RF Harvesting

Ultra-small (Sub-Millimeter Square) Integrated Circuit Solution for simple RF energy harvesting

White Paper

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Concept to Silicon

Abstract

Today, 14.6 billion devices are estimated to be connected and online. By 2027, 30[i] billion devices are projected to be online. Apart from mobile phones, a great majority of such devices are anticipated to be low power consumer and industrial devices that will use both short- and long-range wireless technologies to get online. These device architectures almost always include sensors, *i.e.* temperature, location, motion, etc., that pair with a wirelessly access technology, such as Wireless Local Area Networks (WLAN), Zigbee, or low power wide area networks such as LoRaWAN. The proliferation of such connected devices is referred to as the Internet of Things (IoT). Today, low power devices are often powered by a single 1.7V or 3V lithium-ion cylindrical or coin cell battery. IoT manufacturers aim for devices to last for 3+ years before batteries are to be replaced. To extend battery life, software, hardware and system operations are routinely optimized. But, even in the most optimistic scenario, limited and finite supply of raw materials such as lithium, cobalt and nickel are insufficient to keep up with demand. RF energy harvesting, paired with a rechargeable battery, is a viable solution for developing ultra-low power connected devices operating in such environments.

This paper highlights how an ultra-compact (sub-millimeter square), NoiseFigure Research (NFR) integrated circuit can be used for RF energy harvesting in the 2.4GHz spectrum. It shows the mechanical and electrical characteristics of NFR's RF harvesting integrated solution, including the size offering, frequency of operation, and antenna designs based on FR4 and flexible substrates. Industry use cases are provided to give insight into possible applications and highlight operating conditions customers must analyze prior to adopting an RF harvesting solution.

Customers, Applications, and Operating Environments

RF harvesting can serve as a solution for powering connected device or recharging a battery in connected devices deployed and operating in physical locations where it is difficult, impractical, or impossible to change batteries. However, there are challenges to utilizing RF harvesting solutions in IoT applications. One is the unpredictable nature of RF energy availability, in addition to the RF energy variation that can occur across time and space. And second, even when customers can successfully harvest RF energy, system requirements and data delivery duty cycles may require energy levels that RF harvesting alone cannot supply. Thus, the usability of RF energy harvesting requires an intimate understanding of the system requirement to determine its most cost-effective use. NFR has worked with leading customers across different industries to guide the development of NFR's first generation of Harvesters. An overview of customer, applications, and lessons learned are provided in the sections ahead.

Customer #1: Defense prime developing an asset tracking application for *indoor* warehouse environments

The US government has a strict requirement that the location of all sensitive military hardware assets must always be known. Stored at confidential locations, the precise locations of assets inside warehouses must be immediately identifiable upon request. If an asset moves, vibrates, or shifts location, the warehouse operator must immediately be notified. NFR's defense prime customer was tasked to build a system wide asset tracking network where tags, which are mounted on military hardware, are expected to last indefinitely. This effort required tags to operate in a battery-less manner to avoid manual labor to track and replace the batteries. RF harvesting provided an idea solution to share location data to backend networks, only when assets are polled. In this solution, NFR's harvesters aim to be the sole source of power for ultra-low power sensor with using ambient and intentional RF power delivery.

Customer #2: Industrial IoT solution provider serving *outdoor* equipment tracking in varied terrain

NFR's customer, an industrial IoT solution provider, was hired by a multibillion dollar compressed air and gas provider to develop an outdoor equipment and vehicle tracking device, which is to be deployed across the continental US. The compressed air and gas provider's equipment can be deployed in rural communities, but equally can sit next to a gas station or corporate office in urban and suburban neighborhoods. NFR's customer developed a GPS tracking device powered by a 3.7 Volt battery. To address the compressed air and gas provider's varied needs, NFR's customer developed multiple versions of their device, each powered by a different combination of power sources and wireless networks. Some devices need to last for 5-years, while other devices up to 10-years. NFR's customer has developed two stock keeping units (SKUs), each with different battery architectures, and deployed these SKUs in production. The first architecture is a solar panel coupled with a rechargeable battery. The second is a lithium chloride battery that is drip charged by a super capacitor. The customer is studying a third SKU with NFR using RF harvesting, alongside a standard rechargeable coin cell battery. In this solution NFR's harvesters aim to prolong the battery life.

