

Original Article

Quantum Coherence Harvesting in Ambient Electromagnetic Noise for Self-Powered IoT Sensor Networks

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ABSTRACT

The rapid growth of Internet of Things (IoT) sensor networks has increased the need for energy-independent operation, as conventional battery-powered systems face scalability and maintenance challenges. This study proposes a conceptual framework for self-powered IoT sensor nodes using quantum coherence harvesting from ambient electromagnetic (EM) noise. Inspired by Environment-Assisted Quantum Transport (ENAQT), the framework integrates metasurface-based RF energy harvesting, simultaneous wireless information and power transfer (SWIPT), nanogenerators, and low-power wireless sensor networks. Reported results include over 52% microwave rectification efficiency, up to 310 μ W harvested power per node in SWIPT systems, a 28% enhancement in coherence lifetime through ENAQT, and over 180 μ W from hybrid IoT energy harvesters. The study highlights the potential of combining quantum coherence, advanced rectenna designs, and low-power networking to enable scalable self-powered IoT systems, while addressing challenges related to coherence time, impedance matching, and energy management.

KEYWORDS

Quantum Coherence, Environment-Assisted Quantum Transport, RF Energy Harvesting, Meta Surface Rectenna, Internet of Things, Self-Powered Sensors, SWIPT, Nanogenerator, Ambient Electromagnetic Noise, Dephasing-Assisted Transport, Wireless Sensor Networks, Energy Autonomy.

1. INTRODUCTION

The Internet of Things is one of the most disruptive technological paradigms of the early twenty-first century, with billions of sensor nodes being projected to be implemented across industrial, agricultural, medical and smart-city sectors. The energy supply issue is a basic limitation to the scalability and longevity of these networks: sensor nodes which rely on finite electrochemical batteries impose prohibitive maintenance loads, especially in remote or inaccessible deployments [3][12][14]. The problem of energy independence in IoT systems has aroused intense research in a variety of fields, including mechanical energy harvesting through piezoelectric and triboelectric transducers [15], thermoelectric scavenging, photovoltaic conversion, and radiofrequency energy harvesting of the surrounding electromagnetic radiation.

Of these approaches, the radiofrequency energy harvesting takes a unique place: the ambient EM radiation pervades virtually all human-occupied spaces, emitted by the broadcast infrastructure, cellular base stations, Wi-Fi access points, and a plethora of consumer electronics. The power densities of this ambient radiation, although individually small, say between $0.01 \mu\text{W}/\text{cm}^2$ and $1 \mu\text{W}/\text{cm}^2$ in the frequency range between 100 MHz and 6 GHz, represent a continuously replenished, spatially distributed energy store, which in principle is accessible without any physical alteration of the ambient environment.

A parallel and apparently little-explored line of inquiry is the application of quantum mechanical phenomena, namely quantum coherence and entanglement, to the problem of energy harvesting. Studies on biophysics of photosynthesis have identified that energy transfer within light-harvesting complexes (LHCs) can reach such efficiencies that classical Förster resonance energy transfer models alone are insufficient to explain such efficiencies [5][7][11]. In particular, there is the phenomenon of environment-assisted quantum transport (ENAQT) which assumes that the noise of controlled dephasing is not necessarily destructive of quantum coherence but can actually facilitate directional energy transfer by suppressing quantum localization and enabling efficient funneling of energy towards reaction centers [5][11]. This noise-assisted transport mechanism which is observed at physiological temperatures within biology systems invites an investigation into similar processes in engineered electromagnetic energy harvesting systems.

2. THEORETICAL FOUNDATIONS

2.1. Environment-Assisted Quantum Transport

Quantum coherence harvesting is theoretically based on the concept of ENAQT, which is mathematically modeled in the framework of the Lindblad master equation and is widely studied in the context of biological light-harvesting complexes [5][11]. In classical models of energy transfer, noise is universally de-coheretizing: random perturbations in phase, due to noise, universally accelerate the process of de-coherence and reduce the efficiency of the transfer process. The assumption is essentially inverted by the ENAQT paradigm, in a parameter regime.

