University of Colorado at Boulder WiLDNet and White Space Testbed

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***Abstract*—Four 5.8 GHz band transceivers at the University of Colorado at Boulder (UCB) were first operated as a wide area local area network (WLAN) in April of 2017. The purpose of this WLAN is to serve as a testbed for installations to be made in the developing world as a part of the IEEE Smart Village program. The configuration of the components is discussed in detail. The testbed is self-powered by solar micro-grids that are present at each node. Evidently, the micro-grids are designed for fail-safe 24/7 operation. Test data is presented on the operation of the network when used to provide information on demand from a central server to any of the remote stations. The network provides continuous data on the operation of the micro-grids including their innovative energy storage systems (ESSs) that are based in lithium ferro-phosphate battery technology. This test data resembles that of a smart system monitoring multiple islanded micro-grids. Plans for expanding the testbed to include a mobile station as well as longer distance arms are also presented. A primary purpose of the testbed is to determine the suitability of components, power levels and protocols for application of wireless LANs (WLANS) in remote areas. Discussion of what the testbed test results say about component applicability conclude the paper.**

1 INTRODUCTION

The cell phone has spread rapidly to most areas and people of the world. Broadband internet is a somewhat different story. People of all economic strata will spend income for communication. Revenue potential for cell phone providers, therefore, is more a function of population density than mean or median income. Broadband services (generally defined as internet at rates above 2 MBps) were originally much harder to provide than regular cell phone, analog in the early of the cell phone. Digital technology continues to evolve. 4G, and to a lesser extent, 3G, provide digital broadband as well as voice over IP (VoIP). These technologies can further be used as a hot spot for computers. The cost for such services decreases with time also in direct relation to the profit incentive. Broadband deployment has accelerated over time with respect

Figure 1: A tripod deployed on Niwot Ridge near Nederland Colorado as a part of the IEEE Smart Village testbed project of the University of Colorado at Boulder. The Wi-Fi Long Distance (WiLDNet) station of the testbed is located 25km west of Boulder at an elevation exceeding 12,000'.

to what was seen during the dominance of analog cell phone service.

Cell phone service remains poor or non-existent in some areas, however, especially areas that are both remote and sparsely populated. The Amazon is such a region as as are a number of mountainous areas including the Himalayas. Deserts including the Gobi, Kalahari and Sahara are sparsely populated although not so hard to penetrate with high frequency and/or microwaves as are African, South American and Asian jungles.

In areas where broadband is not economically viable for commercial carriers, private networks may be a viable alternative, especially when sources of revenue such as internet cafes and service provisioning for pay can be found to offset costs. The obvious technical solution for such private networks is to use Industrial, Scientific and Medical (ISM) bands (primarily at 2.4 and 5.8 GHz athough 5.1 and 60 GHz are under debate) that are unregulated by United Nations agreements among the 197 nations of the world [4]. The 2.4 GHz ISM band was the first one to find wide usage, first for internet routers in the mid 1990s. Enterprising individuals realized soon after the introduction of the router that if one were to focus the energy with directional antennas rather than broadcast the power, one could project the Wi-Fi signals over lengths of 10s of km with sufficient power to receive 10s of Mbps data rates at a second router location. The resulting wide area point to point networks would form the basis for private wide area local area networks that became known as Wi-Fi Long Distance (WiLD) Networks (WiLDNets).

Long distance point to point technology in the ISM band allows for great flexibility in network design at reasonable cost. One of the first major private networks to form using, at least in part, WiLD technology was HPWREN [5]. HPWREN spans several counties of southern California and has been self-sustaining since its inception in 1999 [5]–[7]. The Nepal Wireless Networking Project (-NWNP) Fig. 2 is a WiLD Net that presently spans much of the country of Nepal. Clearly the NWNP is self-supporting as evidenced by its steady growth since its inauguration with a mountain link to and from Pokhara from Kathmandu in 2002 [8], [9]. The heterogeneity of both traffic and purpose of these two networks are prime causes of their longevity [10]. Namely, their usage isn't restricted by type, as educational and revenue seeking endeavors find equal footing. The adaptability and reconfigurability of these networks keep them both socially and economically viable [11].


