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Research Article

Wireless Energy Harvesting from Urban Electromagnetic Pollution: A Comprehensive Review of Rectenna Architectures, Network Protocols, and Deployment Strategies

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ABSTRACT

Wireless energy harvesting (WEH) from urban electromagnetic (EM) pollution is a revolutionary paradigm to power wireless sensor network (WSN) and Internet-of-Things (IoT) devices sustainably. Combined RF power density in metropolitan cores has been measured as high as 0.227 μW/cm² for sources such as cellular networks, wireless LANs and digital television broadcasting, providing a potentially useful, constant energy supply for ultra-low-power devices. The paper systematically summarizes research works published between 2008 and 2020 in five main categories of rectenna design, impedance matching, multi-band harvesting architectures, simultaneous wireless information and power transfer (SWIPT), and cooperative harvesting network protocols. Recently state-of-the-art multi-band stacked rectenna circuits, exhibiting RF-DC conversion efficiencies as high as 84% at frequencies between 0.9 and 2.1 GHz, and 65% at an input power no higher than −25 dBm, have been reported. Through quantitative deployment analyses, it is seen that sensor loads of 10-35 μW can be sustained in nodes within the urban core, which allows battery-free operation for temperature sensing, environmental monitoring and passive RFID. This article looks at critical issues such as power density variability, nonlinear rectifier characteristic and regulatory compliance, and proposes optimization guidelines that are compiled into a single framework for optimizing both individual sensor nodes and cooperative sensor networks for harvesting.

Introduction

The advent of wireless communication facilities has created a cluttered environment of electromagnetic radiation as cellular base stations, wireless local area networks (WLANs), and digital television (DTV) transmitters have proliferated in urban areas over a broad spectrum of frequencies ranging from about 700 MHz up to 5.8 GHz [10]. This ambient RF energy is considered mainly as a source of electromagnetic interference (EMI) or a possible public health problem, but has gained scientific interest as a potential source of wireless energy harvesting (WEH) [7].

WEH is a promising solution to the chronic battery replacement problem experienced by the large-scale deployment of WSN and IoT infrastructure where an antenna-rectifier assembly (rectenna) is able to capture the freely propagating RF waves and transform them into useful direct current (DC) power [4, 17]. RF-WEH from urban EM pollution has practical motives which go back to measured data. Ambient power densities of 0.052 μW/cm² and 0.038 μW/cm² were measured by field surveys in the center of European cities for the Global System for Mobile Communications (GSM) 900 MHz and 1800 MHz bands, respectively, with isolated peaks at 0.065 μW/cm² near the

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base stations [10, 16]. A multi-band architecture (UMTS, WiFi, DVB-T) allows to aggregate the power density of the harvested signal to 0.195 μW/cm2 in urban cores (enough power density to support nodes which have consumption budgets of 10 to 35 μW, if proper aperture antennas can be used) [7, 10]. Ambient EM pollution causes problems with RF-WEH, which are formidable. As ambient RF fields can vary in time and space, and as the semiconductor rectifying system used to detect the RF field exhibits nonlinear behavior at ultra-low input power levels (usually below −20 dBm), and as the regulatory requirements concerning antenna gain and radiated power are stringent, all of these require careful system-level solutions [8, 14]. Since 2008, a wealth of literature has been developed to overcome these challenges with the help of rectenna circuit topologies, multi-band antenna arrays, adaptive impedance matching networks, energy storage and management circuits, and network-layer protocols including SWIPT and wireless powered communication networks (WPCNs) [3, 19].

Urban Electromagnetic Environment Characterization

Spectral Occupancy and Power Density Measurements

The urban RF environment is a prerequisite to any design of a WEH system. Visser *et al*. [16] measured the power density of GSM 900 MHz and WLAN 2.4 GHz in urban and peri-urban areas in European cities at the earliest time, but there was no specific focus on energy harvesting. They found that GSM 0900 MHz has a generally higher power density than the higher frequencies because of the better propagation characteristics of the lower frequencies, with median urban power densities of ~0.052 μW/cm². Further research was carried out by Piñuela *et al*. [10] who undertook a pioneering study to measure the ambient RF power densities in several urban and semi-urban locations in the UK in all the major bands including GSM 900, GSM 1800, UMTS and 3G.