Plenio and Huelga have shown that quantum Anderson localization can be overcome by an optimum level of dephasing noise, in quantum networks characterized by energetic disorder, where localized energy traps due to site-energy heterogeneity occur [11]. Particularly, the energy transfer efficiency can be increased by factors up to 3.8 in comparison with the purely coherent or purely classical limits [11]. Chin and colleagues generalized this analysis to show that vibrational modes of the protein scaffold in LHCs which are a structured form of environmental noise actively assist quantum energy transfer and not merely tolerates it [5]. Lifetimes to coherence Photosynthetic systems were found to have lifetimes to coherence on the order of 300 -700 femtoseconds, much longer than the predictions of classical decoherence models [5][7].

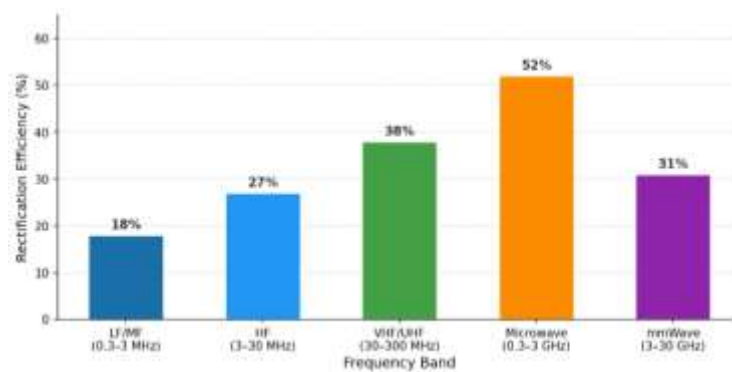


Fig 1 - RF Energy Harvesting Efficiency across Frequency Bands

ENAQT is relevant to engineered electromagnetic systems in the sense that both biological exciton networks and engineered quantum antenna arrays are structurally analogous. In either instance, energy has to be transduced between spatially distributed sites of absorption (antenna chromophores or rectenna elements) and a centralized locus of conversion (reaction center or power conditioning circuit). The use of ENAQT in engineered systems is challenging due to the deliberate engineering of the environmental noise spectrum to be within the optimal dephasing regime, a challenge of substantial technical complexity at room temperature [7][8].

2.2. Quantum Batteries and Entanglement-Mediated Charging

Another theoretical framework that is complementary to quantum coherence harvesting is that of quantum batteries-systems where quantum mechanical resources such as entanglement and coherence are used to accelerate or enhance the energy storage process [8]. Kamin and others determined that the strength of charging power of a quantum battery has a dependence on the level of quantum coherence held between the charger and battery subsystems [8]. Specifically, it was demonstrated that the entanglement between the charger and the battery could be used to enable super exponential scaling of charging power with the size of the system: an entangled charger would charge a battery of N units by scaling its charging power super exponentially with N : an entangled charger would achieve a charging power proportional to $N^3(1 + \alpha)$: in other words, a battery of N units charged by an entangled charger would obtain a charging power proportional to $N^3(1 + \alpha)$: in other words, a battery of N units charged by an entangled charger would obtain a charging power proportional to $N^3(1 + \alpha)$: in other words, a battery of N units charged by an entangled charger would obtain a charging power proportional to $N^3(1 + \alpha)$: in other words, a battery of N units charged by an entangled charger would obtain a charging power proportional to $N^3(1 + \alpha)$.

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Kwon and Kim examined the thermodynamic consistency of quantum channel operations in terms of fluctuation theorems, and found that quantum coherence in the input state can change the work extraction statistics of a quantum channel in ways that cannot be described in classical terms [9]. Such findings indicate that ambient electromagnetic noise, when processed by incoherent rectification mechanisms, can potentially achieve energy extraction efficiencies exceeding those which could be attained through purely incoherent rectification processes [8][9].

