Final Technical Report (FTR)

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Executive Summary: Operant Solar was founded to address a significant problem in residential solar: unreliable, expensive, and insecure monitoring and control of distributed generation sites. Operant Solar's Chief System Architect first noted the problem while employed as principal scientist by a major third-party operator (TPO) of leased residential solar. FleetLink was explicitly aligned with the SunShot technical goals for communications including scalability, availability, response time, interoperability, compliance to open standards, and support of driving to a Levelized Cost of Electricity (LCOE) < $0.06/kWh.

After further research, Operant Solar noted:

1. Site WiFi does not provide enough reliability: 20-25% of PV systems are off-line.
2. Cellular modems may provide needed security and reliability, but at a high cost.
3. Existing wireless mesh approaches were limited in range when deployed as needed by TPOs. A typical TPO sales procedure focused on specific neighborhoods. The result is that 90%+ of systems have a nearest neighbor within 800m
4. For radio communication in general, various solutions have been deployed to meet either short-range (<30m) and long range (>10km) needs. However, there is a lack of solutions targeted to the 600-800m range in a neighborhood type environment.
5. Existing commercially available mesh and internet software stacks were designed with high data bandwidth as a key requirement. In particular, security needs drive continuous data transmissions far exceeding needed information bandwidth.
6. Much of the current Internet of Things (IoT) and communication stack has migrated from TCP/IP protocols and standards. This drives solutions towards larger software stacks, higher performance hardware, and increased software maintenance costs.

Based on this research, the purpose of this project became: 1) demonstrate hardware and software of a redundant mesh radio network to meet the wireless performance, reliability and cost requirements demanded by the TPOs; and 2) gather feedback from customers to validate Operant Solar's approach.

Three critical development tracks were launched and advanced rapidly to meet the window required by the TPOs: software, hardware and business development. These tracks were structured and aligned to achieve the final milestone goals of reliable 800m range in a deployment representative of residential solar installations; demonstration of the Named Data Networking software's ability to seamlessly and securely mesh systems connected via WiFi and sub-GHz radios; and gain feedback on the problem and solution proposed. At the end of the project 800m range and reliability were demonstrated. Feedback from customers indicated Operant Solar is on point for a low cost, reliable solution that would meet their needs.

DOE SunShot funding provided a major accelerating impact on continued development by allowing focus on technology maturity, rapid prototyping, TPO field trials, and manufacturing readiness and less on the distraction of fund raising.

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Background:

FleetLink is a new concept in PV system communications, purpose built for lowering the cost of maintaining active contact with residential end user sites and ensuring that production data is reliably available to third party systems providers. Systems providers require accurate, secure system monitoring and reporting of production data and system faults while driving down overall costs to compete effectively. This plug and play, independently operating communications solution lowers the cost of fleet contact from typically $.07/W down to $.02/W including installation and maintenance expenses.
FleetLink is a breakthrough for residential solar communication. Using an open source network framework with proprietary, application specific enhancements, FleetLink independently manages connectivity, security, recovery, grid control communications, and fleet expansion while presenting a compliant SunSpec interface to the third-party operations centers.

Current State of the Art – As shown in Figure 1, TPOs currently connect each site to the internet in several different ways: 1) directly to the homeowner's WiFi, bridged to a wired Ethernet connector on the homeowner's router, 2) using a ZigBee wireless bridge, 3) through a powerline bridge, or 4) directly through a cellular data modem.

In some cases, the hardware and software required for connectivity is provided by the inverter or revenue grade meter vendor. Alternatively, the TPO may build a custom gateway solution to collect and transmit data. All current methods for connecting the sites have significant shortcomings, as outlined below.

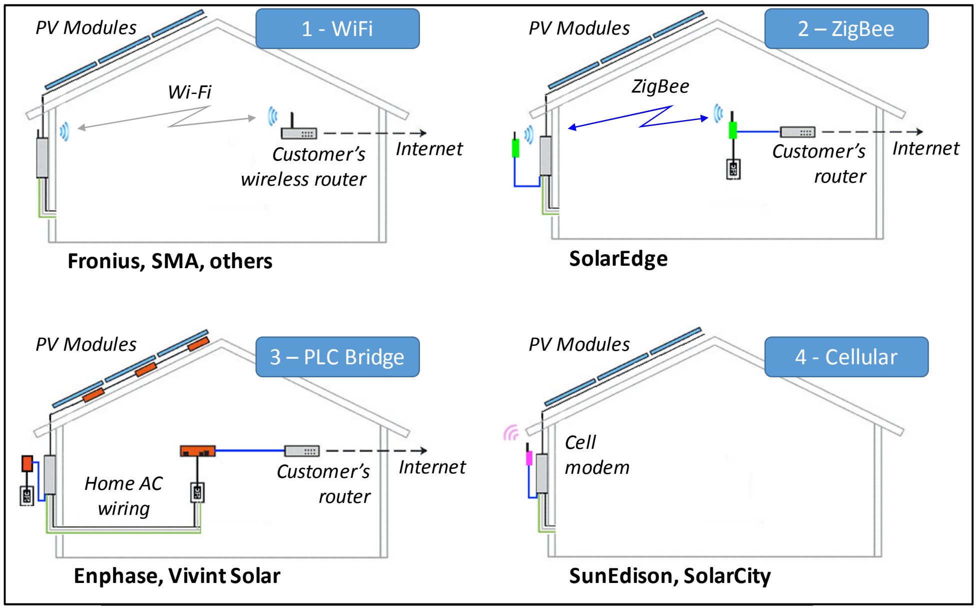

Figure 1 - Current communication link options

Unreliable – TPO contacts have reported that 20% of sites are not reporting their performance data in any given month. The trend for the last several years has been a continued worsening of the problem. Follow up investigations, as well as conference presentations, indicate to the onsite data interconnection path (i.e. not a failure of the inverter) is an industry wide issue. All existing connection methods are similarly unreliable, though their failure modes vary: Wired bridges often fail for problems as simple as the homeowner unplugging their device. WiFi connections fail when the homeowner moves their router or changes the WiFi password. There is currently only limited data available in the industry for residential site cellular connections; there is some hope this method may be more reliable, but issues remain.

Insecure – Equipment connected directly to the homeowner's internet presents difficult security challenges since the inverter companies install some type of computer server at the customer site. There are two main areas of concern that can leave the connection open to hacking. The first is installing a server inside the homeowner's firewall which could potentially be infected with malware. The second is the presence of a physical connection to the home network outside the house. The US Industrial Control Systems Cyber Emergency Response Team commented that a recent increase in attacks was mainly because more control systems are directly connected to the Internet.[1] FleetLink eliminates these concerns as a fundamental element in its network design – using dual layer of security provided by securing data via Named Data Networking[2] and ElectricImp's impSecure™ UL 2900-2-2 certified[3] software technologies.

Expensive – In addition to the capital cost of a communications link, there are operating expenses to consider. The primary components are installation costs, data plan costs, maintenance expenses, and hardware/protocol lifetimes. FleetLink was designed from the beginning to

[1] J. Finkle, "U.S. official sees more cyber-attacks on industrial control systems", http://www.reuters.com/article/us-usa-cybersecurity-infrastructure-idUSKCN0UR2CX20160113
[2] Lixia Zhang, Jeff Burke, et al. ACM SIGCOMM Computer Communication Review "Named Data Networking" https://escholarship.org/content/qt3rt9q3wb/qt3rt9q3wb.pdf
[3] T. Naegele, "New Cyber Standards for IoT Ease – But Won't Solve – Security Challenge", https://www.govtechworks.com/new-cyber-standards-for-iot-ease-but-wont-solve-security-challenge/#gs.jdyAy84

provide the lowest total cost. WiFi and Ethernet bridge solutions add significant maintenance expense from their poor reliability. Some of the disconnection problems discussed before could be corrected by the customer when guided by a support phone call, but many required an expensive truck roll and for the customer to be at home during their work day, a significant customer satisfaction issue. Cellular solutions *may* be more reliable, but add significant data charges and protocol end of life considerations.

Future Extensions of Cellular Solutions – It would be logical to assume that cellular modems would be a solution to PV site communications. Cellular Machine to Machine (M2M) data connectivity is an active area of development and optimized M2M LTE protocols and devices will arrive in the next few years. These will reduce costs to a degree, but an individual cellular link for each inverter will not be practical. Presently, inexpensive M2M data plans' allowable data usage means the inverter can't call frequently or keep a channel open continuously. More expensive data plans are required for a secure low latency bidirectional link. More fundamentally, M2M commercialization will require carriers to develop more value streams, charging more, not less.[4] *"The real limitation for MNOs* [Mobile Network Operators] *is that revenues on M2M communications are simply too low to turn a profit just from the connectivity, even with the most efficient operation."* FleetLink uses the strengths of cellular links efficiently, acting as a gateway for multiple sites to share a single cellular channel. This architecture is highly favored economically: "*We expect M2M gateway/aggregation points to play a key role…"*[5]

FleetLink is a new concept in PV site communications that replaces the remote connection functionality currently inside the inverter and the various associated network connections. It advances the current state of the art in all three key categories: lower cost of cost of ownership, higher reliability, and superior security - a breakthrough development.