Figure 2: Binod Bidari of the Nepal Wireless Networking Project (NWNP) working with University of Colorado at Boulder students on a WiLDNet installation in the Ilam District in eastern Nepal in June of 2009. Binod is aligning a Wi-Fi Long Distance transceiver to form a point to point connection with the village of Namsaling that lies on the far (eastern) side of the Mai River.

The IEEE Smart Village (ISV) program, originated by Ray Larsen of SLAC in Palo Alto and Robin Podmore of Incremental Systems in Seattle in 2013, initially focused on partnering with small businesses owned by IEEE members in developing countries [1] for the purpose of expanding electrical power availability in the developing world. Estimates for those in the world with electric power vary depending on source, but the fact is that in much of the developing world that is considered already supplied, that supply is at best intermittent.

There is much to be done to achieve a stable and universal electric power system. With more than 400,000 members in more than 160 countries, the IEEE serves as an ideal platform from which to deal with problems of development. The ISV program now involves hundreds of IEEE members.

Taking a wholistic view of technical development, ISV early on decided that education must take an equal part with power and entrepreneurship if the ISV program were to lead to sustainable development. Indeed, areas that are lacking in access to electric power are often the same ones that lack educational facilities (textbooks, for example). Internet connectivity [2], [3] is a method for providing educational resources when the social infrastructure exists or can be developed that avail itself of high speed networking. Electric power enables private network connectivity. WiLDNet provides a low cost private networking solution that is competitive with others(for example, television white space) when a public network is not available.

Wireless networking has gone through many generations since 1999 and the innovation is continually accelerating [12]. A goal of the ISV Educational program is to seed the construction of self-sustaining networks that will serve the most necessary of educational purposes while generating revenue. Perusal of the list of sites (from Malawi, Tanzania and Nigeria, to the Galapagos and Himalaya India) presently under consideration indicate the topologies of the different locations are at least as heterogenous as the services that need be provided to achieve economic sustainability. The flora, fauna and topography of the South Sudan have about as much in common with that of the Democratic Republic of Congo as an internet cafe has in common with a government office or a booth for VoIP calls [13]. As such, throughout the site selection process for permanent testbed locations at the University of Colorado at Boulder, the proposal for a WiLD network in the highlands of Papua New Guinea, near Mount Hagan, was emulated for layout.

The work to be discussed focuses on the ISV funded effort at CU Boulder, where a functional testbed is being used to emulate installations of communications systems in remote, rural areas. Currently, the testbed consists of a base station located in the Engineering Center Tower (EC Tower), three local client stations located within 5 km of the base station, a long distance link on Niwot Ridge, 25 km distant from the EC Tower, and a mobile station which can be used to better characterize the ranges of the tested devices. Two more long range sites east of Boulder are under development, with an anticipated summer 2017 installation. The antenna tower for one of these sites is pictures in Fig. 1. The stations consist of a variety of photovoltaic panels, lithium iron phosphate batteries, and associated power electronics to meet the power needs of the various types of equipment deployed. Additionally, computational devices are colocated with the power systems to allow remote controlled network loading to simulation a wide variety of system scenarios. This work is intended to inform, and train, the developers of long distance wireless networks in developing parts of the world.

Figure 3: View from the Wilderness Place client station on the CU Boulder campus. The structure in the background is the Engineering Center (EC) Tower, where the base station is located. This image displays the Line of Sight (LOS) required for systems operating in the 2.4, and 5.8 GHz bands.

2 THE SYSTEM

The choice of equipment for for self-configured, private jungle networks has evolved rapidly since the turn of the millenium (2000). Most recently, with the freeing of television bandwidth, TV White Space (TVWS) equipment has become available.

Figure 4: A map of the Boulder, Colorado showing the locations of the 3 local client stations (Wilderness Place, East Campus (SPSC) and South Complex) all within 5km of the Engineering Center (EC) Tower, a range represented by the green radius. The Betasso Preserve location is intended for mobile unit testing.

TVWS is unlike the earliest point to point links as TVWS can be broadcast. The lower frequencies (460 - 820 MHz) of TVWS as compared with Wi-Fi center frequencies (2.4 and 5.8 GHz) allow for more terrain penetration. relieving the network of the stringency of the requirement of line of sight (LOS). TVWS will be tested in a future testbed generation. Attention for the present remains on WiLD.