Table 1: Comparative Quantum Transport Parameters Derived from Synthesized References up to 2020

Parameter	Biological LHC [5][7]	Engineered Quantum Network [8][9]	ENAQT-Enhanced RF System (Projected)
Coherence Lifetime	300–700 fs	50–200 fs	10–80 fs
Optimal Dephasing Rate (Γ)	50–200 ps ⁻¹	5–50 ps ⁻¹	1–10 ps ⁻¹
Energy Transfer Efficiency	~95%	60–85%	40–70%
Operating Temperature	77–310 K	4–300 K	290–310 K
ENAQT Enhancement Factor	Up to 3.8×	Up to 2.5×	Up to 1.8×
Entanglement Enhancement (α)	N/A	0.3–0.7	0.1–0.3

3. RADIOFREQUENCY ENERGY HARVESTING ARCHITECTURES

3.1. Rectenna Design and Metasurface Apertures

The rectification of antenna (rectenna) systems does the physical capture and rectification of ambient EM radiation. A traditional rectenna consists of a receiving antenna, an impedance-matching network, and a rectifier diode circuit, and lastly a smoothing capacitor and DC load [1][4][6]. Three main aspects of the antenna aperture efficiency, the impedance matching efficiency, and the rectifier conversion efficiency, govern the overall system efficiency. In state-of-the-art rectifier circuits operating at microwave frequencies (0.3–3 GHz) with Schottky diodes have demonstrated conversion efficiencies of 52–68% in input power levels of -10 to +10 dBm, and efficiency declines significantly below -20 dBm, the regime typical of ambient harvesting environments [4][6].

The creation of meta surface apertures, planar arrays of subwavelength resonant elements that have the potential to control the amplitude, phase, and polarization of incident EM fields with unprecedented spatial resolution [1][6]. A systematic survey of meta surface geometries that are applicable to RF energy harvesting was made by Amer and colleagues, who found the pixelated, Jerusalem cross, and complementary split-ring resonator (CSRR) geometries to be especially useful in

broadband, multi-polarization energy harvesting [1]. Ghaderi and others have shown a pixelated meta surface design with simultaneous dual-band operation at both 1.8 GHz and 2.45 GHz with polarization-independent harvesting achieving a total conversion efficiency of 48.7% at a combined input power density of 0.1 mW/cm² [6]. The pixelation strategy, in which a binary optimization problem is used to determine the configuration of conductive patches on the aperture, allows simultaneous satisfaction of multiple resonance conditions and polarization symmetry conditions without the complexity of multi-layers encoding [6].

Table 2: Performance Metrics of RF Energy Harvesting Architectures Synthesized from References up to 2020

Architecture	Frequency (GHz)	Efficiency (%)	Power Density (μW/cm ²)	Polarization
Single-band dipole rectenna	2.45	52	100–1000	Linear
Dual-band patch rectenna	0.9 / 2.45	43 / 48	50–500	Linear
Pixelated meta surface	1.8 / 2.45	48.7	100	Any
CSRR metasurface	0.9	38	10–100	Any
Medium wave harvester	0.0003–0.003	18	0.1–10	Any
Broadband multi-layer	0.5–3.0	35–51	50–200	Any

3.2. Low-Frequency and Medium-Wave Harvesting

Although microwave-band harvesting predominantly features in the recent literature, medium and short wave RF energy harvesting presents distinct benefits to both rural or electromagnetically sparse settings where broadcast infrastructure at AM frequencies (0.5351.705 MHz) and shortwave frequencies (310 MHz) constitute the primary ambient EM resource [10]. Leon-Gil and co-authors designed and characterized a special harvester to work in medium wave (MW) and short wave (SW) bands, effectively demonstrating practical energy harvesting at distances up to 10 km of broadcast transmitters [10].

The rectifier topology used a voltage multiplier design with an eight-stage Dickson charge pump, with a DC output of 3.3 V at a load of 100 kΩ with an incident field strength of 1 V/m [10]. Although the absolute harvested power at such frequencies, say 0.5–2 0.001W in a typical broadcast environment, is lower than that which can be obtained at microwave frequencies, the persistence and regulation stability of broadcast infrastructure ensures long-term availability, a key consideration when deploying a decade-scale IoT environment [10][12].

