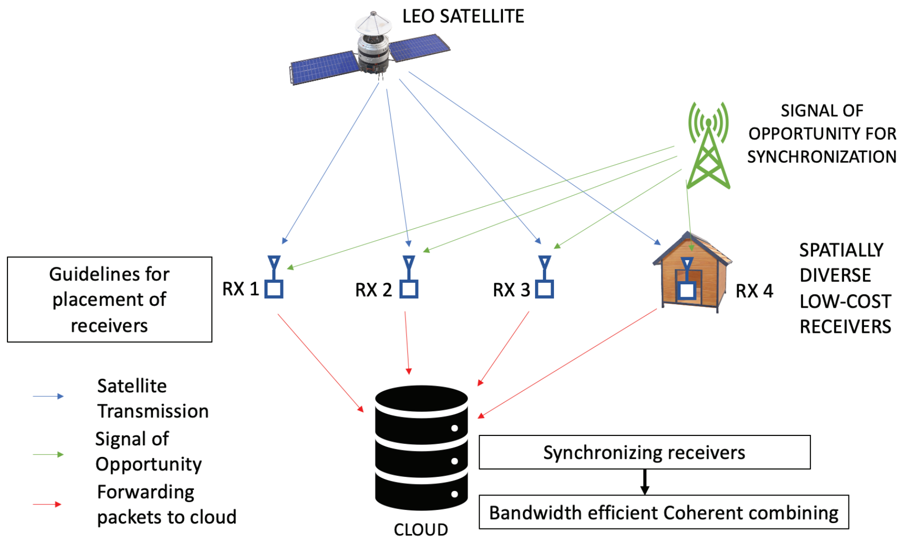


**FIGURE 2.** Quasar uses spatially distributed low-cost receiver modules to generate high-quality satellite signals after coherently combining noisy signals in the cloud in a bandwidth-efficient manner. This is made possible after utilizing Signals of Opportunity beacons for synchronization and appropriate antenna placement techniques for optimal receiver deployment.

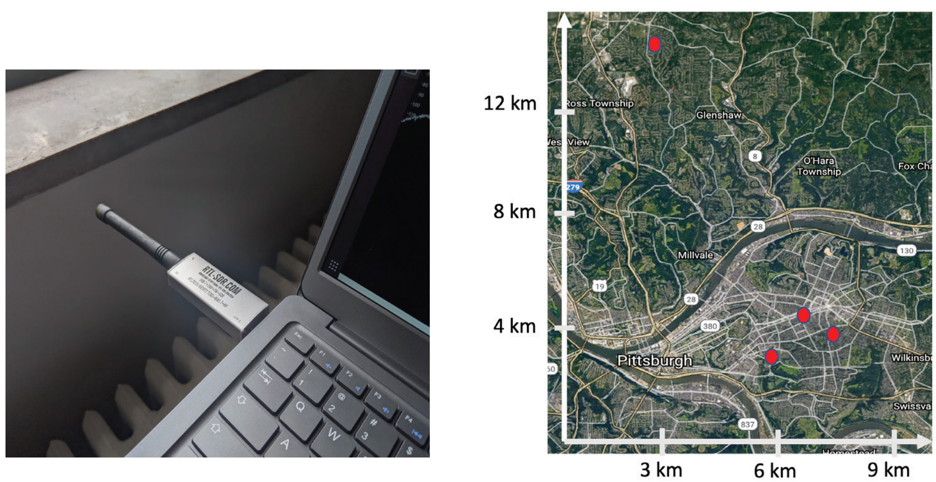


**FIGURE 3.** Left: Quasar uses tiny RTL SDR receivers with Laird Tuf Duck Antennas, which can be deployed anywhere. Right: Quasar was evaluated on a city scale testbed consisting of both urban and suburban indoor and outdoor structures; red dots indicating locations where low-cost receivers were deployed.

## Distributed Ground Station Synchronization:

The most important component of any distributed receiver/MIMO system is the synchronization required to make sure each of the signals received on each of the antenna components/receiver modules are processed in a phase synchronous manner. What makes a distributed MIMO receiver different from a distributed satellite receiver is the nature of the signals that they are designed to receive. Preamble based phase-synchronization techniques fail in the case of multiple tiny receivers since the signal is often buried under noise making any of the individual phase values extracted unusable for synchronization. One would argue that GPS sync could be used to synchronize all of the distributed receivers. However, there are two barriers to this approach: this would require modifying the commercial off-the-shelf hardware which many people would