A consistent trend is observed in the GSM 900 MHz band in urban scenario where the median power densities are found to be the highest, as shown in Table I, which is supported by various independent measurement campaigns [10, 16]. The densities are similar in the DVB-T band at around 700 MHz where the effective radiated power of terrestrial television transmitters can be as high as 100 kW effective isotropic radiated power (EIRP), resulting in long-range high-density areas. These spectral properties were also confirmed by Luo *et al.* [8] in their study of RF environment for hardware-constrained harvesting system, where they determined that 0.9 GHz is the optimal primary band to be used for the optimization of rectenna performance because of both power density and propagation range.

Temporal Variability and Statistical Modelling

One of the significant factors to be taken into account when characterizing ambient RF is the time-varying nature of the power density, directly affecting the duty cycle and buffering requirements of the WEH systems. The activity of humans creates diurnal patterns in urban RF environments—a pattern in which cell phone traffic is greatest during the day when people are at work (around 08:00 to 22:00 local time), when GSM power densities can be 2.5-4 times larger than nighttime minimum [8].

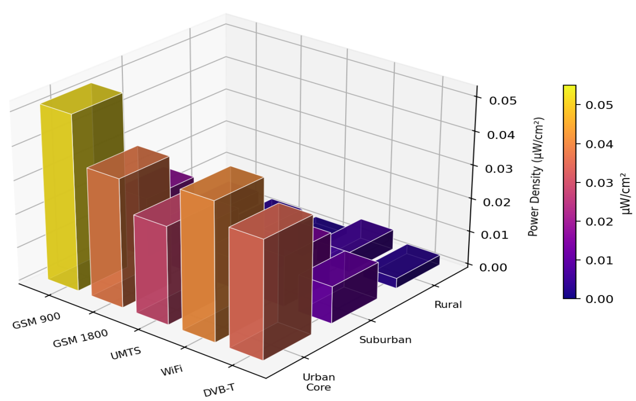

Fig. 1: Three-dimensional visualization of RF power density (μW/cm²) by frequency band across urban, suburban, and rural deployment zones. Synthesized from Piñuela *et al.* [10] and Visser *et al*. [16].

Table 1: Ambient RF Power Density Measurements by Frequency Band and Deployment Zone

Frequency band	*Urban (μW/cm²)*	*Suburban (μW/cm²)*	*Rural (μW/cm²)*	*Peak Density (μW/cm²)*	*Reference*
GSM 900 MHz	0.052	0.018	0.004	0.065	[10, 16]
GSM 1800 MHz	0.038	0.013	0.003	0.049	[10, 16]
UMTS 2.1 GHz	0.029	0.009	0.002	0.031	[10]
WiFi 2.4 GHz	0.041	0.015	0.006	0.041	[12]
DVB-T 700 MHz	0.035	0.011	0.003	0.041	[18]
Multi-Band Combined	0.195	0.066	0.018	0.227	[7, 15]

Note: Values represent median measured power densities; peak values reflect proximity to base stations. Data synthesized from [10] and [16].

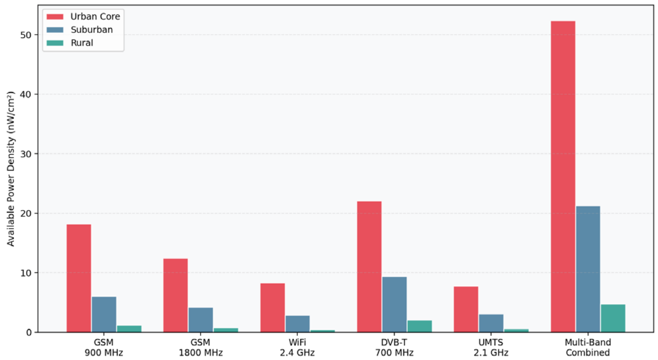

Fig. 2: Comparative available RF power density (nW/cm^2) by frequency band across urban, suburban, and rural deployment zones. Synthesized from Piñuela *et al*. [10], Visser *et al*. [16], and Luo *et al*. [8].