Customer #3: A consumer electronics device manufacturer serving *indoor* consumer use cases

The proverbial "smart home" ecosystem exploded with the launch of voice assistants embedded inside consumer electronic (CE) devices. Starting with Amazon's introduction of Alexa in 2014, and subsequently with Google's Assistant in 2015, adoption of hardware products, such as smart and connected speakers, have created consumer demand for companies to *reinvent* old products. Photo frames that were historically intended to be static devices, must now connect to the Internet and photos displayed must regularly be refreshed. In locations where daylight savings required wall mounted clocks to be manually adjusted twice a year, consumers now expect clocks to automatically adjust themselves. These peripheral devices were not intended to be wall powered and in limited instanced, required batteries. NFR works with leading CE manufacturers to investigate how NFR's harvesters can be embedded inside manufacturer's end devices and consumer routers to power a battery-light, if not a battery-free, world while maintaining non-interrupted smart home functionality. In these solutions, adoption of NFR's harvester is explored using a hybrid architecture where some functions or system will be powered entirely by harvested energy, while others require harvesters complementing batteries.

Lessons Learned & What We Found

From customer engagements, NFR has observed select operating environments or design parameters must be applied before RF harvesting solutions can reach ubiquitous usage. The first is harvester must be integrated and agnostic to antennas (e.g., harvest with any antenna) in the system. For some customers, harvester form factors must be small enough that they can be used anywhere. And where additional RF transmitters may be needed to augment and supply the local environment with RF energy, the total cost of ownership (TCO) of an integrated transmitter and receiver solution must be less than the business value created. Lastly, physical distance between harvesters and local transmitters and battery size impacts how quickly NFR's harvester chips can recharge a connected device.

NFR's Chip Solutions

Customers developing devices that serve low power applications (microwatt) and utilize low connectivity duty cycles (less than 5%) can use NFR's RF Harvesting ICs to prolong battery life (e.g., +10 years) and in select instances, replace batteries altogether. NFR understands system power efficiency is a function of optimized transmitter and receiver architectures. NFR's RF harvesters opens new frontiers for extending the life of battery operated low-power sensor and brings RF harvesting closer to reality to possibly eradicating battery from ultra-low power low duty cycle applications.

Today, most providers solving battery life problems with RF harvesting focus on RF transmitter architectures using beamforming, more antennas, or more power. Few are solving for the entire RF energy harvesting system. For outdoor environments, NFR expects mobile cellular standards, such as 5G to incorporate beamforming techniques allowing operators to effectively direct power beams to different end devices. NFR's RF harvester chips are also designed to be transmitter agnostic and will detect and harvest signals as they appear. In environments where NFR's customers cannot change the transmitter configuration, NFR's harvester chips are optimized against receiver sensitivity with an ability to detect less than –10dBm of energy and subsequently, harvest this energy into a form usable by the end device. However, where customers have access to deploy both the transmit and receive hardware infrastructure, NFR's beamforming chips can yield even higher levels of harvesting efficiency.

NFR's current technology can harvest 0.9 V to run simple wake up operations and send frames from an ultra-low power BLE device. As circuitry geometries shrink in size and new semiconductor materials advance technology nodes, harvesters will become more efficient. Devices will be able to operate with nanowatt power consumption while staying in sleep mode, further unlocking the RF harvesting opportunity to serve as a battery enhancer and in some systems as a sole power source.

NFR Test Information

NFR RF harvesters have been tested in an open warehouse environment where a 4x4 patch antenna phased array is used to create a directed beam. In this test, all antennas are fed the same power with the same phase to create a 0-Azimuth and 0-Elevation static beam. Figure 1 shows NFR's coupon held directly in front of the array. An NFR harvester is mounted on the coupon and fed RF power via the broadband antenna The antenna acts as a tunned feed to the harvester, which provides a rectified DC output fed into a diode load regulated by a resistor. Figure 1 shows the diode lighting up. Figure 2 shows the flexibility of the coupon in use.

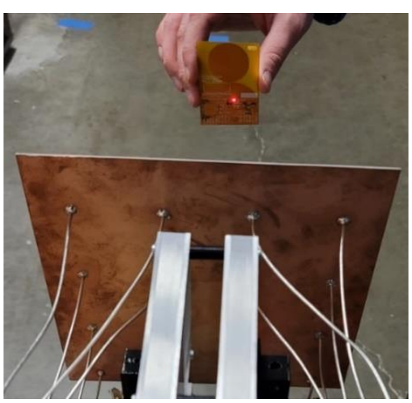

Figure 1: RF harvester operating at 2.4GHz receiving incident signal from a 4x4 patch antenna array using a 1W distribution feed. The distance between the RF Harvester is around 30 cm.