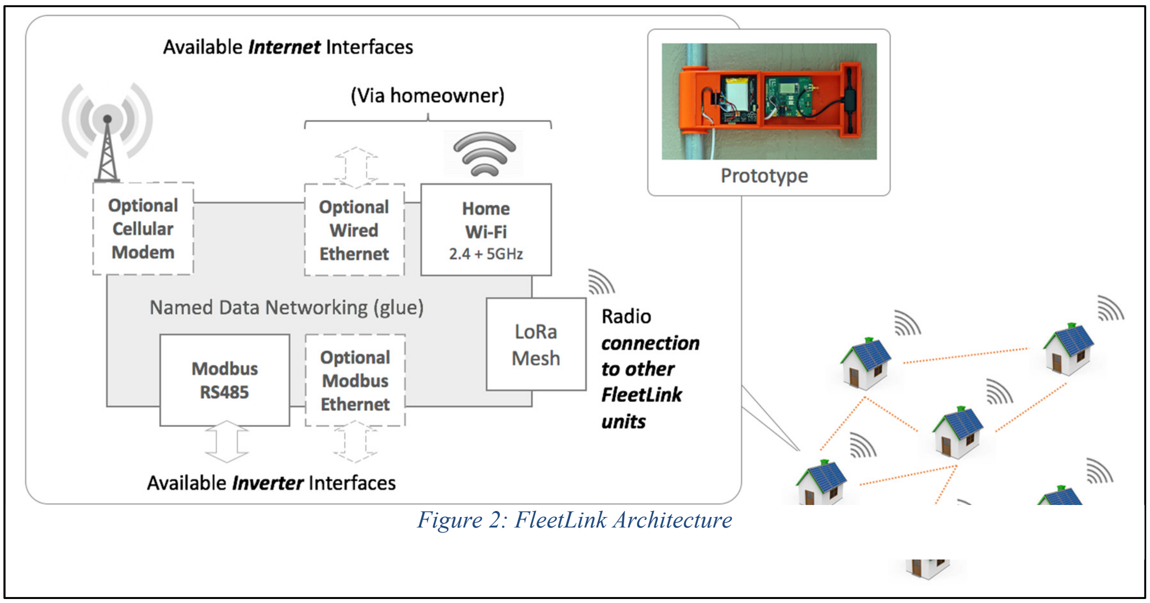

Figure 2: FleetLink Architecture

[4] A. Laya et al, "Future challenges in efficiently supporting M2M in the long term evolution (LTE) standards", Machine-to-machine (M2M) communications, architecture, performance and applications, 12 January 2015.

[5] Geng Wu et al, "M2M: From Mobile to Embedded Internet", IEEE Communications Magazine, April 2011

FleetLink achieved significant improvements in link reliability by using flexible and parallel connectivity paths in a single integrated product. Since the solution must accommodate the customers' installed base, regional, and business model variations, the product architecture allows for the multiple network connectivity options. The standard FleetLink product connects to the internet via WiFi. Should that link fail, the solution automatically falls back to a mesh neighborhood network. Unique intelligence in the mesh network allows a disconnected site to share a neighboring unit's internet connectivity, as shown in Figure 2 and Figure 3. Other interfaces (such as cellular or wired Ethernet) will be optional for customers with differing requirements.

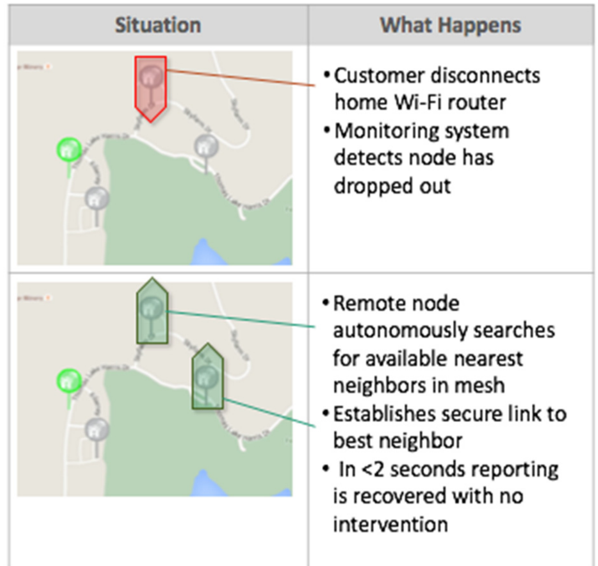

Figure 3: User View of FleetLink

An important and unique capability of the FleetLink network software is that all communication interfaces can be enabled in parallel, providing path diversity for assured recovery from failures and changes. In contrast, an implementation using TCP/IP connections would require more expensive interfaces and routers with complex site by site address knowledge to achieve the same parallel connectivity and recovery. Inverters on a site connect via Modbus, either serial or Ethernet. A single FleetLink aggregates all onsite equipment's communications and delivers it through highly reliable parallel connections.

To accomplish this solution, FleetLink uses two new technologies that integrate with and leverage two existing technologies that form a cohesive lower cost architecture:

<u>New Technologies</u>

1. LoRa mesh Neighborhood Area Network (NAN)
   - Provides the principle communications link if the WiFi connection should drop out.
2. Named Data Networking (NDN) software
   - Enables multiple parallel links that would be more complex and more expensive to implement in an IP network

<u>Existing Technologies</u>

1. Commercial WiFi, cellular, and Ethernet modules and software for IoT applications
   - Simplifies product development by providing a low-cost base upon which to innovate the FleetLink solution
2. Modbus and SunSpec connectivity
   - Saves cost by simplifying the inverter datacomm card required at each site

NAN Requirements Analysis – Existing wireless NAN technologies and implementations, such as Silver Springs Networks, were primarily developed for the smart meter infrastructure market, in which sites and aggregation points are physically close, typically within 200 meters. Residential solar sites, however, are much more widely separated and this constraint was analyzed in the research. Detailed fleet geolocation data was obtained from a top tier TPO and a statistical analysis performed to derive the underlying data for the design of a wireless link for this application. A Monte Carlo model was run using the site distribution data, measured WiFi link failure rates, and various wireless radio ranges. The results are that an 800-meter range is necessary to provide sufficient redundancy and to achieve <1% communications disconnects. Otherwise stated, 90% of the TPO solar sites have two neighbors within 800 meters, but less than half have neighbors within 200 meters. Therefore, smart meter infrastructures are not readily applicable to residential solar remote communications.

Radio Technology – Achieving the necessary 800-meter neighborhood range inexpensively required a new approach. Wireless range in an obstructed environment is a complex function of carrier frequency, channel bandwidth, data rate, interference immunity, practical IC technology, and FCC regulations. Available only recently, the Semtech LoRa IC provides a uniquely optimized solution to the needs. Utilizing the 900 MHz ISM unlicensed band, it penetrates buildings and vegetation well. LoRa is a chirped spread spectrum modulation, which combines low data rates (for range) with a wide signal bandwidth (for immunity). The wide signal bandwidth also enables the FCC to allow a very high, +30 dBm output power that supports an improved link budget 20-30 dB better than previously achievable. LoRa transceivers were built and tested to perform validations of the range in the application. Each of the transceivers were mounted three meters above the ground, simulating their end use on the side of a house. Greater than 95% network connectivity was demonstrated even with up to 20% of the WiFi connections broken.

Named Data Networking – A major breakthrough in FleetLink is the networking protocol. Several approaches including mesh IP were considered, significant limitations were found. For example, existing mesh networks are built on IP protocols developed fifty years ago for static wired networks and are fundamentally unsuited for dynamic wireless routing since a node's identity is inextricably bound to its location. This severely limits the flexibility of making changes and increases the complexity of connection recovery[6]. Mesh IP networks are complex to develop and existing LoRa-applicable networking protocols provide only for a tower-based star topology[7].

There is a match between solar application requirements and a next generation networking approach known as Named Data Networking (NDN) being developed by a UCLA-led consortium and funded by NSF.[8] In the context of distributed sensing and control, NDN provides many benefits, key among them are: 1) data is addressed by name rather than by location, removing the complexity and infrastructure expense of routing tables, 2) the network can utilize application level information. ex; NDN can efficiently forward data requests to sites because of known geolocation to support in FleetLink's self-healing network, and 3) NDN inherently supports multiple parallel network interfaces that will allow Operant Solar to achieve the needed reliability breakthrough.

Modbus and SunSpec–A large majority of solar equipment supports the Modbus interface and many also support the SunSpec standard. SunSpec compliance brings along integration with advanced communications standards such as IEC 61850, IEEE 2030.5, and DNP3, meeting SunShot goals of supporting open standards development. Fortuitously, Modbus and NDN are also quite synergistic. First, the register based Modbus protocol provides the required data language naming needed for NDN, secondly, the pairing of Modbus and NDN enhances security

[6] M. Amadeo et al, "Named Data Networking: A Natural Design for Data Collection in Wireless Sensor Networks", 2013
[7] http://www.link-labs.com/what-is-lorawan/
[8] http://named-data.net/project/

by enabling a "service aware" firewall, which checks the data structure and session flow follow the expected patterns.[9] This project successfully tested the proposal with LoRa radio transceiver prototypes with integrated Modbus interfaces and successfully connected to a SunSpec inverter and revenue grade meter.

Project Objectives:

Operant Solar's goals for the Tier 0 stage were to integrate key technology demonstration elements into a complete, single PCA (Printed Circuit Assembly) prototype, then use twenty units to perform network field tests. Operant Solar also developed network software, based on a new open source IoT library developed in cooperation with the NDN Named Data Network) Consortium. Network field testing was performed in a representative neighborhood, with the site spacing matching residential solar densities. The project exited the Tier 0 project at TRL 6: "Representative model or prototype system….is tested in a relevant environment"

Overview of software tasks: Operant Solar defined, coded, integrated, and tested multiple software components into a practical prototype FleetLink product suitable for real world testing. Initially, Operant Solar set up the development tools for the four software environments that Operant Solar target. In parallel, Operant Solar defined the requirements for the product by working with customers, software domain experts, and university partners. Operant Solar developed user stories, largely in an initial story-writing workshop; the output became the product functionality backlog.
Upon the completion of these two initial efforts, Operant Solar began to implement actual code. Using Agile project methodology, the team continually delivered functional code to both internal and external customers during the bulk of the project duration. As subsystems were completed, Operant Solar continually tested for both functionality and quality, repairing defects as soon as practical. As soon as a functional network was implemented, the team began to test and demonstrate performance at the system level, culminating with a customer-focused field trial.

Overview of the hardware tasks: Operant Solar specified, designed, fabricated, tested and deployed needed FleetLink prototypes. The general development process was: 1) characterize the four-module solution, 2) integrate the functionality of the four modules into a single PCA over several iterations, 3) validate performance, 4) resolve defects for each iteration, 5) deploy the various iterations to team members. In parallel, a COTS housing capable of outdoor deployment for the duration of the Tier 0 project was selected.
It was expected to have the PCAs fabricated and assembled at one or more contract manufacturers. Since the quality, cost and delivery performance from the initial vendor was good enough to stay with that supplier and avoid extra costs associated with sourcing from alternative suppliers. Top level assembly, test and repair of FleetLink units was done by Operant Solar project cost reasons. Range testing was performed by Operant Solar personnel.
In addition, Operant Solar created, maintained and performed tests and test plans to support the FleetLink product development. There were two main categories of test plans. The first, was standard test and alignments performed on each unit and prototype version. The second class of

[9] Understanding Deep Packet Inspection for SCADA Security – Tofino Security, December 2012

tests were performed on representative samples to verify design performance of sub-systems and overall performance in an outdoor environment.