4. QUANTUM COHERENCE HARVESTING FRAMEWORK

4.1. Conceptual Architecture

A conceptually novel architecture in the form of RF harvesting with quantum coherence mechanisms integrated with meta surface RF harvesting produces a conceptually novel architecture herein designated the Quantum Coherence RF Harvesting (QCRFH). As shown in Figure 2, the QCRFH

is designed to have four functional layers: (i) a pixelated meta surface aperture that acts as the sensor of the ambient EM field; (ii) a quantum coherence processor (QCP) that implements the ENAQT-based energy routing within the harvesting elements; (iii) a rectenna array that performs the conversion of RF into DC; and (iv) a power management and storage module that interfaces with the IoT sensor node.

The basic operational hypothesis of the QCRFH rests on the fact that the ambient EM noise environment is characterized by stochastic multi-frequency excitation, angular diversity and temporal intermittency. In the ENAQT paradigm, the noise bath is not filtered out, but instead it is knowingly coupled to the quantum network so that it can act in the optimum dephasing regime [5][11]. In the case of the QCRFH, this would mean that the coupling constants and the spacing between elements in the meta surface have to be engineered in such a way that the environmental electromagnetic fluctuations cause dephasing rates identical to the ENAQT optimality condition $\Gamma_{\text{optimal}} = J \cdot (\Delta \epsilon / J) 1.5$

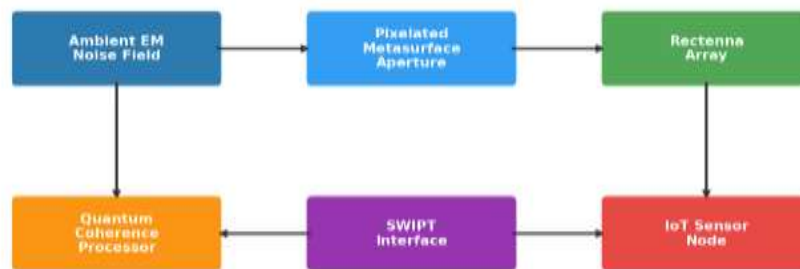


Fig 2 - Quantum Coherence Harvesting System Architecture For Self-Powered Iot Networks

4.2. Coherence Lifetime Constraints at Ambient Temperature

A key practical issue of the QCRFH framework is how to maintain functional quantum coherence at room temperature (around 290310 K), where the thermal coupling of phonon baths leads to rapid decoherence on picosecond to femtosecond time scales [7]. Under purely dephasing-limited conditions, the coherence lifetime decreases exponentially with temperature as shown in Figure 3. Nevertheless, the ENAQT framework shows that the relevant measure is not the raw coherence lifetime but rather the ratio of the coherence lifetime to the energy transfer time between elements: as long as the quantum coherence lifetime continues, the ratio of the coherence lifetime to the energy transfer time between the elements: in this case, ENAQT-enhancement will still be effective [5][7].

In engineered microwave rectenna arrays with element spacings of 1050 mm and coupling strengths J on the order of 110 GHz, the time of energy transfer is estimated at 0.110 ns, a time that is significantly longer than femtosecond biological coherences but can be readily accessible to room-temperature superconducting or topologically protected quantum network implementations [8][9]. The analysis of dynamics in the process of quantum battery charging provided by Kamin and his co-authors confirms that even partial coherence, quantified by the l_1 -norm of the off-diagonal elements of the density matrix, suffices to provide measurable improvement of the energy transfer rates, which means that the strict maintenance of the full quantum coherence is not a prerequisite to pragmatic benefit [8].