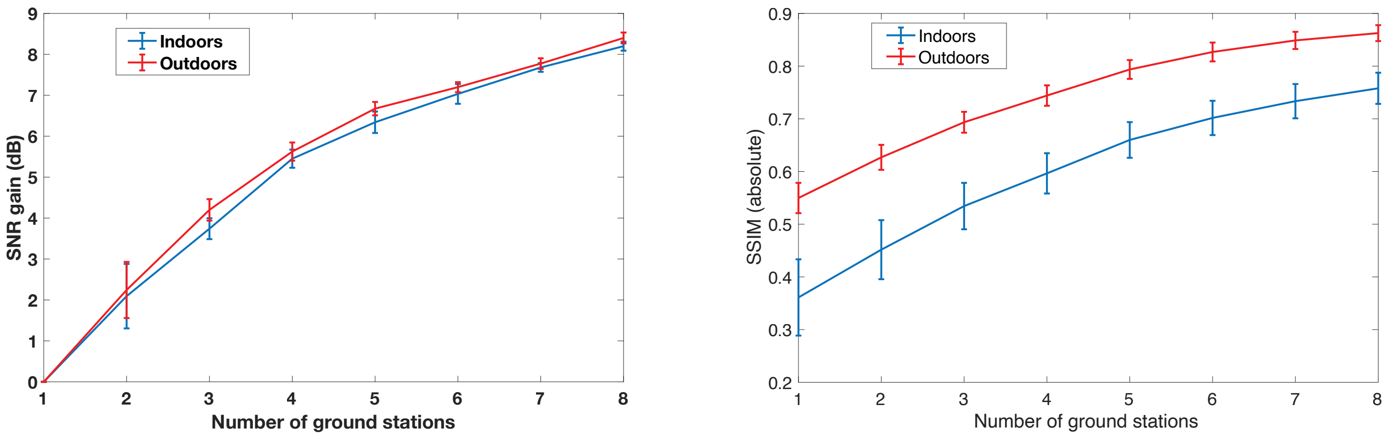


**FIGURE 4.** Quasar achieves 8 dB average SNR gain (left) and improves SSIM to 0.85 (right) using 8 low-cost ground station receivers.

not have the expertise to do, and GPS sync performs poorly in indoor environments, which would limit the use case of our system. We seek to build a system that is easy to use due to its plug and play nature and works smoothly both indoors and outdoors. LEO satellite signals are further affected by trajectory dependent frequency offsets, called doppler shifts, that make the synchronization process even more challenging.

### Antenna Orientation and Bandwidth Constraints:

Since we are using cheap and tiny hardware for our receivers that could be deployed anywhere, the received satellite signals are significantly attenuated, particularly in dense urban and indoor environments. This is due to the coupled effect of tiny antennas' orientation and radiation pattern, satellite trajectory and the additional attenuation due to signal occlusion in indoor settings. As we are trying to combine multiple such attenuated signals in the cloud, it is desirable to have as large a number of received signals, which would in turn improve the chances of signal recovery. However, this would mean the ground stations would have to continuously stream all the received signals to the cloud – even those that are buried under noise beyond the point of detection. This can create significant demands on uplink bandwidth, which is often limited in home broadband scenarios. Hence, we need to overcome these challenges of indoor signal attenuation and uplink bandwidth strain in order to incentivize public adoption of our system.

## SYSTEM DESIGN

Our system combines weak signals received from multiple tiny receivers deployed in optimal orientation at different locations, after appropriately synchronizing them in the cloud to produce the desired high SNR signal. Below we describe how we overcome the challenges of synchronization, antenna orientation and bandwidth constraints:

### Synchronization:

Working with satellite signals and tiny receivers makes traditional approaches of distributed receiver synchronization based on preamble and GPS inapplicable as described earlier. Hence, in order to frequency-, time- and phase-synchronize the weak received signals before combination, we use the presence of "signals of opportunity" – terrestrial signal sources like amateur radio towers in the vicinity. The operating frequency of many satellites overlap or lie adjacent to the ones allocated for amateur radio. As a result, we can use the presence of these high-powered terrestrial amateur radio signals (which can penetrate indoors) as beacons to aid synchronization of our tiny receivers. The choice of amateur radio frequencies is driven by the fact that access to these bands is free and most amateur radio towers transmit in frequency modulation format, similar to ones used by many satellites. Therefore, in places or times without access to an amateur radio tower, one member of the community can take up the task of installing a transmitter operating the amateur radio band to serve the vicinity. We also use the trajectory of the satellite to estimate the Doppler frequency offset experienced by each of our receivers to negate its effect. The details of our approach are explained in [1].