Operant Solar performed reliability testing at an early phase in the project. Later in the project, the testing was outsourced to an external lab. Some activities required hiring of consultants, external test labs and redirecting Operant Solar personnel to review and/or accomplish the main task and subtasks depending on needed expertise.

Business development track summary: Operant Solar increased customer interaction, verified the cost model, ensured proper regulatory filings were met, developed any needed infrastructure for the business and protect IP. The three main areas for customer interactions were 1) to find new customers, 2) further develop existing and new customer relationships and 3) to gain feedback on the concept of various customers sharing the same bandwidth for communications. In the broad category of filings, Operant Solar scanned for required filings, created the needed filings, supporting documents and reports and consulted and met in person and/or electronically with reviewers, customers, potential customers, third party business, legal and technical experts, etc.

The overall project plan required staffing the needs of the project along the three major project tracks. For the hardware and software development tracks the following steps were taken. First, a senior software architect was added to develop the NDN proprietary network forwarding daemon. Second, a contract was secured with the UCLA NDN Project to consult and build the underlying NDN network library. Finally, a contract senior electrical engineer incorporated and tested FleetLink transceiver blocks into a single, integrated design. Executing tasks for the business development track was initially performed by Operant Solar personnel. Later in the project a consultant was brought on to add to industry contacts and increase business intelligence.

SOPO Task Summary:

1. Integrate the hardware technology demonstration elements (WiFi, LoRa, Modbus and RF amplifier/antenna functions) into a complete single PCA prototype with a IP65 or better enclosure.
2. Demonstrate the real-world neighborhood wireless range required to provide redundant connectivity for typical residential solar fleets
3. Develop a new open source IoT networking software library in cooperation with the Named Data Networking partner.
4. Integrate the NDN library into a practical prototype FleetLink product software suitable for real world testing
5. Perform network field testing of a 20-unit fleet in a representative neighborhood, with the site distribution matching typical residential solar densities
6. Develop the business by: increasing customer interaction, reviewing the cost model, making proper regulatory filings, developing any needed infrastructure for the business and protecting IP.

SOPO Deliverables Table, Milestone and Go-No Go Criteria:

The project work was broken into five major phases of three to four month durations: 1) define engineering requirements, 2) build and demonstrate a minimum viable prototype, 3) build and demonstrate networking software including security, 4) demonstrate real world networking performance of software and hardware; and 5) gather feedback on the results. Since the results of the final Deliverable, D4 were built on the prior deliverables, the final Go-No Go criteria was served by the D4 criteria.

	Performance Metric Description: Specific, Measurable, Quantitative	State the Success Value	How Metric is compared to Success Value	Goal Met (Y/N)	Verification Process & Additional Notes
Define the engineering requirements of a communication network *Note: all demonstrations may be held in Santa Rosa or on-line at EERE discretion.*					
D0 Month 2 18%	SW01 - Define and document the simplified IoT NDN framework SRS with the open source NDN Project.	Agreed on document with NDN partner	Agreement between NDN Partner and Operant Solar documented and communicated between Operant Solar, NDN Partner and EERE	Y	SRS and agreement letter or email from NDN Partner to the EERE.
	SW02 - Demonstrate interoperability of NDN devices with current web technology	Complete HTTP-based web interface to our existing breadboard NDN devices	Web interface successfully can query and receive data from NDN network	Y	Demonstration to EERE of web interface to 3 unit NDN network, including continued online access to functional demo system for the following 3-day period. Network shall be configured to show direct WiFi access to each unit as well as single and double hop forwarding. Annotated web transaction log with descriptive screenshot attached will be provided to EERE
	HW01 - Number of Printed Circuit Assemblies (PCAs). Used as a proxy for BOM cost.	≤ 4	Count of assemblies needed for Modbus, Sub-GHz Radio, Wifi and Sub-GHz Power Amp functions.	Y	Photograph of Modbus RTU, LoRa radio, PA/Switch and WiFi modules in 3D housing sent to EERE.
	HW03- Design of PCA(s) to reduce board count for D1HW01 deliverable completed	PCA(s) on order with supplier	Order acknowledged by PCA supplier	Y	Copy of invoice from supplier sent EERE.
Build and demonstrate minimal viable prototype hardware and software What: SW NDN libraries and hardware functionality implemented and verified *Note: all demonstrations may be held in Santa Rosa or on-line at EERE discretion.*					
D1 Month 3 10.1%	HW01 - Number of PCAs	≤ 2	Count of assemblies needed for Modbus, Sub-GHz Radio, Wifi and Sub-GHz Power Amp functions.	Y	Design files and photograph of sample unit sent to EERE.
	HW02 – COTS Housing selected for rest of Tier0.	≥ IP65	Documentation from supplier of compliance to industry standard IP65.	Y	Sample of COTS housing with dust and water intrusion compliance data from supplier sent to EERE.
	HW03a –Sub-GHz radio range Line-of-Sight (LOS) range	≥ 5km	LOS range at LOSsite01 as defined in test report. Pair of units in continuous loop back test with BER less than 1%	Y	Demonstration or report of range sent to EERE.
	HW03b –Sub-GHz radio Range	≥ 600m radius	One unit shall be mounted on a representative home in Neighborhood01. A second unit shall be placed in a loopback test mode and a minimum of 50 random locations shall be drive tested within the specified radius. 90% of the test locations shall pass test.	Y	Demonstration or report of range sent to EERE.
	HW04 – Early Reliability testing	Internal completion of preliminary test plan.	Tests 3.004 (IP6x), 3.005 (Op Temp) and 3.006 (Survival Temp) per test plan completed and results documented. Tests shall conform to applicable IEC standard as closely as possible.	Y	Internal testing executed and report to be used for improvements to next turn of HW/FW. Report and action item tracking sent to EERE.
Build and demonstrate basic networking functionality, including security. What: Software Functionality Implemented					

Note: all demonstrations may be held in Santa Rosa or on-line at EERE discretion.					
D2 Month 7 35.9%	SW01 - Initial version of IOT NDN library and solar equipment control functional	Functionality completed and demonstrated	Simple web demo of a 5 unit NDN network where D0 SW02 has been refactored to utilize IOT NDN library rather than ad hoc NDN framework. At least three nodes will have representative solar equipment connected for data collection. Network shall be configured to show direct WiFi access to each unit as well as single and double hop forwarding.	Y	Demonstration to EERE of web interface. Continued online access to functional demo system for the following 3-day period. Annotated web transaction log with descriptive screenshot attached will be provided to EERE
	SW02 - Routing of Interest and Data Packets using simple broadcast forwarding strategy functional on 5 nodes.	Functionality completed	Demonstrate: a. A web page submission of Modbus Interest Packets and b. Reception by unit and return of correct Data Packet to browser.	Y	Demonstrate functional network to EERE
	SW03 – Network performance measurement capability of node paths and latency implemented.	Functionality completed	Route trace information including numeric metrics shown.	Y	Demonstrate parametric testing of network performance to EERE
	BU01 - Validate the Operant Solar cost model of current and proposed residential solar communication methods.	Submission of the cost model to EERE for a 3rd party for review.	Annotated Excel spreadsheet and accompanying narrative that models current cost of top four residential solar communication methods vs. the solution proposed by Operant Solar submitted to EERE	Y	Spreadsheet and narrative sent to EERE for third party review. Third party selection is at the discretion of EERE.
	BU02 – Discussions with TPOs, owners, operators and/or a major solar distributor regarding sharing a portion of network BW to forward packets regardless of customer origin	≥1 TPO, 1 major distributor and or 1 owner / operators	Discussions occur and results documented and acknowledged. Three or more letters in total.	Y	Submit emails from each company's technical or management leaders acknowledging Operant Solar's discussion summary
	HW01- Design of PCA to reduce board count to one board completed	PCA on order with supplier	Order acknowledged by PCA supplier. Used for D3-HW01/02, SW01 and D4 deliverables	Y	Copy of invoice from supplier sent EERE.
Demonstrate the superior networking and real world wireless range capabilities of our NDN approach. What: NFD routing network and hardware performance verified. *Note: all demonstrations may be held in Santa Rosa or on-line at EERE discretion.*					
D3 Month 10 25.2%	SW01 - Improved routing of Interest and Data Packets using Intelligent NFD strategy functions on 8 nodes.	Functionality completed	Measure and compare the number of node paths, response latency and % bandwidth utilization both with and without NFD. Network latency with NFD to be 10% improved over the case without NFD. Zero increase in packet loss for the NFD case when compared to the case without NFD.	Y	Demonstrate improvements to network latency and send log report to EERE.
	SW02 - Browser interface presenting SunSpec solar performance data functional.	Functionality completed	Show selected inverter performance parameters via browser.	Y	Demonstrate functional network to EERE
	SW03 - Symmetric key encryption implemented.	Functionality completed	Security demonstrated by showing data packets before and after encryption/decryption process.	Y	Demonstrate correct AES 128-bit encryption by transmitting at least 10 sequences correctly from the NIST-supplied 'AES Known Answer Test (KAT) Vectors' to EERE
	HW01 – Sub-GHz radio range Line-of-Sight (LOS) range	≥ 10km	LOS range at LOSsite01 as defined in test report. Pair of units in continuous loop back test with BER less than 1%	Y	Demonstration or report of range sent to EERE.
	HW02 – Sub-GHz radio Range – In	≥ 800m radius	One unit shall be mounted on a representative home in Neighborhood01. A second unit shall be	Y	Demonstration or report of range sent to EERE.