Many of the original point to point lines, stars, and meshes consisted of Wi-Fi transceivers mounted on high gain antennas and enabled by custom protocols that would allow for communication over 10's of km's on equipment originally designed to broadcast from tens to hundreds of meters [13]. These early systems that were almost solely based on IEEE 802.11 (b, d, n, ac) standards that were generally referred to as 'WiLDNets' (Wi-Fi Long Distance Networks). The simple Wi-Fi unregulated (2.4 and 5.8 GHz) band solutions have now given way to numerous off-the-shelf solutions that are turnkey plug and play. The bands are unregulated but the protocols are not necessarily standard and/or open source. The testbed system has been constructed to be modular to support as many different solutions as easily as possible. protocols as possibly as easily as possible.

As it stands, our system is composed of a base station located on one of the towers of the Engineering Center at CU Boulder, and four client stations. These are referred to as Wilderness Place, SPSC, South Complex, and Niwot Ridge for ease of identification and are located at 2.57 km, 1.52 km, 3.89 km, and 21.60 km from the base station, respectively. Figure 4 shows the locations of the closer stations, with Niwot ridge due West from the EC Tower. A mobile unit has also been constructed, which is essentially a client station that can be set up wherever to test a variety of radio/technology scenarios. A representative antenna mast, the southern one on the Engineering Center base station, is pictured in Fig. 5.

Figure 5: The Base Station mast on the south side of the Engineering Center Tower. Shown are a Ligowave DLB 5-90-17 with a 90 degree sectoral (lower) for point to multipoint transmission and Ligowave PTP 5-N-23 long range point to point unit that will be used for longer (greater than 20 km) links.

Each client station has its own renewable energy source (RES) and energy storage system (ESS) as well as a dedicated charge controller that controls ESS charging and the distribution of energy to the communications equipment. Both the panels and batteries differ by site, as they have been tailored to the specific needs of each station, as outlined by Table 6. Having a robust energy management system is essential to ensure the proper operation of each station, as most are left in inaccessible areas for extended periods of time. With this in mind, the power systems have been designed to operate for multiple days without charge from the PV. See Fig. 7 for picture of the client stations, and Fig. 9 for a schematic of the client station electronics.

Station	PV Panels	Battery Ratings
Wilderness Place	1 x 100W	12.8V, 150 Ah LFP
Space Sciences	1 x 140W	12.8V, 200 Ah LFP
South Complex	1 x 140W	x2 12.8V, 40 Ah LFP
Niwot Ridge	4 x 100W	x3 12.8V, 160 Ah LFP
Mobile Unit	1 x 100W	x1 12.8V, 200 Ah LFP

Figure 6: Summary of the installed renewable energy sources (RESs) and energy storage systems (ESSs) by location within the University of Colorado at Boulder (UCB) testbed.

All stations currently employ a computational system, consisting of a network switch that connects a Raspberry Pi 3 and the LAN port of each PoE injector, two being 24V PoE, and the third a 48V PoE.. This allows for remote shell access to the Pi, as well as the transfer of data between it and the central server. In addition to the Pi, an Arduino is also present on the board, where information is sent between the two through a USB-A to USB-B cable. There is also a jumper wire present between one of the GPIO pins on the Pi and the Reset digital I/O pin on the Arduino, that allows for it to be reset in case of failures.

In order to monitor our system from afar, we have set up current sensors for the board current, PV panel current, and battery current. The Arduino actively captues these currents in addition to the voltage difference across all three of these points. This data is sent out over a USB Serial UART interface that feeds into the Pi. The Pi is set up in such a way that it creates a new text file every day at 12:00 AM, timestamps it, and begins to append the data that is being received. Python is then used to compute the stations daily consumption, daily charge, daily discharge, daily PV production, maximum battery voltage, minimum battery voltage, and state of charge (SOC). It also produces insightful graphs of the varying battery voltage, PV production, communications consumption, and SOC. This information is used to characterize the absolute radio energy consumption under varying degrees of network load. See Fig. 8 for a chart of the PV production of the South Complex.