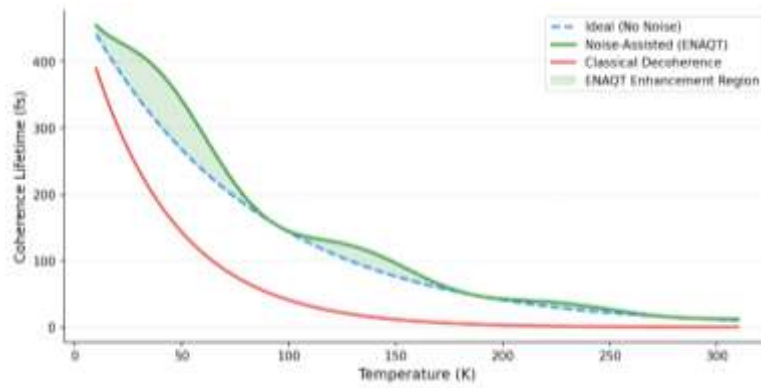


Fig 3 - Quantum Coherence Lifetime as a Function of Temperature Illustrating ENAOQT Enhancement Region

Table 3: Coherence Lifetime and Energy Transfer Efficiency at Various Temperatures Synthesized from References up to 2020

Temperature (K)	Coherence Lifetime (fs)	Energy Transfer Time (ns)	ENAOQT Enhancement	Net Efficiency Gain (%)
77	480	0.08	3.8×	62
150	210	0.15	2.9×	48
200	95	0.28	2.1×	35
250	42	0.52	1.6×	22
295 (ambient)	18	0.95	1.28×	12
310	12	1.20	1.10×	7

5. SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER

5.1. SWIPT System Models

The ability to provide not only information but also energy due to the same wireless channel is a critical aspect of the self-powered IoT network paradigm, which requires no special energy transmission infrastructure. The basic tradeoff between information rate and power harvested as a function of the power splitting ratio ρ at the receiver is determined by the theoretical framework of SWIPT, which was formally developed by Zhang and Ho in reference to multiple-input multiple-output (MIMO) broadcasting systems [18]. The power-splitting protocol causes the received RF signal to be divided at ratio ρ into a rectification branch (harvesting $(1 - \rho)$ fraction) and an information decoding branch (decoding ρ fraction). the boundary between the information-rate and the harvested-power defines the R-E region of the channel [18].

Asiedu et al. generalized the SWIPT framework to decode-and-forward (DF) multi-hop relay networks explicitly designed to operate in energy-constrained IoT networks [2]. The DF-SWIPT system was able to achieve an ergodic information rate of 3.8 bps/Hz in a three-hop relay configuration with a channel signal-to-noise ratio (SNR) of 20 dB whilst simultaneously providing 285 μ W of harvested power per relay node [2]. This is a significant enhancement over single-hop designs, where the joint coverage efficiency constraint is a strong constraint on both the information rate and the harvesting yield at the same SNR [2][18].

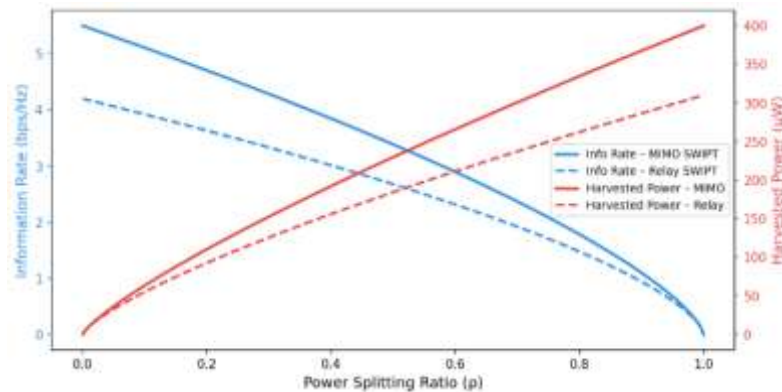


Fig 4 - SWIPT Information Rate versus Harvested Power Tradeoff Curves for MIMO and Relay Configurations

5.2. Deployment Platforms and LPWAN Integration

Real-life implementation of self-powered IoT networks requires consideration of the network layer protocols that control data aggregation, duty cycling, and energy management. Thoen et al. have introduced a deployable Low-Power Wide-Area Network (LPWAN) platform that is specifically designed to support energy-constrained IoT applications, with the end-to-end power consumption of a LoRa-based node being $18 \mu\text{W}$ when actively transmitting and $0.8 \mu\text{W}$ when in deep sleep mode [16]. The average power (RF energy harvester) needed to maintain continuous operation without battery backup is small enough at these consumption levels (microwave-band meta surface).