	residential Neighborhood01		placed in a loopback test mode and a minimum of 50 random locations shall be drive tested within the specified radius. 90% of the test locations pass test.		
	BU01 - Receive letters of feedback from customers on performance demonstrations.	≥ two letters	Letters or emails providing feedback on performance received by Operant Solar	Y	Forward letters to EERE.
	BU02 - Install units at customer site.	≥ four units installed.	Letters or emails received by Operant Solar verifying installation of units and initial performance feedback.	Y	Letter from customer sent to EERE.
Validate the completed network prototype through customer viewable field trials. What: Prove network performance in real world conditions on a 20 unit, single Access Point network. *Note: all demonstrations may be held in Santa Rosa or on-line at EERE discretion.*					
D4 Month 11 10.8%	SW01 - Network performance outdoors	Functionality completed	A 20-unit outdoor representative neighborhood network will remain functional for 24-hour period while subjected to random service interruptions of the direct WiFi connections to each site. Network will route, when necessary, through both single and double hop wireless mesh connections to maintain connectivity. Data accuracy and latency during mesh fallback will be: ≥ 95% correct data packets returned in < 2.5 seconds/hop.	Y	Demonstration to EERE of web interface to NDN network, at least ten of which have representative solar equipment connected for data collection. Network shall be configured to show direct WiFi access to each unit as well as single and double hop forwarding. The web interface will provide a manual method for disabling each site's direct WiFi connection in order to demonstrate fall back routing. Continued online access to functional demo system for following 3-day period. Annotated web transaction log of 24-hour reliability test with descriptive screenshot attached will be provided to EERE
	HW01 – Reliability verification	Pass preliminary test plan.	Tests 3.004-3.006, 3.008 per test plan performed using applicable IEC standard 60529 and IEC 60068-2 by external test facility.	Y	Test report to be used for improvements to next turn of HW/FW. Report and action item tracking sent to EERE.
	HW02 – Number of PCAs.	1 PCA	Integrated Modbus RTU, LoRa and PA/Switch, and WiFi functions.	Y	Photographic evidence sent to EERE.
	BU01 – Receive letters of feedback from customers on updated demonstration.	≥ 2 customers	Letters or emails providing feedback on demonstration performance received by Operant Solar	Y	Forward letters to EERE.

Project Results and Discussion:

Overall Project Results

The following presents the project accomplishments in order of deliverables achieved. There were five deliverables D0 through D4 executed during the 12-month project. In the following, the nomenclature of deliverables is embedded in the tasks. Ex; D0:SW02 denotes the SOPO deliverable D0, task SW01.

D0 - Define the engineering requirements of a communication network

D0 was approved November 30, 2016 by the EERE team. Significant results during the D0 period were:

- Completed proof of web interface query demonstrated by the functioning web page and web transaction log.
- Accomplished an incredibly large amount of learning during the activities to define and document the simplified NDN IoT framework. One of the key results is confirming that the framework will work well in the application.
- Significant growth with the university partner relationship. One early concern was the amount of focus Operant Solar could maintain with the university. That risk is now considered closed in the risk tracker.
- A hardware design that incorporates more functions than originally planned for this stage into a single PCA.
- Business development discussions with potential customers continue to validate the magnitude of the problem FleetLink addresses.

D0 Results:

1. D0:SW01 Define and document the simplified IoT NDN framework SRS with the open source NDN Project. Result: The SRS was completed, with approval email from NDN partner received and submitted as part of the technical milestone review.
2. D0:SW02 Demonstrate interoperability of NDN devices with current web technology The web interface was demonstrated at the 11/15/2016 milestone review meeting. Result: The annotated web transaction log was submitted to EERE. In addition to the annotated log, this document included instructions for website use, the data flow of a website request and a description of key elements of the software such as 'Cloud Agent'.
3. D0:HW01 Number of Printed Circuit Assemblies (PCAs) ≤ 4. Used as a proxy for BOM cost. Result: Breadboard hardware was functional. Four assemblies were required.

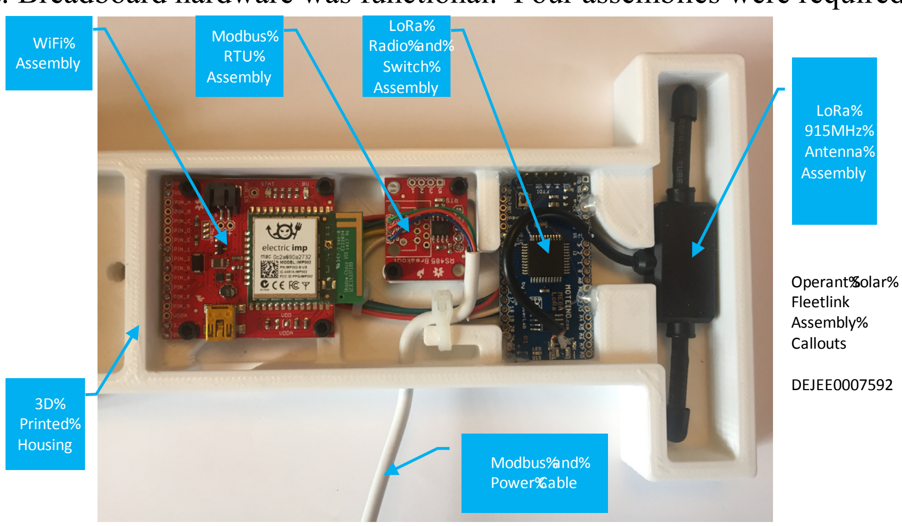

Figure 4: Functionality of each module in 3D printed housing

4. D0:HW03 Design of PCA(s) to reduce board count for D1HW01 deliverable completed The board design was completed and boards received from the CM. The boards were tested and passed all tests in the lab.

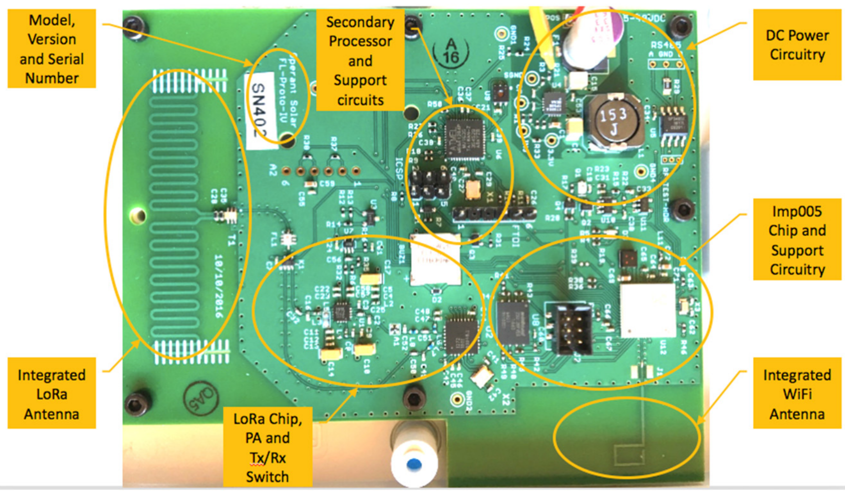

Figure 5: Received PCA (Printed Circuit Assembly) showing approximate locations of major functional blocks

D1 - Build and demonstrate minimal viable prototype hardware and software

The D1 technical milestone was approved on December 28, 2016. Significant results during the D1 period were:

- Selected COTS housing for the rest of the project.
- Number of PCAs was reduced to one vs. the Performance Metric of ≤ two. This was accomplished by risk reduction methods in the hardware design to allow adding more functions into the PCA while providing an alternative path should the new function not work out as designed.
- It was clear better range was needed to accomplish 800m neighborhood range. Two paths to achieve that were investigated. One was selected and implemented in the next phase.
- DC input voltage range needs improvement to guarantee operation at 5VDC input to the wiring harness.

D1 Results:

1. D1:HW01 Count of assemblies needed for Modbus, Sub-GHz Radio, WiFi and Sub-GHz Power Amp functions. Design files and photographs of sample unit sent to EERE. Status: The target of a single assembly was met. The following high resolution schematic/block diagram and layout views may be expanded for better visibility.

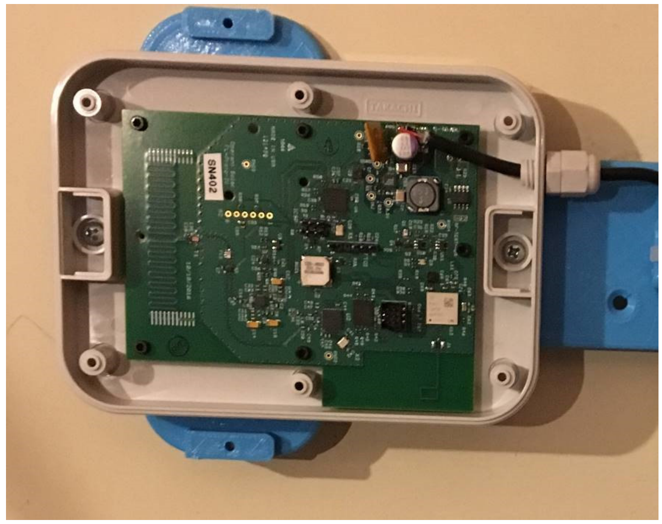

Figure 6: unit in COTS housing

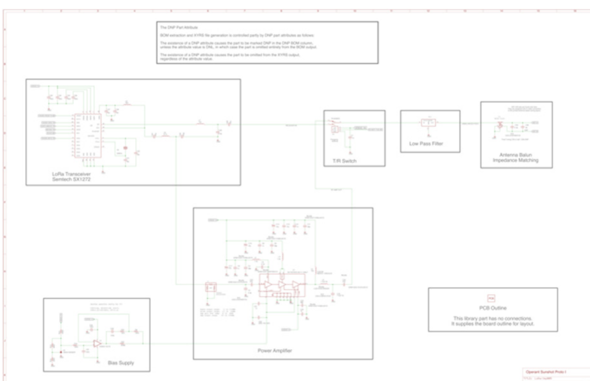

Figure 7:ProtoIV sheet 1

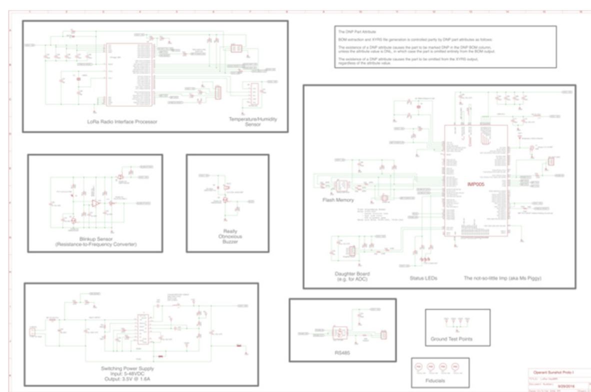

Figure 8: ProtoIV sheet 2

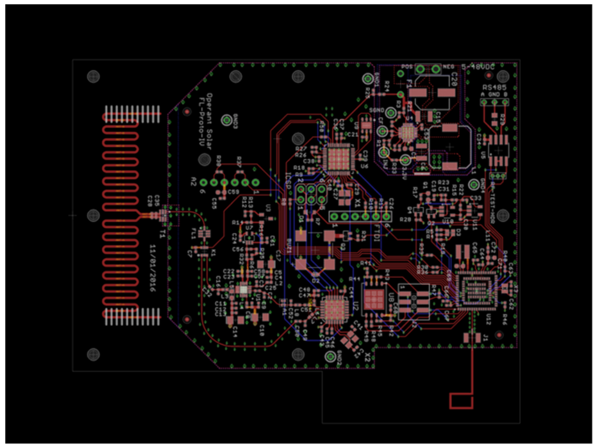

Figure 9: ProtoIV layout all layers turned on

2. D1:HW02 COTS housing selected for rest of Tier 0. Documentation from supplier of compliance to industry standard IP65 provided as part of the milestone review. Results:

   Based on specifications and initial measurements, Takachi Electronics enclosure and cable gland part number WP11-15-3, with cable gland RM10S-6S were selected for the Tier 0 project. In addition to IP65, the enclosure is made from a plastic with excellent UV resistance.