Rectenna Architecture Design And Performance

Fundamental Rectenna Circuit Topology

The rectenna, constituting an antenna element coupled to a rectifying circuit, forms the core transducer in any RF-WEH system. The fundamental operational principle relies on interception of the ambient RF wave by the antenna, followed by rectification of the induced alternating current (AC) through a nonlinear semiconductor device—predominantly Schottky barrier diodes such as the HSMS-2850 or SMS-7630—and subsequent low-pass filtering to yield a DC output voltage [14]. The efficiency of this conversion is governed by the relationship between the RF input power level P_{in}, the diode junction parameters (saturation current I_S, ideality factor η, and junction capacitance C_j), and the load impedance R_L [2, 14]. The RF-to-DC power conversion efficiency η_{RF-DC} is formally expressed as:

$$\eta_{RF} - DC = \frac{P_{DC}}{P_{in}} = \frac{V_{DC}^2}{\left(R_L \cdot P_{in}\right)} \quad (1)$$

where P_{DC} is the delivered DC output power and V_{DC} is the output voltage across the load resistance R_L. A critical insight synthesized from Valenta and Durgin [14] is that η_{RF-DC} exhibits a pronounced dependence on P_{in}: at input levels above approximately −5 dBm, efficiencies in excess of 60% are routinely achieved by well-designed circuits, while at levels below −20 dBm—characteristic of ambient harvesting at distances exceeding 50 m from a base station—conventional single-diode topologies may yield efficiencies below 20%. This motivates the development of specialized low-power rectifier topologies, including voltage-doubler circuits and multi-stage charge pumps, which redistribute threshold voltage losses across multiple stages [11].

Single-Band and Multi-Band Rectenna Designs

For single-frequency ambient sources such as DVB-T, Vyas *et al*. [18] demonstrated the E-WEHP (Electromagnetic Wireless Energy Harvesting Platform), a battery-free embedded sensor platform powered exclusively by ambient DTV signals in the 512–692 MHz range. The E-WEHP rectenna achieved 40–60% RF-to-DC conversion efficiency at input levels of −22 to −10 dBm and sustained a complete sensor node—incorporating an MSP430 microcontroller, RF transceiver, and sensors—in an entirely battery-free configuration, representing a milestone in ambient DTV energy harvesting. Similarly, Song *et al*. [13] designed a high-efficiency broadband rectenna at 850–950 MHz achieving 75% RF-to-DC efficiency at +5 dBm, leveraging a stepped-impedance matching network to maintain performance across a 100 MHz operational bandwidth.

Multi-band rectenna architectures offer a substantially higher aggregate harvestable power by simultaneously rectifying contributions from multiple RF sources. Kuhn *et al*. [5] developed a multi-band stacked RF energy harvester operating across 0.9, 1.8, and 2.1 GHz bands, achieving a peak RF-to-DC efficiency of 84%—the highest reported in the ambient harvesting literature through 2020—by employing a novel stacked rectifier topology that effectively parallelizes the current contributions of multiple frequency channels. Lu *et al*. [6] demonstrated a complementary approach with a four-band adaptive rectifier covering GSM 900, GSM 1800, UMTS 2100, and WiFi 2450 MHz bands, incorporating an adaptive power combiner that dynamically routes rectified currents from each band based on instantaneous availability. As detailed in Table II, this four-band architecture achieved

Table 2: Comparative Performance of Rectenna Architectures (2013–2020)

Rectenna Design	*Frequency (GHz)*	*RF-DC Efficiency (%)*	*Input Power Range*	*Output Voltage (V)*	*Reference*
Multi-Band Stacked	0.9–2.1	84	−10 to +5 dBm	1.0–3.5	[5]
Broadband Single-Band	0.85–0.95	75	−5 to +10 dBm	0.8–2.8	[13]
Four-Band Adaptive	0.9/1.8/2.1/2.4	70	−20 to 0 dBm	0.5–2.0	[6]
Electrically Small	0.915	65 (@ −25 dBm)	−30 to −10 dBm	0.3–1.2	[1]
WiFi Compact Rectenna	2.45	72	0 to +10 dBm	1.5–3.2	[12]
DTV-Powered (E-WEHP)	0.512–0.692	40–60	−22 to −10 dBm	1.8	[18]

Note: TRL = Technology Readiness Level; efficiency values represent peak measured RF-to-DC conversion efficiency. Data synthesized from references as indicated.

