A Wideband, Quasi-Isotropic, Kilometer-Range FM Energy Harvester for Perpetual IoT

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***Abstract*— Unlike conventional energy harvesters that are tuned to individual frequencies and are directional, the proposed wideband (23% fractional bandwidth), omnidirectional system harvests from all FM towers in vicinity. Hence, it does not require each sensor node to be carefully aligned to any one source and makes itself suited for mass-deployment applications such as precision agriculture and structural health monitoring. It harvests as much as 923 μW on a rooftop at 1.54 km from an FM tower while retaining omnidirectionality partly thanks to the proposed antenna, which has a wider bandwidth and a higher measured gain (2.0 dBi) than the commercial reference wideband antenna. It achieves competitive efficiency (56%) and sensitivity (−17 dBm) while retaining wideband operation rather than being specifically optimized to individual frequencies. The system (fabricated on low-cost FR4) harvested outside ambient FM energy indoors at the same 1.54-km location to power a wireless sensor node without needing to shut down periodically.**

***Index Terms*— Ambient energy harvesting, FM, wideband.**

I. INTRODUCTION

PROLIFERATION of wireless sensor nodes (WSNs) and Internet-of-Things (IoT) devices is accentuating the need for energy-harvesting solutions that can fulfill the power demands of these connected devices. Energy harvesting saves labor costs associated with replacing batteries and allows devices to be deployed in hard-to-reach places where replacing the batteries would be impractical (e.g., bridges, chemical plants, and aircraft) [1]. It reduces the environmental impact associated with battery production and disposal. Photovoltaic harvesting has the advantage of high-power density, whereas radio-frequency (RF) harvesting has the advantage of being available day and night [1]. They can be implemented to operate in tandem to complement each other [2]–[5]. FM energy harvesting, in particular, is an attractive solution as its relatively long wavelengths allow less attenuation through mediums and enable appropriately sized antennas to harvest more energy without needing to form arrays [6]. An FM radio is also widely available especially in urban areas. FM-harvesting research thus far focused on the proof-of-concept, lab-environment testing of subcomponents [7]–[9], and deserves further advancement.

In this letter, we demonstrate, through real-world field-tests, an FM energy-harvesting system (fabricated on low-cost FR4) capable of harvesting outside ambient energy from all nearby FM towers in all FM frequencies simultaneously to power a WSN indoors without needing to periodically shut down.

II. PROPOSED FM ENERGY-HARVESTING SYSTEM

A. Proposed Omnidirectional Antenna Design

A classic bow–tie (design1) has a shorter segment a, a longer segment b, and infinitesimal segments of intermediate sizes between them [see Fig. 1(a)]. These segments resonate at different frequencies, allowing broadband operation. The bandwidth can be widened by adding c (design2), but its S_{11} becomes less steep as its current distribution becomes less focused [see Fig. 1(b)]. The proposed antenna transposes a smaller bow–tie and creates another S_{11} dip around 257 MHz, which stretches the original S_{11} dip across the FM band to be wider and deeper.

The proposed antenna (1064×592 mm^2) was fabricated on MG Chemicals 521 substrates without any backside ground plane. Fig. 1(a) indicates the 50-Ω, 4-mm-gap feed point. The measured S_{11} achieves <-10 dB across the entire FM band [29% antenna fractional bandwidth (FBW); see Fig. 1(c)]. In comparison, the measured S_{11} of the commercial reference wideband antenna (Diamond SRH789) achieves <-10 dB in only about half of the FM band. The proposed antenna also has a superior measured gain [2.0 dBi; see Fig. 1(d)]. Fig. 1(e) and (f) shows the proposed antenna's omnidirectionality.

B. Rectifying Circuit With Matching Network

Multiple stages of shunt capacitors and series inductors form broadband matching [10], [11]. The optimal number of