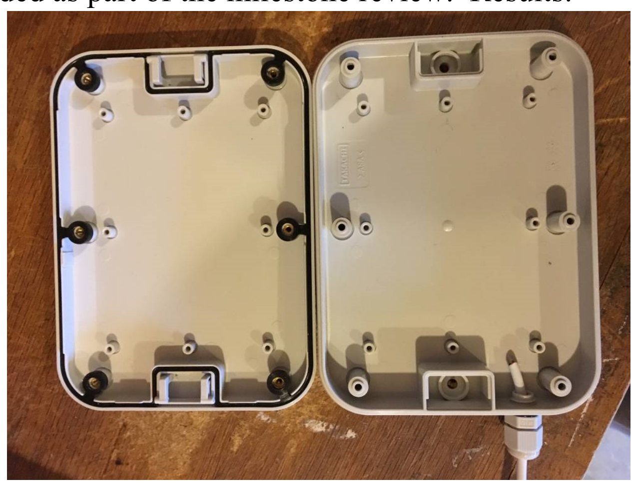

Figure 10: COTS housing with cable gland installed in the lower right hand corner

Standard	Water Intrusion
IP65	Water projected by a nozzle (6.3 mm) against enclosure from any direction shall have no harmful effects. Distance from nozzle to target 2.5m, width of the primary cone of water 40mm.
IP67	Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under defined conditions of pressure and time (up to 1 m of submersion).

Figure 11: IP65 vs IP67 specifications

3. D1:HW03a – Sub-GHz radio range Line-of-Sight (LOS) range ≥ 5km. LOS range at LOS site01 was defined in the test report submitted as part of the milestone review. The criteria for passing was a pair of units in continuous loop back test with BER less than 1%. Result: LOS was 5.5km with BER 0%. In addition to the photo below showing 5.5km LOS measurement, the report included procedural details, close-up photos of the Tx site, radio settings, logs of received signal strength indicator (RSSI) on the Rx radio for various antenna orientations. BER was evaluated by monitoring for missed packets as evidenced by error messages from the receiver software.

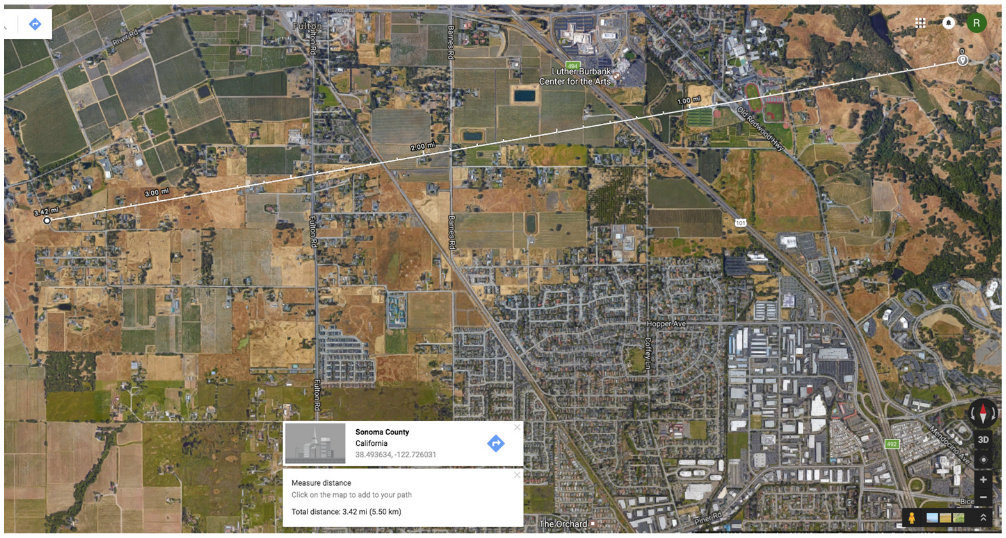

Figure 12: Overview of the LOS path below in white

4. D1:HW03b – Sub-GHz radio range in representative neighborhood. Range ≥ 600m. One unit was mounted on a representative home in Neighborhood01. A second unit was placed in loopback test mode and a minimum of 50 random locations shall be drive tested within the specified radius. 90% of the test locations shall pass test. Result: 93% of the sites within 600m pass. Highlights from the test report submitted as part of the milestone review document follow. The transmit (Tx) unit was mounted at a height of 8 feet on the NW side of a wooden wall of a house at the center of Neighborhood01. Coordinates: 38°30’49” N, 122°45’23” W. The receive (Rx) unit was mounted on a non-conducting pole 8 feet above ground in an automobile as shown in Figure 14.

Figure 13: Tx unit setup

The Rx unit was driven about the neighborhood at a speed of 10-15mph. GPS and LoRa radio RSSI data and messages were captured during the drive test. Data was evaluated for BER <1% and marked pass/fail per the green and red squares in Figure 15 below.

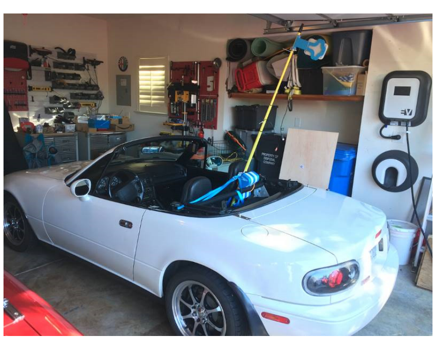

Figure 14: Rx unit setup

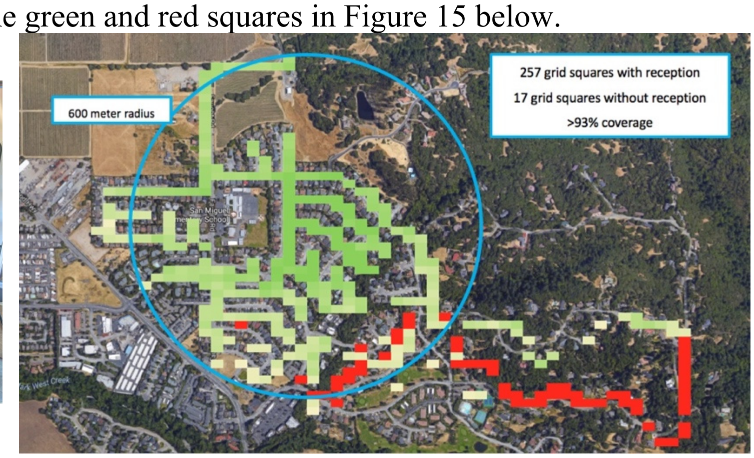

Figure 15: result of drive test

5. D1:HW04 – Early reliability testing. Tests 3.004 (IP6x), 3.005 (Op Temp) and 3.006 (Survival Temp) per test plan completed and results documents. Tests shall conform to applicable IEC standard as possible. Details of the procedures, results and observations were reported in the milestone review document. Overall result: Units passed all testing.
   Summary of results:
   Operating temperature: A Peltier based chamber was used with a PID controller used to stabilize temperatures. The temperature was held constant for 10 minutes per temperature to allow the DUT to stabilize. FleetLink units passed tests from -30ºC to +60ºC.
   Survival temperature: The same setup as in the Operating temperature test above. The figure of merit is return to normal operation after being exposed to the high/low survival temperatures for one hour of dwell time. Result: Tx pass at +70C. Rx pass at -37C
   IP6x: Water intrusion was tested as closely as possible per IEC standards for IP65 testing. IP 65 was the selected target intrusion protection for the FleetLink product. Dust testing was considered not essential for this round of testing. The procedure details were submitted as part of the milestone review package. The unit passed test criteria with no visible water inside the enclosure. Additional criteria of <60% relative humidity in the enclosure after exposure was added to add margin to the decision. Humidity is not part of the IP65 test specification.
   Note: the water cone was approximately 80mm in diameter vs. the standard 40mm at 2.5m distance from the target. To account for the lower force due to the wider cone, the test was repeated at 1m in addition to the specified 2.5m distances from the target. The unit was not opened between the two test runs. No water intrusion detected for either distance as evidenced visually and by examination of the humidity card enclosed in the unit. Shown below the opened unit post exposure.

Figure 16: post water intrusion test

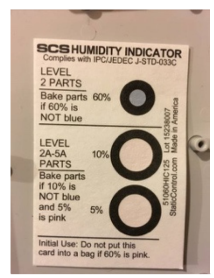

Figure 17: humidity test card post-exposure

D2 - Build and demonstrate basic networking functionality, including security

The D2 technical milestone was approved on May 12, 2017. Significant results during the D2 period were:

- Five-unit network running in the lab using the more robust IoT NDN library.
- Three letters of feedback on the shared bandwidth concept received
- FleetLink ProtoV PCA design out for fabrication with improved antenna.
- A lifetime cost model was created and scenarios run to validate the model and methodology

D2 results:

1. D2:SW01 - Initial version of IOT NDN library and solar equipment control functional
   Status: functionality completed. Demonstration completed during the monthly project call on 3/21/2017. The goal of SW01 was to demonstrate that Operant Solar could create the basic functionality of a wireless NDN network using the open source UCLA Named Data Network ('NDN') library. The UCLA NDN team, as part of this SunShot grant, rewrote their base

JavaScript library into the lighter weight scripting language Squirrel as used in the Electric Imp WiFi platform.