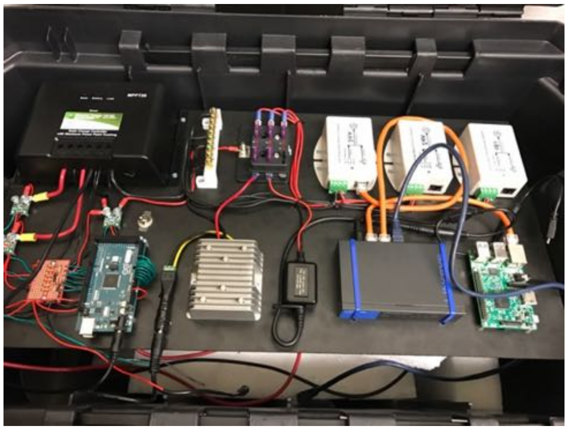

Figure 7: The array of electronics found at each client station. Starting in the upper left and moving clockwise there is: LFP Charge Controller, DC Bus, two 24V PoE Injectors, one 48V PoE Injector, Raspberry Pi 3, Linksys five port Switch, Buck Converter, Voltage Regulator, Arduino, Circuit Board, and three Current Monitors.

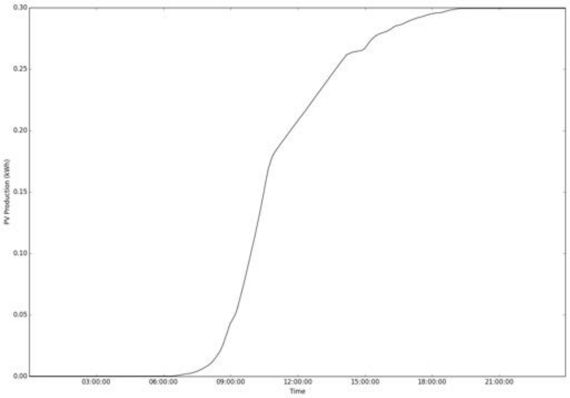

Figure 8: The Solar Photovoltaic power production at the South Complex station on June 22. This panel is rated at 140W, which means this days production is low, indicating a full charge was achieved earlier in the day.

The main server, located in the EC Tower, runs an Ubuntu 16.04 operating system and its role is to ensure that all clients and radio systems are running in the intended fashion, as well as send out requests and commands to client stations for data transfers. The server has been set up to send out a request for the days data to each of our client stations which should be acknowledged and responded to with everything the station has compiled over the day.

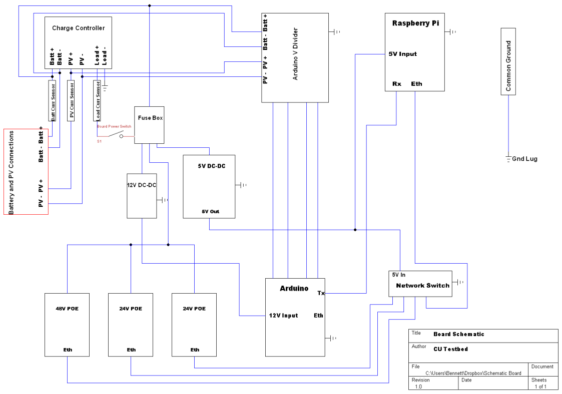

Figure 9: A high-level shematic of the equipment connections at each client station. Fig. 7 depicts the actual compenents in the wired up form.

The advantage to requesting the transmission before it actually occurs can be seen in the prevention of saturated lines or excessive timeouts, which might ultimately cause the system at the client station to stop responding.

2.1 Current WiLD Configuration

As the testbed only recently came into operation (April '17), and it was modelled after a proposed system in Papua New Guinea, the current WiLD configuration uses the equipment intended for PNG. Namely, Ligowave and DLB equipment WiLD equipment. The network consists of a long range link, created between the Niwot Ride and EC Tower locations, as well as a local distribution setup that uses a PTmP setup. For the PTP links, the Ligowave PTP 5-N-23 is employed. For the PTmP system, the DLB 5-90-17 90 degree sectoral integrated radios are used at the base station, and the APC Propeller 5s populate the client stations. The equipment distribution is presented in Table 10, as well as a network diagram shown in Fig. 11.

3 DEMAND SIMULATIONS

The inclusion of comprehensive current and voltage monitoring has allowed an accurate portrayal of the consumption and PV production of each station. This data provides the ability to quantify the device consumption, while under load and static, of each station for a robust analysis of the system.