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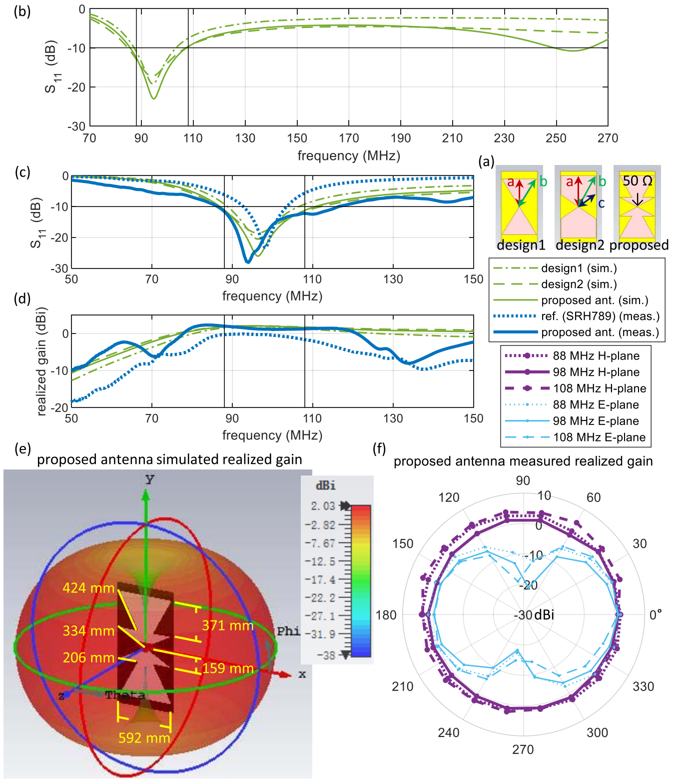

Fig. 1. (a) Antenna illustration. (b) and (c) S_{11}. (d) Realized gain. (e) Proposed antenna simulated realized gain. (f) Proposed antenna measured realized gain.

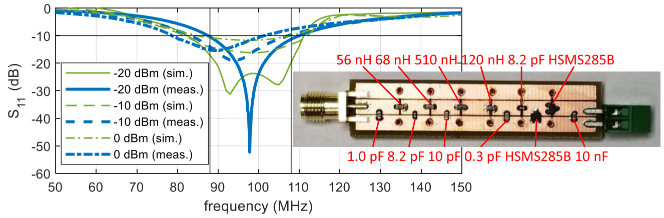

Fig. 2. Matching + rectifier S_{11} with a 3.3-kΩ load.

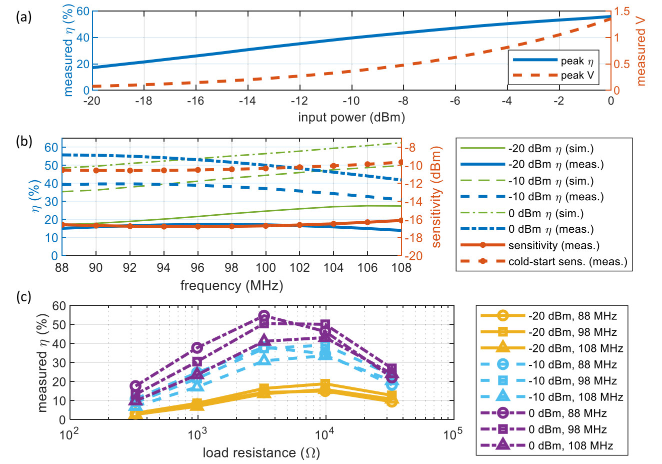

Fig. 3. (a)–(c) Matching + rectifier η. (a) Output voltage and (b) sensitivity in the FM band. 3.3-kΩ load for (a) and (b).

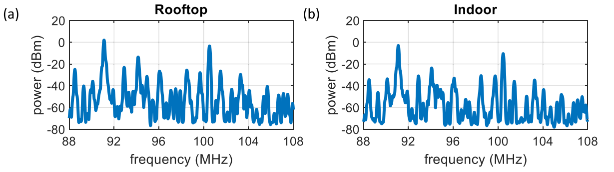

Fig. 4. (a) Rooftop and (b) indoor power spectrum at the test location.

rectifier stages according to the Fano limit was calculated to be less than 3 [12]. One stage was chosen for low-leakage and insertion loss [1], [13]. To align the S_{11} dip with the FM band postfabrication, a 680-nH inductor was replaced by the 510-nH inductor, and a 0.5-pF capacitor was removed from the now vacant space between the 10- and 0.3-pF capacitors. This contributed to the discrepancy between the shapes of the simulation and the measurement results (see Fig. 2).

At the targeted input power level of −20 dBm, the matching + rectifier assembly (fabricated on MG Chemicals 555) achieves <−10 dB across the entire FM band (23% matching + rectifier FBW). Even at −10 dBm, the highest S_{11} in the FM band is ≈−10 dB. The input resistance of the power management unit (PMU; TI BQ25570EVM-206) fluctuated around 3.3 kΩ during the cold-start and initial charge–discharge cycles; hence, this is the reason for the 3.3-kΩ load.