The FleetLink application functionality demonstrated was similar to that shown with the breadboard in summer of 2016; the key difference was the underlying networking libraries were from the UCLA NDN Project. Thus, the code was robust and extensible; implemented by the world leader in NDN technology.

Figure 18 shows the memory usage which highlights the NDN library's importance.

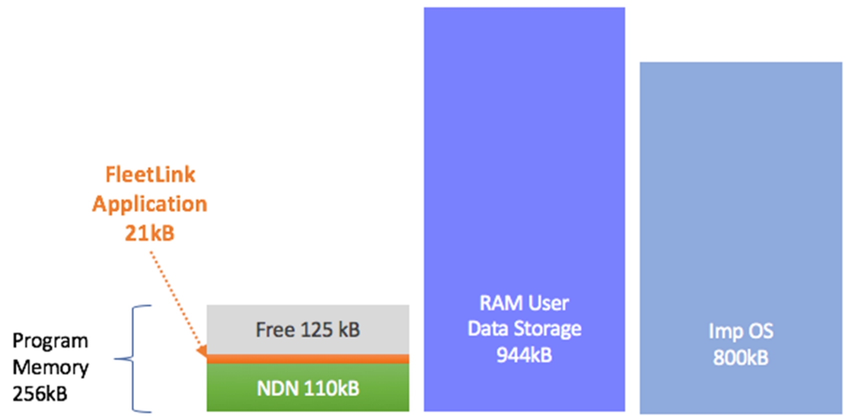

Figure 18: D3 FleetLink memory usage

Note the application is very lightweight for a full featured wireless network. This includes most of the library code for packet encryption and authentication, though Operant Solar did not implement this function until the D3 deliverable.

2. D2:SW02 - Routing of Interest and Data Packets using simple broadcast forwarding strategy functional on 5 nodes. Functionality completed and demonstrated during the monthly project call on 3/21/2017. The following two figures show the website and hardware configuration for all the software deliverables and demonstrations.

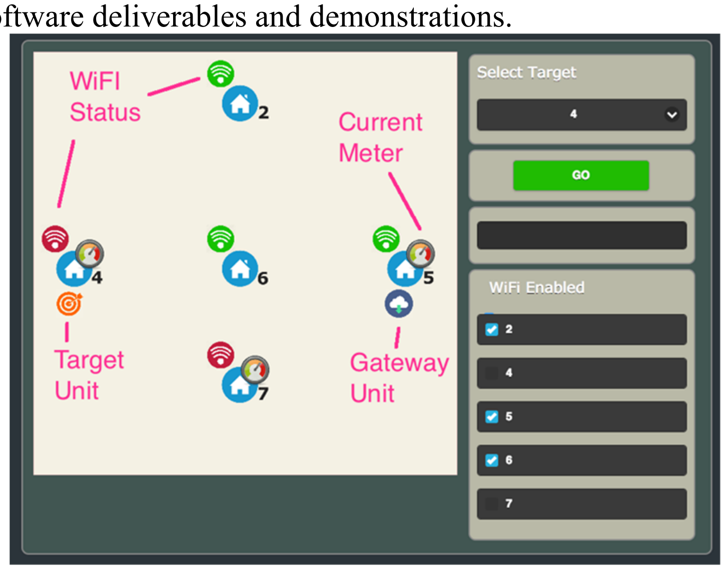

Figure 19: Webpage screen shot

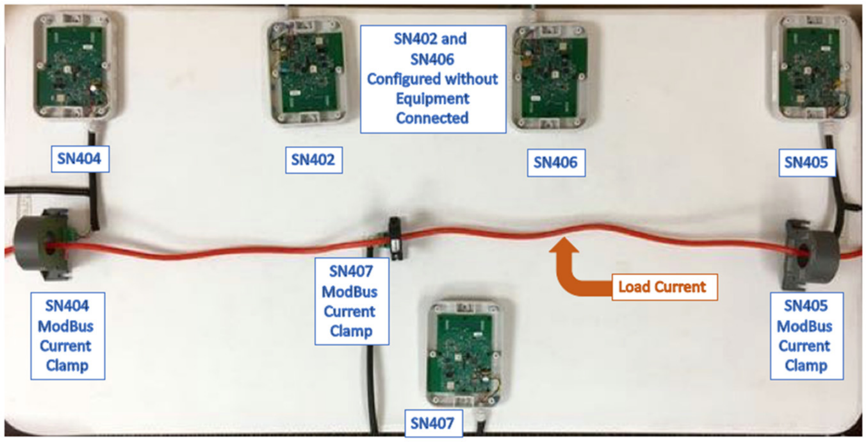

Figure 20: Five-unit characterization network in the lab

3. D2:SW03 – Network performance measurement capability of node paths and latency implemented. Functionality demonstrated during the monthly project call on 3/21/2017. A discussion of results from the Milestone report follows. To quantify the current networking performance, Operant Solar presented the following summary statistics for the test log. This consisted of 81 requests for unit data where both the target and the gateway units were chosen at random. Though the requirement was only to develop a functional measurement, data was collected to establish a jumping off point for the next milestone. The first, Message Success Rate measured 79/81 (98%). The second key measure was Mean Network Time per Successful Transaction (MNTST). MNTST measures the time from an Express Interest event to a Consume Data event. A histogram of the times is shown in Figure 21. Note that there are three groupings of the actual transaction times (in blue), corresponding to a direct WiFi request (nearly 0), a single hop wireless request (averaging 3.5 seconds), and double hops (around 7 seconds). Also, note that the network stays busy (orange bars) much longer than strictly needed. This was a focus of the smart forwarding algorithm developed in the next phase.

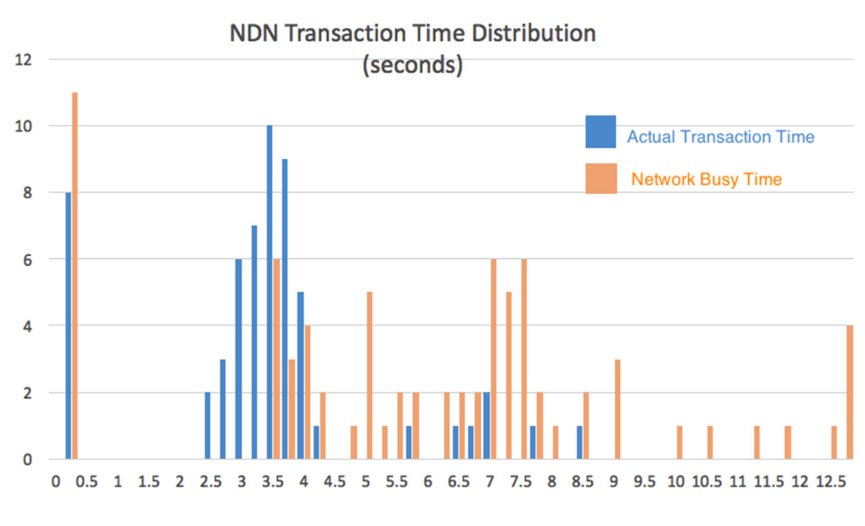

Figure 21: MNTST measurements

4. D2:BU01 - Validate the Operant Solar cost model of current and proposed residential solar communication methods. The cost model was completed and sent to EERE for review on 3/27/2017. As background to the cost model and to describe the methodology, Operant Solar also submitted, "Residential Solar Communications Link Cost Model Narrative" with the milestone review package.
   A summary of the narrative: As part of the SunShot award DE-EE0007592, Operant Solar developed an incremental lifetime cost model evaluating various methods of connecting DER sites to the internet[10]. During research of commercial communication links, a lack of consistent cost modeling across the solar industry was discovered. Anecdotally, in the absence of a quantitative model, Operant Solar observed stakeholders weighting initial site monitoring capital costs higher than an NPV analysis would suggest. Rising ongoing operational costs are, however, now forcing a reevaluation of this approach. To address this issue, Operant Solar has leveraged the existing 'Solar PV O&M Cost Model' to provide this needed analysis.
   For the purposes of this analysis, Operant Solar deleted the Measures not relevant to the specific question of O&M monitoring costs in the Residential Rooftop Details tab by setting the Boolean to 0 in the "Applicable" column. The following 10 measures were added to the 'Detailed Measures' column:

Activity Description	Activity Type	Component Type
Carrier Data Charges	Preventive	Monitoring
Security (VPN) Charges	Preventive	Monitoring
Replace Comms Card at HW Failure	Corrective	Inverter
Replace Comms Card at Protocol Sunset	Corrective	Inverter
Differential Comms Cost if Inverter Fails (infant Mortality)	Corrective	Inverter
Differential Comms Cost if Inverter Fails (Constant Failure Rate)	Corrective	Inverter
Differential Comms Cost if Inverter Fails (Wear Out Phase)	Corrective	Inverter
Install software updates, comms card and specifically related inverter updates	Preventive	Inverter
Restore lost internet connection - Phone call	Corrective	Monitoring
Restore lost internet connection - Site Visit Required	Corrective	Monitoring

   The conclusion from running test scenarios detailed in "Residential Solar Communications Link Cost Model Narrative" are the model provides a complete and accurate picture of the cost of monitoring. The model brings together the three key elements of total cost of ownership, initial capital, operation and long term expense.

	NPV Lifetime Cost
WiFi + 4G LTE	$414.20
WiFi + NB-LTE	$281.52
NB-LTE Only	$253.04
WiFi Only	**$228.14**
FleetLink (WiFi + LoRa)	$169.88

Figure 22: Cost modeling result

[10] Downloaded from the SunSpec Alliance Best Practices Guide webpage March 2017 - http://sunspec.org/wp-content/uploads/2015/06/PVOMcost-Model-Rev-1-0a-100-kW-Ground-Example-6OCT2014.xlsx

5. D2:BU02 – Discussions with TPOs, owners, operators and/or a major solar distributor regarding sharing a portion of network BW to forward packets regardless of customer origin. Discussions with one TPO and two installer/project companies were completed. In summary, the feedback was sharing Sub-GHz bandwidth can be acceptable, however, an opt in/out option must be available. Sharing actual internet access points was reported as undesirable by all parties queried. The three letters of feedback came from a TPO, Willard MacDonald, VP of Vivint Solar Labs; a Developer/Installer, Duane Hartley, CEO EnergyElective; and an Installer, Zach Franklin, Chief Strategy Officer of Grid Alternatives.
6. D2:HW01- Design of PCA to reduce board count to one board completed.
   Status: Operant Solar completed the design. Fabrication of the boards by the CM was done on time, on budget and with zero assembly defects.