Station	Equipment
Base Station (North)	two DLB 5-90-17s one PTP 5-N-23
Base Station (South)	two DLB 5-90-17s one PTP 5-N-23 (temp)
Wilderness Place	one Propeller 5
Space Sciences	two APC Propeller 5s
South Complex	one APC Propeller 5 one PTP 5-N-23 (temp)
Niwot Ridge	two PTP 5-N-23 (tbi)
Mobile Unit	one APCPropeller 5 one PTP 5-N-23

Figure 10: Summary of installed network radio communications equipment currently installed at the CU Boulder testbed. This equipment array emulates a future WiLD installation in the highland of Papua New Guinea. (tbi : to be installed)

With the accurate characterization of device consumptions, we can make sound recommendations for minimal costs power systems installations in developing countires. Moreover, the relaying of data back to our central server every day enables a tight watch on any anomalies that might arise during normal operation, further reinforcing our ability to detect problems or faults and deal with them rapidly. Again, these deviations from normal behavior combined with robust monitoring allow us to identify whether a device is operating in a capacity for which it isn't suited, and extend these analyses to future systems.

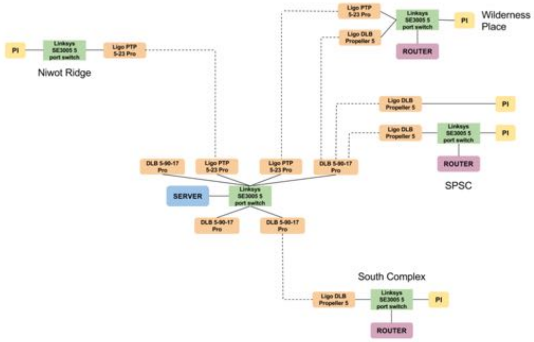

Figure 11: The Summer '17 network of WiLD radios at the CU Boulder testbed. This system emulates the network structure of the Papua New Guinea installation, scheduled for Summer '17.

Simulated loads apply not only to the energy system of the boards, but also to the communications between board and server. Regular transmission of large files between stations allow for us to identify the effect of weather and other variables on the throughput of our radios. Inevitably, radio bands become saturated at peak hours and line of sight is easily lost with moving obstructions, especially when LOS is just skirting the canopy. These tests also give us the ability to gather data on each radio and find which are most appropriate for specific applications.

Figure 12: The installation at the Space Sciences (SPSC) building. Visible is the 140W PV Panel, the mast with two DLB Propeller 5s attached, and the electronics enclosure slightly obscured by the wall shadow. Two Propellers are colocated to with a second Raspbery Pi to add more load to the network without the need of additional power electronics.

Currently, scripted transfers over FTP facilitate the communications testing of our network. These allow for relatively risk free trials, as these are conducted with test files, ranging from approximately 2 MB to 2.5GB. Having different sized files transmitted allows the characterization of long time duration transfers, as well as repeated short duration transfers. Performing these regular tests also ensures that our system is working properly and that no actual important data will be lost in transmission.

Figure 13: The South Complex installation, where the panel, electronics enclosure, and mast/radios are clearly visible. This client station if located 3.89 km southeast of the EC Tower base station.

The network created handles data transfers quite well, achieving speeds in optimal conditions of up to 4.06 MB/s with the LigoPTP 5-23 PRO radios and up to 5.63 MB/s with the LigoWave APC Propeller 5s. However, the fluctuations were large, with speeds dipping as low as 458 kB/s for the Propellers, and 158 kB/s for the 5-23s. We have also found that our system has a bit of trouble with larger files, especially if the environment it is set up in is prone to interrupt connections between radios, which don't maintain the transfer after a connection is reestablished. Additionally, in less than optimal conditions, the throughput of our radios tends to drop, leading to long transfer times and possibly a higher chance of unsuccessful transfers. We have noted that physical and electromagnetic interference both play a big role in this. Physical obstructions are easier to deal with, mainly because they are easier to detect. However, the cause of electromagnetic interference is vastly more difficult to detect and often times is impossible to eliminate in its entirety.