Efficiency (η) of 17%, 40%, and 56% are, respectively, achieved at −20, −10, and 0 dBm [see Fig. 3(a)], owing to the fact that the efficiency of Avago HSMS285B improves from −20 to 0 dBm [14]. Setting the design target to 0 dBm would improve η beyond 56% but would compromise sensitivity. Sensitivity according to the PMU specification was measured to be −17 dBm (−11 dBm for cold-start) [see Fig. 3(b)]. With varying load resistance, the highest η are achieved with 3.3 and 10 kΩ. η decreases with 1 and 33 kΩ but still maintains double-digit values at −10 and 0 dBm [see Fig. 3(c)].

III. SYSTEM DEMONSTRATION AND COMPARISON WITH RELATED WORK

A. System Demonstration

The test site (33.775869, −84.389824) is 1.54 km from the 91.1-MHz 100-kW effective radiated power (ERP) FM tower (33.778056, −84.406111). At 91.1 MHz, 2 and −3 dBm were, respectively, received on the rooftop and indoors (closed walls, windows, doors, floor, and ceiling) by the proposed antenna [see Fig. 4(a) and (b)]. The full-band and omnidirectional nature of the harvester will aggregate power from this entire spectrum, yet the 91.1-MHz signal will serve as the prominent source of energy, allowing the harvester's performance to be characterized with respect to the distance from the 91.1-MHz tower. (The next highest power received on the rooftop and indoors was, respectively, 6 dBm less and 8 dBm less.) According to the Friis formula, the theoretical maximum power to be received is 9.8 dBm [15].

The maximum, minimum, and average amount of power harvested throughout a day on the rooftop were, respectively, 923, 738, and 822 μW [see Fig. 5(a)]. The corresponding rectifier output voltages were 2.5, 2.1, and 2.3 V. The amount of power harvested indoors was 159 μW (1.9 V). Even in indoors, the harvested power was enough to cold-start the PMU and to power the WSN (Kontakt.io S18-3, measured consumption 141 μW) without needing to periodically shut down [see Fig. 5(b)]. The reserve capacitor (three parallel Seiko CPH3225A) and the PMU's charge cycling capability serve to maintain stable power output during interruptions.

TABLE I

COMPARISON OF AMBIENT RF ENERGY-HARVESTING WORK

	region (MHz)	-10 dB match (FBW)	end load	antenna (gain, dimensions)	harvested power @ distance	η (RF-dc)
[16]	400-600 band	partial TV (2 %)	MCU	log-periodic (7.3 dBi, $0.87\times0.51\ \lambda^2$)	17 μW @ 6.3 km	21 % @ -4.74 dBm
[17]	400-600 band	partial TV (4 %)	WSN	horiz. dipole (1.33 dBi, $0.38\times0.06\ \lambda^2$)	NA @ 6.3 km	40 % @ -5 dBm
[18], [19]	400-600 band	NA	sensor	log-periodic (5 dBi, NA)	60 μW @ 4.1 km	30 % @ 0 dBm
[20]	400-600 band	NA	WSN	log-periodic (6 dBi, NA)	NA @ 4.2 km	23 % @ -8.8 dBm
[21]	400-600 band	partial TV (7 %)	LED	loop (4.48 dBi, NA)	3.6 μW @ NA	28 % @ -12.2 dBm
[21]	880-960	partial GSM (5 %)	LED	loop (4.73 dBi, NA)	5.5 μW @ NA	18 % @ -15.2 dBm
[21]	1710-1880	partial GSM (1 %)	LED	loop (4.73 dBi, NA)	2.4 μW @ NA	7 % @ -15.1 dBm
[21]	1920-2170	partial 3G (7 %)	LED	loop (4.76 dBi, NA)	1.1 μW @ NA	40 % @ -25.4 dBm
[9]	76-95	partial FM (4 %)	capacitor	loop (1.83 dBi, $0.22\times0.11\ \lambda^2$)	NA	26 % @ -18 dBm
this	**88-108**	**full FM (23 %)**	**WSN**	**omnidirectional**	**923 μW (rooftop) @ 1.54 km**	**56 % @ 0 dBm**
work				**(2.0 dBi, $0.35\times0.19\ \lambda^2$)**	**159 μW (indoor) @ 1.54 km**	**49 % @ -5 dBm**
					60 μW (extrapolated) @ 6.3 km	**33 % @ -13 dBm**
						26 % @ -16 dBm