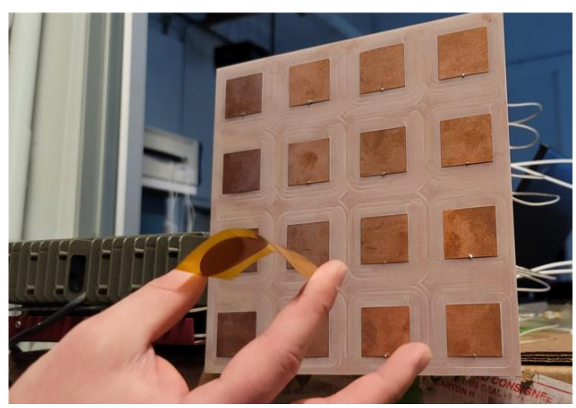

Figure 2: Flexible coupon used for testing RF Harvester. The coupon can receive power and data while moved and flexing.

Test Results

Figure 3 shows NFR's RF harvester voltage output at different distances and angles from the transmit antenna. There is a drop in voltage levels detected the farther we are away from the transmitter, per free space path loss. These measurements are taken with a fixed power beam and a non-polarized patch antenna array tunned to 2.4 GHz without further enhancements (see Figure 4) and an equally receiving single antenna. The power fed to the antenna array transmitter is 1W, allowing NFR's NFW310M harvesters to capture energy up to 5m away. *NOTE: Data below is shown for incident wave without flexing the coupon. And, more harvesting use cases can be served by implementing a higher element, dynamic beamform.*

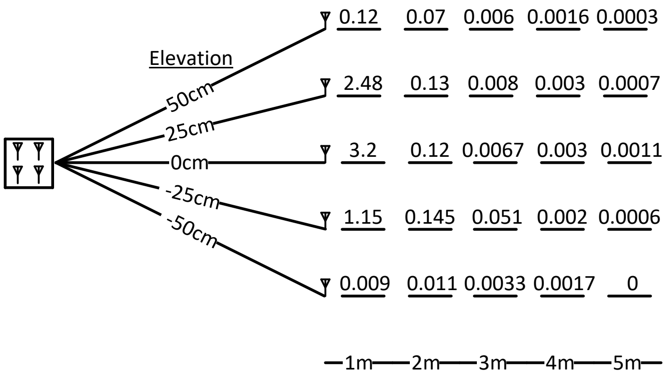

Figure 3: NFW310M Vout comparison at different distances from the phased array plan. Data is shown from 1m to 5m.

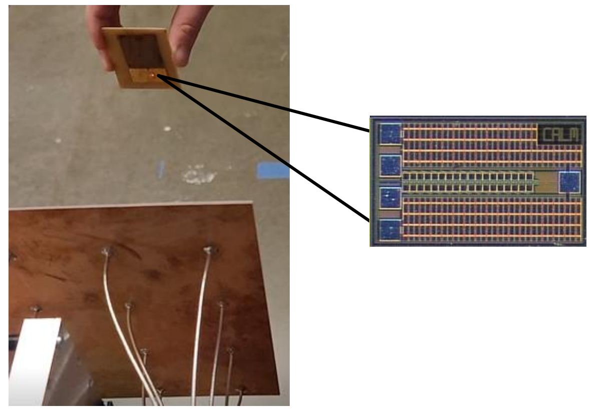

Figure 4: Antenna used for obtaining data in Fig. 3. A non-flexible patch antennas dual layer FR4 is used in this case. NFW310M total size is 600µm x 900µm.

Contact

Order a Harvester hardware developer kit (HDK) today by emailing hello@noisefigure.com or to learn more, please visit www.noisefigure.com/harvesters.html.

About

NFR is a team of 35 semiconductor designers and product inventors based in Renton, Washington. NFR's leadership brings over 50 years of combined industry experience to serve customers and over 50% of NFR's team members hold advanced degrees. NFR's products are used across Defense, Commercial, and Aerospace industries. NFR has taped out ASICs using 1µm to 14nm process technologies and has global supplier partnerships for manufacturing, packaging, and testing to deliver first prototypes and volume production chips to customers.

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[i] Ericsson Mobility Report, November 2021. IoT Connections Outlook.