D3 - Demonstrate the superior networking and real world wireless range capabilities of our NDN

The D3 technical milestone was approved on August 8, 2017. Significant results during the D3 period were:

- A change request was approved. This change request consisted of: 1. modified where monies were allocated across cost categories and between Milestones to better align with needs. 2. a minor change to the Success Value for Deliverable D2:BU02; and 3. the SOPO schedule was updated to align the milestones with the project plan.
- A four-unit network was installed in Neighborhood01 in mid-June to validate real-world range. Of note, sites 03 and 04 were communicating over a 1km distance. An additional four units were installed at the local Vivint Solar Labs facility.
- FleetLink's improved antenna design provided the expected improvement in LOS and neighborhood range testing.
- Significant SW progress was made in improving network reliability during the "find and fix" phase.
- Customer feedback validated Operant Solar's solution for communication needs.

Figure 23: Neighborhood01 installations

D3 Results:

Demonstrated >95% coverage for an 800m range in a typical suburban neighborhood with varied terrain and building features. A single report for software deliverables was embedded into the milestone review document. Highlights are outlined below. The report explained the web page setup and operation; showing the routing of interest, browser interface and demonstration of symmetric key encryption.

1. D3:SW01 - Improved routing of Interest and Data Packets using Intelligent NFD strategy functions on 8 nodes. Functionality completed and demonstrated during the monthly project call on 6/27/2017.
2. D3:SW02 - Browser interface presenting SunSpec solar performance data functional. Functionality demonstration made during the June 2017 monthly project call.
3. D3:SW03 - Symmetric key encryption implemented. Demonstration completed during the June monthly project call. Details of the encryption were included in the milestone review document.
4. D3:BU01 - Receive letters of feedback from customers on performance demonstrations. Success Value: ≥ two letters. Summary of feedback received. EnergyElective is a renewable project company. The CEO's feedback was security, reliability and lower complexity are the right areas of focus. Feedback from Vivint Solar Labs VP of R&D confirmed the problem magnitude, price point of $300 NPV over a ten-year life span is desirable and communication reliability is being used by some DER battery manufactures to validate their warranty.
7. D3:BU02 - Install units at customer site. Success value: ≥ four units installed. An email verifying installation was included in the milestone review. Four units were installed at a TPO site and four additional units installed in Neighborhood01. At the TPO site, one unit was successfully connected to a SunSpec compliant SolarEdge HD Wave inverter via the Modbus port. The Neighborhood01 four units' primary purpose is to validate network performance in the wild and to discover issues with the network. One FleetLink in the neighborhood was connected to a SunSpec compliant MeasurLogic DTS SKTD-92-4M-N-2S-200 meter via Modbus.
8. D3:HW01 – Sub-GHz radio range Line-of-Sight (LOS) range. Success Value: ≥ 10km. The result was 13.8km LOS range measured. The test report submitted included information on radio settings, procedure and test setups. The key design change from the prior LOS measurements was the improved antenna design.
   As expected, compared to results from D1, an 8-10dB improvement in RSSI was seen. Operant Solar's ProtoIV design used in D1 was a traditional folded dipole. The folded dipole design's problem was the large amount of resistive loss through the edges of the folded trace creating large RF losses. The ProtoV design for this deliverable uses a flattened biconical antenna design which greatly reduced the edge loss.
   The improved antenna topology also simplified the requirements for the matching circuitry between the RF amplifier and the antenna. This further reduced the RF losses.

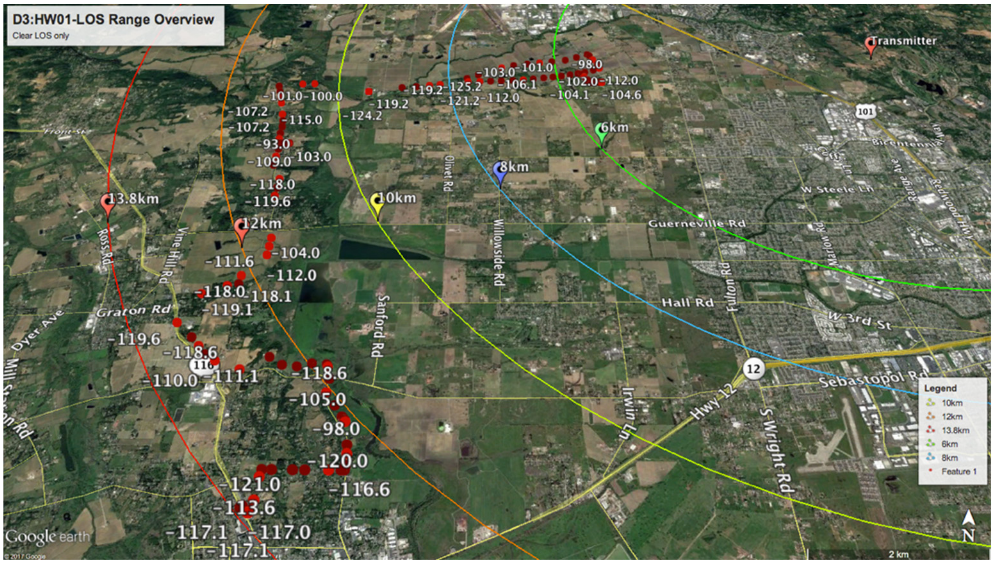

Figure 24: D3 LOS measurement map

9. D3:HW02 – Sub-GHz radio Range – In residential Neighborhood01. Success Value: ≥90% coverage at ≥800m radius. Result was 95.3% coverage within an 800m radius. Operant Solar's test report submitted included information on locations, radio settings, procedure and results. Discussion and conclusions from that report:

   Two factors improved range. The first was the improved antenna and impedance matching design. The second was increasing the Tx unit height from 2.4m to 3.9m.
   As expected, varying the antenna height from 2.4 to 3.9m had no negative effect on coverage at radius <700m. Significant improvement in connection for sites >~750m depending on terrain and line-of-sight (LOS) obstacles was obtained at the higher heights. The implication for the residential network is a diverse range of antenna heights from 8 to 16ft (2.4-3.9m) would improve Received Signal Strength Indicated (RSSI) 5 to 10dB. Effectively improving neighborhood network robustness from ~750m to 800m separations.
   Expected improvement in RSSI due to change of antenna from folded dipole to the flattened half biconical implementation was 8-10dB. Using the data from this report, this translates to a linear range improvement of approximately 25-75m through obstacles.
   A discussion of specific areas with marginal coverage using *Figure 25* follows.

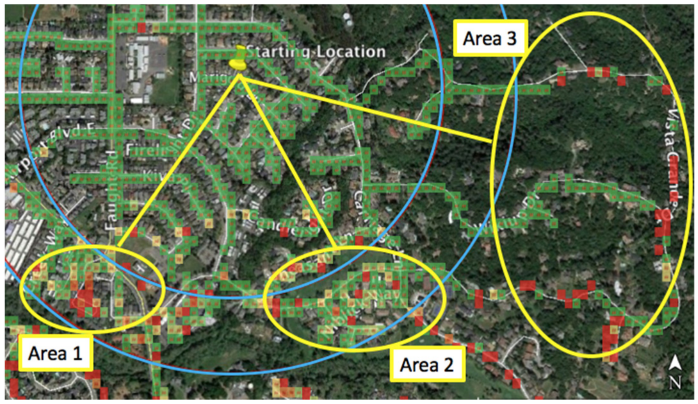

Figure 25: Areas for discussion

Area 1: All buildings are two story, wood construction, with attic spaces. The primary reason for reduced coverage in this area is three two story buildings in the LOS path "shadowing" the RF signal. Looking just slightly to the NW, there is good coverage, further evidence of the shadowing effect.

Area 2: Single story condominiums with stucco walls. The main path loss contributor was two tree lines totaling 70-150m along LOS paths to this area, resulting in 14-30dB additional loss over free space. Additionally, the stucco walls provided higher loss than wood due to its composition.

In Area 3, up to 1300m range was observed. Tree line losses would predict 40-60dB path loss. However, the average 70-80m height difference from center of neighborhood to the driven unit results in lower mean path loss due to fewer obstacles in LOS path.

D4 - Validate the completed network prototype through customer viewable field trials.

The D4 technical milestone was approved September 21, 2017. D4 summary results:

- SW01 Network Performance Outdoors complete. 20 units installed in the field. 24-hour test run completed. Website demonstration to EERE completed.
- HW01 – Reliability Verification is complete. All tests passed.
- HW02 – Reduction of the number of PCAs completed.
- BU01 – Customer feedback completed. Demonstrations of the 20-unit network completed the week of 9/3.

Significant results and learning during the D4 period were:

- Discovery of the impact of wind induced Doppler shifts on the sub-GHz radio performance and methods to mitigate the effects.
- The difficulty of finding willing homeowners to install units was much bigger task than anticipated.
- Installation time was much higher than anticipated. The time impact of dealing with different houses and the homeowners' wishes was significant.

D4 Results:

1. D4:SW01 – Network performance outdoors. Success Value: Functionality completed.

   Twenty units were deployed in a typical Californian residential community over an area approximately 7 km square, 24-hour test run completed and documented. Video and live demonstrations were presented to the EERE team at the last milestone review for the project. This demonstration showed operation and performance of the deployed neighborhood networks with as many as 20% of the WiFi connections disabled.
   The sites were clustered as shown in Figure 27 into three independent regions. Region 1 represents a typical suburban solar density of ~2 sites per square kilometer (~5 sites per square mile). Region 2 represents an "isolated pair". These types of sites, with no other neighbors, do not benefit from mesh forwarding capabilities and rely on one of the units being connected to the internet. Region 3, Figure 26was installed to test the effects of several closely spaced sites; more representative of multi-family or urban settings.