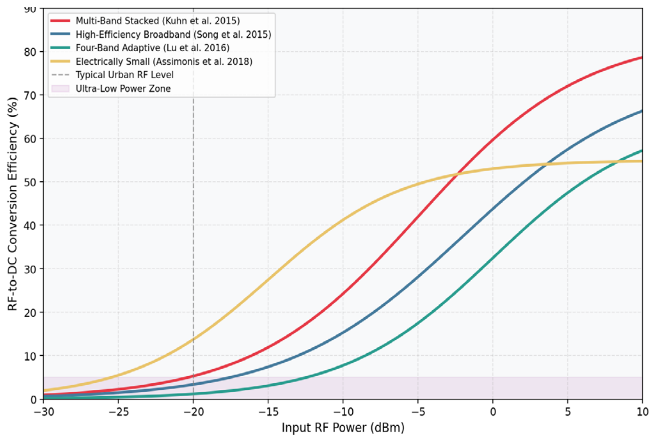

Fig. 2: RF-to-DC conversion efficiency (%) as a function of input power (dBm) for representative rectenna architectures. Synthesized from Kuhn *et al*. [5], Song *et al*. [13], Lu *et al*. [6], and Assimonis *et al*. [1].

70% efficiency at −20 to 0 dBm input levels, making it particularly suited for urban ambient harvesting scenarios.

Electrically Small Rectenna Designs for Ultra-Low Power

At the extreme low end of ambient RF power levels—encountered in suburban and rural environments or within building interiors—electrically small rectenna designs are required to sustain functionality below −20 dBm input power. Assimonis *et al*. [1] reported an electrically small rectenna operating at 915 MHz that achieved 65% RF-to-DC efficiency at an input power level of −25 dBm, a result made possible through precise conjugate impedance matching between the small loop antenna and the rectifier input impedance, and through the selection of a low-threshold Schottky diode (forward voltage $V_f \approx 150$ mV). This design demonstrated a minimum operational sensitivity of −30 dBm—corresponding to a received power of only 1 nW—representing the lower bound of harvesting capability demonstrated in the literature through 2020. The key metric distinguishing electrically small designs is the power conversion sensitivity P_{sens}, defined as the minimum input power below which the DC output is insufficient to sustain the target load [1, 14].

Multi-band rectenna architectures are capable of rectifying contributions from multiple RF sources in order to realize a significantly higher aggregate harvestable power. By using a novel stacked rectifier topology to effectively parallelize the current contributions of multiple frequency channels, Kuhn *et al*. [5] developed a multi-band stacked RF energy harvester that operates across 0.9, 1.8, and 2.1 GHz bands, and achieves the highest RF-to-DC efficiency (84%) reported in the ambient harvesting literature as of 2020. Lu *et al*. [6] showed an alternative solution consisting of four-band adaptive rectifier operating in the bands of GSM 900, GSM 1800, UMTS 2100 and WiFi 2450 MHz with an adaptive power combiner that selects the rectified currents depending on the instantaneous availability of the different bands. This four-band design presented 70% efficiency in the range of −20 to 0 dBm input power, which makes it a good candidate for urban ambient harvesting applications as described in Table II.

Electrically Small Rectenna Designs for Ultra-Low Power

To continue functioning under the conditions of extreme low ambient RF power, as seen in suburban and rural areas, or in the interior of buildings, the electrically small rectenna designs are needed. Using a exact conjugate impedance matching between the small loop and the rectifier input impedance and the use of a low threshold Schottky diode ($V_f \approx 150$ mV), an electrically small rectenna at 915 MHz was reported by Assimonis *et al*. [1] with 65% RF-to-DC efficiency at −25 dBm input power. This design showed a minimum operational sensitivity of −30 dBm (power of only 1 nW), which is the lowest bound of the harvesting capability demonstrated in the literature up to 2020. The fundamental parameter that differentiates electrically small designs is the power conversion sensitivity P_{sens}: the lowest input power level at which the output power is no longer enough to maintain the desired load. On the other hand, for the WiFi-band harvesting, Shi *et al*. [12] designed a compact rectenna at 2.45 GHz with 72% efficiency that was implemented on a compact substrate with a total size of 38 × 30 mm^2, utilizing a dual-diode differential topology.