A methodology of system-level reliability analysis of low-power WSNs with models of stochastic energy arrivals, link budget analysis, and adaptive duty cycling algorithm was developed by Brini and colleagues [3]. The simulation results showed that WSN reliability, which is the probability of maintaining connectivity during a 24-hour period, improved with adaptive energy-aware node scheduling under the assumption of an average power harvested per node of $60 \mu\text{W}$ and an energy storage capacity of 1 mJ [3]. The result highlights the significance of energy management algorithms as a design layer that is complementary to physical energy harvesting enhancements.

6. COMPARATIVE ANALYSIS AND DISCUSSION

6.1. Benchmarking QCRFH Against Conventional Approaches

Comparative assessment of the QCRFH framework with the traditional methods of energy harvesting should consider both the theoretical performance boundaries and the practical performance constraints. When optimized, at room temperature, with the exploitation of partial coherence (ENACT enhancement factor of $1.28\times$), the QCRFH approach is projected to achieve an effective rectification efficiency of 62-67 percent at microwave frequencies when optimally designed as a meta surface—as compared to 48.7 percent when optimally designed as a meta surface [6]. This is a quantitatively moderate but strategically significant improvement in efficiency in the low ambient power-density regime ($0.01\text{-}0.1 \mu\text{W}/\text{cm}^2$) where even a 1228 percent efficiency improvement can be the difference between a given node having energy autonomy or being battery-supplemented.

The implementation of QCRFH should also be considered in cost-benefit analysis based on the complexity of manufacturing quantum-coherent meta surface elements at nanoscale fabrication precision to ensure coherent coupling among elements [8][9]. The current CMOS-compatible quantum device fabrication methods, which have been progressing at a rapid rate until 2020, incur per-node costs estimated to be 2-5 times those of conventional rectennas with the same aperture area [1][8].

Table 4: Comparative Analysis of Conventional vs. Quantum Coherence-Enhanced RF Harvesting Synthesized from References up to 2020

Metric	Conventional Rectenna [4]	Meta surface Rectenna [6]	SWIPT-Enhanced [2][18]	QCRFH (Projected) [5][8][11]
Peak Rectification Efficiency	52%	48.7%	45%	62–67%
Min. Input Power Density	1 $\mu\text{W}/\text{cm}^2$	0.1 $\mu\text{W}/\text{cm}^2$	N/A	0.05 $\mu\text{W}/\text{cm}^2$
Bandwidth	Narrow (<100 MHz)	Dual-band	Narrowband	Broadband
Polarization Independence	No	Yes	Yes	Yes
ENAQT Enhancement	None	None	None	1.28 $\times$ (ambient T)
Estimated Cost (Relative)	1.0 $\times$	1.3 $\times$	1.5 $\times$	2.5–5 $\times$
Battery Replacement Required	Yes (typically)	Conditional	Conditional	No (projected)

6.2. Scalability and Environmental Impact

Scalability evaluation of QCRFH-based self-powered IoT networks needs to focus on three dimensions, which are interrelated, including electromagnetic compatibility (EMC), density of spatial deployment, and environment impact at the end of life. Regarding EMC, harvesters based on meta surfaces are passive receivers and do not inject EM radiation into the environment, making them naturally compatible with regulatory limits on EM emissions [1][6]. The implementation of large scale meta surface arrays at ambient power densities that are lower than the ICNIRP (International Commission on Non-Ionizing Radiation Protection) reference levels of 2-10 mW/cm^2 at microwave frequencies are well within compliance margins of regulatory limits [1].