### Antenna Placement and Bandwidth constraints:

Most LEO satellites today operate in polar orbits to support coverage of the earth for applications like providing internet or monitoring weather. As a result, an LEO satellite's pass at any location would only be from north to south or south to north, with varying degrees of elevation angle. Based on this observation as well as the toroidal omnidirectional radiation pattern of our terrestrial radio antenna, we recommend vertically orienting the antenna when the satellite is at the beginning and end of its pass when it is near the horizon to maximize reception gain. Similarly, the antenna gives maximum gain when oriented in horizontal direction during the middle of the satellite's pass when it is more or less overhead. We provide further guidelines detailed in [1], to help improve the quality of the received signal both indoors and outdoors, which might otherwise be degraded due to improper orientation and antenna placement.

In addition to synchronization and antenna placement, we build an open-source portal, where multiple users in a vicinity can upload their raw received signals for coherent combination. In general, the larger the number of signals to be combined, the better the recovered signal quality. While this makes sense when the average power of all the receptions is equally poor not all received signals have the same SNR due to differences in the location and orientation of the receiver antenna. As a result, there is only a limited number of raw signals that one needs to combine to achieve the desired SNR for recovery, which is based on the application and type of signal. Based on these factors, we throttle the number of raw signal uploads to the cloud using initial local SNR measurement reports made by each user. This reduces the uplink bandwidth strain on the network, by ensuring that only a few of all the received signals are actually uploaded to the cloud rather than all the received signals being streamed all the time to the cloud. Once the appropriate signals are uploaded to the cloud, they are synchronized and coherently combined by Maximal Ratio Combination to boost the resulting SNR.

## SYSTEM EVALUATION

We implement Quasar using 136-150MHz Laird Technologies EXS136SMI Tuf Duck antenna attached to RTL-SDR dongle R820T2 RTL2832U as the radio front end. This radio can be connected to an internet connected-Raspberry Pi or laptop using a USB port to stream the received signals to the cloud. We evaluate our system on Carnegie Mellon University campus as well as a city scale testbed in Pittsburgh, where the receivers were distributed across multiple locations (both indoors and outdoors) to receive signals in urban and suburban neighborhoods. For all our experiments, we receive earth image signals from NOAA 15, NOAA 18, NOAA 19 and METEOR M2 weather satellites transmitting continuously in the 137 MHz band. While we present exhaustive evaluation of our system for a different number of receivers, satellites, elevation angels, bandwidth savings and recovered image quality in [1], here, we describe only two crucial results regarding average SNR gain and SSIM improvement of the recovered image across the number of ground station receivers.

We increase the number of ground station receivers used for coherent combination by deploying the receivers in different indoor and outdoor settings in our city scale testbed. Using the average received SNR as the baseline, we measure the average SNR gain after combination. Figure 4 (left) shows the logarithmic increase in the average SNR gain in both indoor and outdoor settings, achieving an average gain of 8.1 dB using 8 receivers. Figure 4 (right) also shows the Structural Similarity Index (SSIM) between the decoded image after coherent combination and the ground truth image received from a bulky UC1374-531R quadrifilar helix antenna connected to LNAU-0137-648 low noise amplifier and USRP N210 SDR. It shows improvement in average SSIM from 0.52 to 0.85 outdoors and 0.35 to 0.74 indoors from single ground station to 8 ground stations. Figure 5 presents how the recovered image evolves as more and more receivers are added in coherent combining. We believe further improvements in image quality are possible with better image coding available in other LEO satellites.

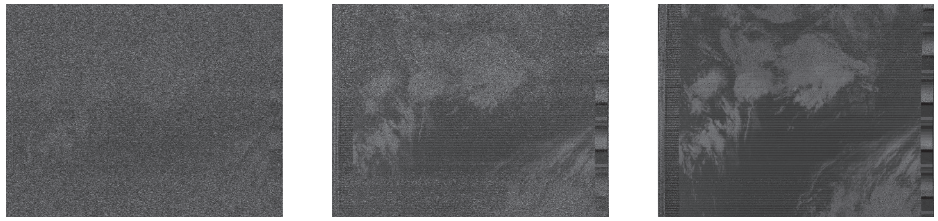

**FIGURE 5.** NOAA 18 image with one receiver (i.e., baseline) vs. Quasar with 4 and 8 receivers (left to right).

## CONCLUSION

We present Quasar, a community-driven LEO Satellite ground station infrastructure using multiple easy-to-deploy tiny low-cost receivers to recover satellite signals after coherent combination. We show the promise of such a ground station infrastructure in overcoming the barrier to entry for enthusiasts to access satellite data using a distributed approach. A limitation of our design is that the amount of data required to recover the satellite data scales linearly with the number of the ground stations used. However, this burden on each individual user remains the same, while reducing the cost burden significantly. We envision that Quasar will open the doors for future research in satellite communication and sensing using distributed satellite IQ-data across large geographic areas. ■

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