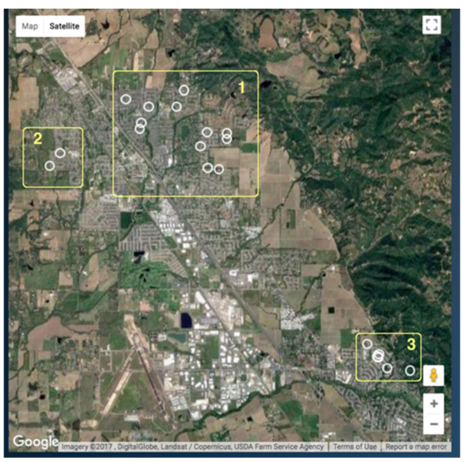

Figure 27: 20-unit geographic distribution


Figure 26: Region 3

   Each site had a FleetLink gateway installed, connected to site WiFi, and powered via and AC adapter. To meet the requirement of "representative solar equipment" as called out in the SOPO, ten of the sites had a small solar panel with a Modbus adapter to read the panel short circuit current. This served as a site irradiance meter. The other ten sites simply had a FleetLink which could report its presence and forward data as needed wirelessly.

Figure 28 depicts the result of a 24-hour test. Since each test cycle tested 4-5 wireless data retrievals, 2317 wireless requests were issued. Of these 2317 requests, 153 were retried after an initial link failure. The number of finally successful retrievals were 2217, for a success rate of 95.7%, exceeding the SOPO pass/fail rate criteria of 95%.

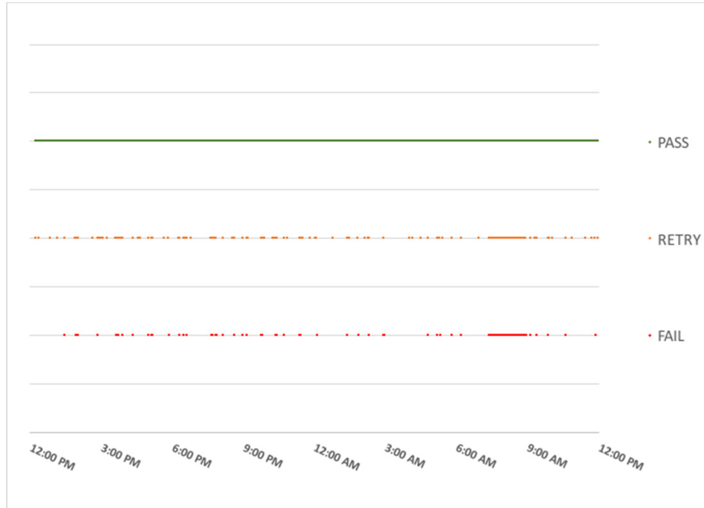

Figure 28: D4 24-hour test run result

Note, however, that 38 of these failures were consecutive at approximately 7:30 AM. These were due to a FleetLink unit that was battery-powered (rather than through an AC adapter) which became unexpectedly discharged. Excluding these failures, the success rises above 97%, which is more indicative of the true network performance. In either case, the SOPO requirements were met.

2. D4:HW01 – Reliability verification. Success Value: Pass preliminary test plan.

The samples passed all tests per the test plan. A summary of test status below. Temperature tests were performed per ETSI standards for Outdoor Units (ODU).

Preliminary Test Plan Number	Test Name	Status
3.004	IP65	Pass
3.005	Operating Temperature, -40C to +85C	Pass
3.006	Storage Temperature, -45C to +60C	Pass
3.008	Operational Temperature Cycle, -40C to +85C.	Pass

Test reports for IP65, Operating, Storage and Cycling of Temperature performed by Quanta Labs, Santa Clara, CA were submitted to the EERE. Communication during Operating Temperature and Temperature Cycling testing passed with 99.6% success rate.
Storage (non-operating) Temperature testing passed. Post exposure performance measurements matched pre-exposure performance to within specification. IP65 testing completed. Pre- and post- exposure parametric performance met specifications. No contaminants were observed in the units after exposure.
Four communication failures observed during operating temperature testing fell into two categories. Two failures were from the test lab's WiFi disconnecting from the internet. The

test lab confirmed during that time their service went down. The other two failures were deemed a low-level priority since the units recovered without intervention and an immediate retry, which is part of the normal network strategy, would have resulted in a pass.

3. D4:HW02 – Number of PCAs. Success Value 1 PCA. Figure 29 shows the final single board design.

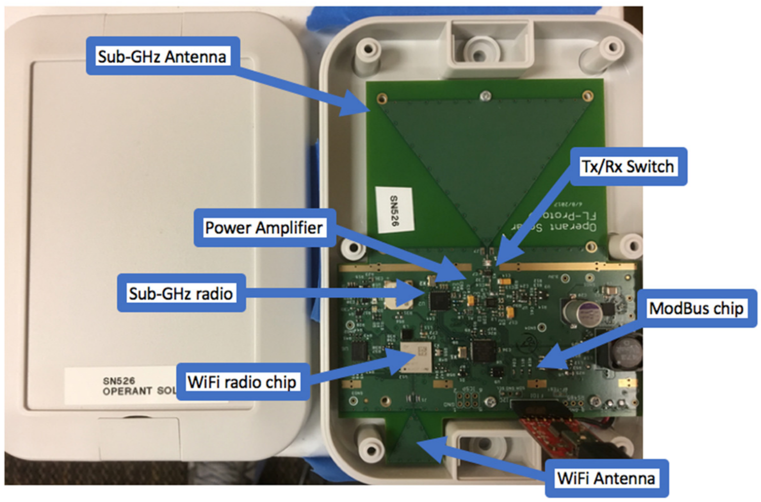

Figure 29: Annotated final board design

4. D4:BU01 - Receive letters of feedback from customers on updated demonstrations. Success Value: ≥ two customers. Two letters of feedback were received. One each from the VP of Vivint Solar Labs and the CEO of EnergyElective and submitted to the EERE. The main points of feedback were:

   - Overall fleet connectivity results met the needs of DER and PV
   - Security is important and the Operant approach appears solid
   - Cell modems were noted as a needed alternative for specific situations
   - Redundant communication path is the best way to get needed reliability
   - FleetLink cost point is appropriate
   - Remote diagnostic and repair using the redundant link is a key selling feature
   - System functionality is clear and intuitive

Significant Accomplishments and Conclusions:

- The problem of unreliable internet prevalent in DER industry was validated
- Operant Solar's FleetLink gateway was optimized for DER sites and demonstrated:
  - ½ mile real world range
  - Fleet connectivity >99.3% with >20% sites disconnected
  - Bidirectional and scalable to large fleets
  - Lightweight software stack enables inexpensive hardware

- Secure: encrypted w/ key exchange & authenticated
- Connectivity to industry standard SunSpec Modbus interface

The one unexpected learning from this project was the amount of time and effort required for installations into the neighborhood. Homeowner preferences and individual installation requirements were solvable, but very time consuming. Fortunately, Operant Solar was on track for the project schedule so the extra time was absorbed without undue hardship.

Inventions, Patents, Publications, and Other Results:

During this award, Operant Solar did not submit any patents. The development of the flattened half biconical antenna using the PCB ground plane as the mirror image while novel was not seen as patentable.

Publications, Collaborators, etc.

This project was originally based on a collaboration between Operant Solar and the UCLA-led Named Data Project.

https://named-data.net/

They provided, under contract, an open-source software library for the unique IoT version of their Named Data Networking. Operant Solar continues to base its work on that collaboration and consider it a keystone to success.

Another key partner is Electric Imp, who supplies the secure WiFi link.

https://electricimp.com/

They are the market leader in WiFi IoT hardware and software platforms. They have just helped by implementing a specific software feature: a cryptographic hash algorithm. They issued a press release regarding Operant Solar's use of their platform earlier in 2017:

http://www.businesswire.com/news/home/20170419005365/en/Electric-Imp-OS-Packs-Advanced-Security-IoT

Presentations

UCLA NDN Project partners, Alex Afanasyev and Jeff Thompson delivered a workshop paper at this years Named Data Networking Community Meeting in Memphis.

NDNcomm 2017

It was titled "FleetLink: NDN-Powered Low-Cost, Low-Rate, Reliable, Secure Communication for Neighborhood Solar"

Direct link to paper

Operant Solar, as part of this DOE SunShot program, attended the 2017 Solar Power International trade show. As a member of the DOE Startup Alley, a project overview was presented at the Innovation Showcase.

Path Forward/Commercialization Plan:

The project in award DE-EE0008135 will add a cellular option in addition to WiFi, allowing multiple sites to share cellular data charges. By sharing the expensive cellular hardware and data the resulting data charge savings is significant as is the capital cost reduction. Operant Solar will add a unique and newly developed cloud agent network forwarding layer to the software system architecture, greatly simplifying customer interaction with the fleet. Operant Solar will develop a manufacturable FleetLink product: lowering the hardware cost, improving the software quality, and meeting environmental and regulatory requirements. Finally, Operant Solar will execute a business development plan that will exit the Tier 1 project with private funding and a significant beta development partner. The net system cost savings of at least $.05/W supports the SunShot cost goals and the flexibility and scalability of the solution accelerates the velocity and ubiquitous adoption of solar.

The targeted improvements will include:

- Business Development
    - Extend the FleetLink concept beyond simply reporting solar production to command and control of all DER assets, such as energy storage and demand response
    - Using contacts established as part of the EE0007285 award, forge a deeper alliance with DER installers for beta testing
    - Explore the burgeoning low income multifamily housing solar market
- Hardware
    - Execute a comprehensive cost reduction effort to improve the commercial viability of the product
    - Add a cellular option to replace the primarily WiFi primary link to increase the addressable market
    - Perform extensive environmental and regulatory testing and redesign as appropriate
- Software
    - Add ‘Agent to Agent’ network forwarding. To be described more fully later, this is a breakthrough software abstraction that allows an extremely simple and secure API to the fleet
    - Continue the partnership with the UCLA Named Data Networking Project to further develop the open source IoT NDN library
    - Perform significant field and lab testing and associated SW defect repair

Over the next 18 months, the Tier 1 SunShot award project will advance the FleetLink product beyond the concept stage. Operant Solar will successfully commercialize the NDN software concept and complete UL and FCC testing required for a commercial product. Through the long-term field trails, Operant Solar will build more confidence in the redundant link technical approach and believe it superior to competing industrial IoT approaches.