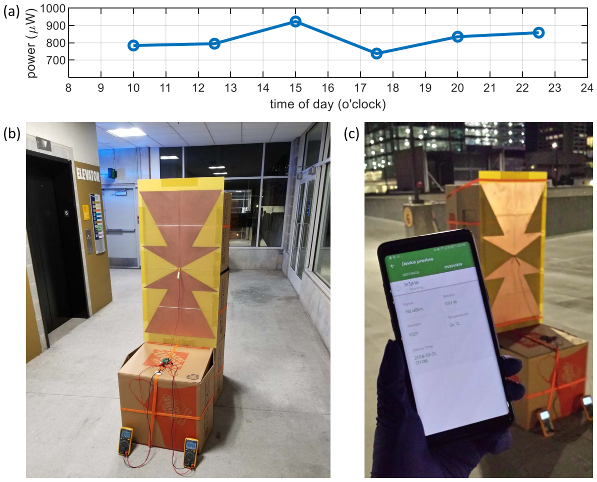

Fig. 5. (a) Power harvested on rooftop. (b) Indoor and (c) rooftop test setups.

The WSN was able to communicate its temperature and orientation information via Bluetooth while being powered by the harvester [see Fig. 5(c)].

B. Comparison to Related Work

Table I compares a list of ambient RF energy-harvesting work [9], [16]–[21]. This letter is the only one in the list, which achieves full −10-dB matching in the respective frequency band (for both the antenna and the rectifier at the targeted power level). The FBW is as high as 23%, whereas the others only achieve single-digit FBWs. For the point-to-point power transfer, a wider spectrum allows the transmitter signal to carry more power. For ambient harvesting, energy can be aggregated from multiple sources that broadcast in different frequencies. The proposed omnidirectional antenna enables simultaneous harvesting from all FM towers in vicinity, whereas others focus on harvesting from single sources using directional antennas. Carefully aligning the antenna with calibration equipment during every installation can be impractical when deploying in mass scale, when the broadcasting tower is visually obstructed, or when it is unknown which of the surrounding towers provide the most power to each harvester location [22]. Careful installation process must be repeated every time an antenna becomes out of alignment, which may defeat the purpose of not having to replace batteries. Wideband and omnidirectional operation alleviates such burden for mass deployment over large areas, making this letter suited for applications such as precision agriculture and structural health monitoring. The system harvests as much as 923 μW at 1.54 km away from the FM tower while retaining omnidirectionality. This is equivalent to harvesting 60 μW at 6.3 km away as the Friis formula [15] dictates that power is inversely proportional to the square of distance. With or without considering distance, no other work in the table harvested as much power as this letter. It achieves competitive η and sensitivity while retaining wideband operation rather than being specifically optimized to individual frequencies. This is due in part to minimizing the number of rectifier stages. The η is higher than seven of the other work in Table I (higher η at lower input power). References [16] and [20], respectively, offer sensitivities of −14.6 and −8.8 dBm (as configured for the best field-test scenario). This letter is more sensitive at −17 dBm, which translates to being as far as 10.6 km away from the broadcasting tower and still being able to harvest usable energy [15]. The proposed system (fabricated on low-cost FR4) harvests outside ambient energy indoors to power a WSN without needing to periodically shut down, which no other work cited in this letter demonstrated, FM or otherwise, with or without periodic shutdown.

IV. CONCLUSION

The full-FM-band, high FBW (23%), and omnidirectional nature of the proposed ambient FM energy-harvesting system (fabricated on low-cost FR4) allow simultaneous harvesting from all FM towers in vicinity. Not requiring careful alignment to the most prominent source makes this system well suited for mass-deployment applications such as precision agriculture and structural health monitoring. As much as 923 μW was harvested at 1.54 km away from the FM tower (extrapolated 60 μW at 6.3 km), which is higher than the power harvested by any other work compared in this letter. The proposed antenna improves the bandwidth of the classic bow–tie (design1) while achieving steeper S_{11} than the traditional wideband bow–tie (design2) in the FM band. Its bandwidth and measured gain (2.0 dBi) are superior to the commercial reference wideband antenna. The system achieves higher η (56%) than the majority of the compared work and is more sensitive (−17 dBm) than all of the compared work (as configured for the best field-test scenario). This is the only system among the compared, which achieves harvesting outside ambient FM energy indoors to power a WSN without needing to shut down periodically.

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