This sort of interference can be caused by other communications systems -such as Wi-Fi routers- or by the radios themselves. Since they all operate on very similar frequencies, those that are set up in Point-to-Multipoint (PTMP) mode have a harder time distinguishing signals coming from different devices. To get around this, we have set up all Propellers to operate in smart channel width mode, allowing for each to broadcast on a slightly dif-

	SPSC	Wilderness Place	South Complex
Type	APC Propeller 5	APC Propeller 5	LigoPTP 5-23 Pro
Max	5.63 MB/s	3.56 MB/s	4.06 MB/s
Min	458 kB/s	693 kB/s	158 kB/s
Mean	1.89 MB/s	3.19 MB/s	2.48 MB/s
Median	1.16 MB/s	3.38 MB/s	2.67 MB/s
SD	1.58 MB/s	0.55 MB/s	0.85 MB/s

Figure 14: A table of end to end data transmission rates that were recorded for the transmisson of large packets from base station to each of the remote stations. A notable feature is a variability of the data throughput. This is a matter of present research as the result is not expected for an unloaded network.

ferent frequency. Additionally, having all propellers assembled horizontally makes it so that the beam width in the vertical polarization will be narrow, but also wide in the horizontal polarization, allowing for simple alignment. These changes, combined with LigoWave proprietary iPoll 3 protocol, has made for much more stable connections.

As the system is continually developed we are interested in heavily loading our network during peak traffic times. This will involve sending out large data files to every station at the same time; in essence, saturating the system. The purpose of this test will be to observe what will happen with high demand situations in real networks deployed in developing areas. Understanding the results, and subsequent reactions, of these high usage scenarios will allow to identify more appropriate technology when appropriate.

4 FUTURE EQUIPMENT TESTS

Future simulations and analyses are planned for the system, including a variety of loading on the current system of proprietary radios, as well as the installation of other devices such as ISM Cambium radios, and White Space equipment from Carlson.

Having constant test data transfers will allow us to observe the effect on weather patterns on our communications. This eventually might become incorporated into the decision making algorithm for the server that will poll each station for the days data, as it makes more sense to have these occur at times where throughput will be maximized.

Figure 15: The north side of the EC Tower with two DLB 5-90-17s and a LigoWavePTP 5-23 installed. Installation location is the 8th floor of the Engineering Center, atop a mesa, allowing a commanding view for 40+ km to the north.

Raspberry Pis are present on all of the boards which feature GPIO pins that allow for user interaction with external devices through digital signals. Combining these with FETs and power resistors allow us to simulate much greater loads than what is present on our boards at the moment. This gives us the ability to reach much lower discharge depths on the batteries and truly test how our system would operate in the pessimal scenarios.

5 DISCUSSION

After a long process of permissions, equipment acquisition, fabrication, and installations, a functioning WiLD testbed is in place in Boulder, Colorado. This testbed contains robust client stations with full power system monitoring and computational devices to simulate network clients, as well as perform local analysis and share results with the central server. The base station is located high in the Engineering Center Tower of the CU Boulder campus, with towers on the North (see Figure 15 for an image of the North Tower) and South sides allowing for 360 degrees of connectivity. Currently, 3 client stations populate the shorter range (<5km), and a long range site is nearly complete 26km distant from the base station in a very remote location on Niwot ridge. Additionally, a mobile test station is under construction which will allow the testing of short, and long range, radios at any location. This testbed has been constructed with modularity in mind, such that all varieties of telecommunications equipment can be installed upon the mechanical, electrical, and computational equipment for testing.

Currently, the telecommuncations equipment installed emulates a future WiLD installation in the highlands of Papua New Guinea (PNG)) using DLB and Ligowave equipment. At this time, the testbed operates as the PNG system is intended, with all local client stations accessing the main network with the prescribed APC Propeller 5s. However, greater demand simulations are still underway to determine if the quantity of clients intended in the PNG system is supported by the DLB/Ligowave system. While the long range radios are operational within short ranges, full assessment cannot be made until the long range site is complete in early July. These successes indicate that the selected PNG equipment is appropriate, and the lessons learned in setting up the network in Boulder will be catalogued and shared with the PNG installers. Were the system to fail in Boulder, this is a much easier problem to fix than if it failed while installed in PNG.

With the completion of the PNG testing, the testbed will then be outfitted with Cambium WiLD radios to assess the applicability, strengths, and weaknesses of the proprietary system. Finally, White Space equipment from Carlson will be installed on the short range network to provide hitherto unavailable benchmark testing against proven WiLD technology. These categorizations will provide much needed information for the design of telecommunications networks around the developing world. Even now there are over 20 proposals to ISV for such networks, with the interest growing every day.

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