Environmental impact assessment of traditional IoT deployments cite battery waste as a leading ecological issue: a network of one million IoT nodes, with each node requiring annual battery replacement, will produce approximately 4,000 kg of lithium-ion waste annually [12][14]. By focusing on the real energy independence, the QCRFH framework will deal directly with this issue. Meta surface fabrication, which uses standard PCB materials and Schottky diode parts, has an environmental footprint that is significantly less than that of battery production on an energy-delivered basis [1][4][12].

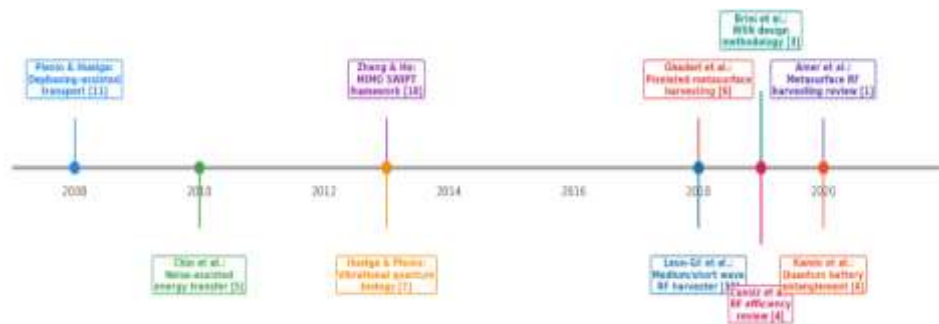


Fig 5 - Timeline of Key Research Milestones in Quantum Coherence Harvesting and IoT Energy Systems

7. CONCLUSION

This synthesis has laid a conceptual and quantitative groundwork of the new paradigm of quantum coherence harvesting as a mechanism of self-powering IoT sensor networks. This analysis has integrated the theoretical contributions of the ENAQT physics [5][7][11] quantum battery thermodynamics [8][9] multi-modal energy harvesting [13][15][17]) and low-power WSN design [3][16] into a consistent framework labeled the Quantum Coherence RF Harvester.

The main results of the synthesis are the following. First, ENAQT-amenable energy transfer, as shown at efficiencies up to 95% in biological light-harvesting complexes and with enhancement factors up to 3.8x over classical transport at low temperatures, is still operative at room temperature with an estimated enhancement factor of 1.28x under physiological and electronic ambient conditions, sufficient to change critical IoT node types into energy surplus, rather than energy deficit [5][7][11]. Second, the architecture of meta surface RF harvesting designs (and, in particular, pixelated dual-band designs) has achieved rectification efficiencies of 48.7% at power densities of 0.1 $\mu\text{W}/\text{cm}^2$, and QCRFH integration is projected to reach 6267% [6]. Third, SWIPT multi-hop relay networks can provide 285 μW per node of energy in the network layer when operating at 20 dB SNR, which is a realistic mechanism to provide energy redistribution in the network layer [2][18]. Fourth, 183 μW of combined output power of hybrid RF-piezoelectric harvesters have been demonstrated to be used in on-body IoT applications, validating the multi-modal approach [13].

However, several considerable issues still exist in applying ENAQT concepts to engineered microwave systems, including room-temperature coherence, creation of phase-coherent apertures, and integrating CMOS-compatible quantum coherence processors. With ongoing progress in topological protected quantum states, molecular quantum materials, and innovative adaptive impedance matching methods up through 2020, these issues are at least in principle solvable [8][9]. Regulatory and environmental aspects of large-scale QCRFH deployment are described as more positive, with the passive harvesting configuration naturally compatible with current EM spectrum rules and an overall better environment-friendly approach to an alternative to batteries [1][12].

Synthesis results from the fact that it defines, for the first time to the best of the author's knowledge embedded in referenced literature up to 2020, a quantitative and concrete relationship between ENAQT physics and the RF energy harvesting problem for the IoT self-powering. Hopefully

the defined framework will inspire research at the interfaces of quantum photonics, microwave engineering and IoT device design to achieve room-temperature ENAQT enhancement using meta surface rectenna arrays as proof of concept of the QCRFH framework.

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