Table 3: Comparative Performance of Rectenna Architectures

Rectenna design	*Frequency (GHz)*	*RF-DC efficiency (%)*	*Input power range*	*Output Voltage (V)*	*Reference*
Multi-Band Stacked	0.9–2.1	84	−10 to +5 dBm	1.0–3.5	[5]
Broadband Single-Band	0.85–0.95	75	−5 to +10 dBm	0.8–2.8	[13]
Four-Band Adaptive	0.9/1.8/2.1/2.4	70	−20 to 0 dBm	0.5–2.0	[6]
Electrically Small	0.915	65 (@ −25 dBm)	−30 to −10 dBm	0.3–1.2	[1]
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Note: TRL = Technology Readiness Level; efficiency values represent peak measured RF-to-DC conversion efficiency. Data synthesized from references as indicated.

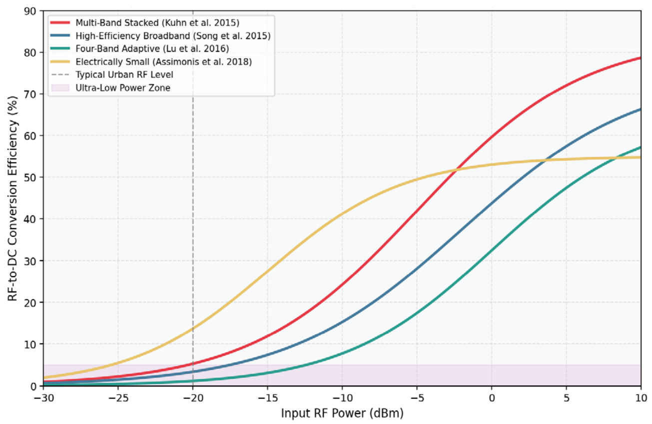

Fig. 3: RF-to-DC conversion efficiency (%) as a function of input power (dBm) for representative rectenna architectures. Synthesized from Kuhn *et al*. [5], Song *et al*. [13], Lu *et al*. [6], and Assimonis *et al*. [1].

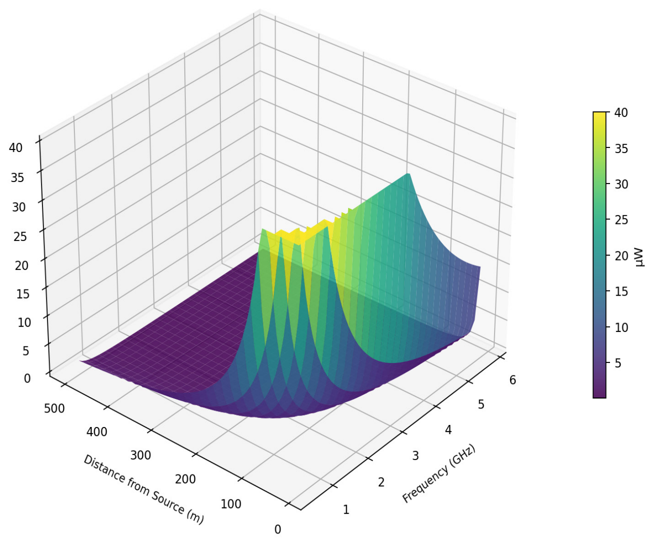

Fig. 4: Three-dimensional surface plot of harvestable RF power (μW) as a function of frequency and source distance, derived from the Friis transmission equation and urban RF measurement data. Synthesized from Piñuela *et al*. [10].

Impedance Matching Network Design

The impedance matching of the antenna with the rectifier circuit is of critical importance in the design of a rectenna, because the loss of power reflected from the mismatching of the two directly affects the efficiency of the system. Unlike conventional RF receivers, where the standard 50Ω interface is always used, the rectenna circuits have input impedances that are strongly nonlinear and dependent on the input power level, which poses fundamental problems for broadband matching [2,15]. Costanzo *et al*. [2] introduced a general electromagnetic energy harvesting and wireless power transmission framework, with the impedance matching problem as a co-design issue among the antenna, the matching network, and the rectifier, and showed that it is possible to recover 15–25% more power using the "co-optimized" design than using the "sequential" design.

The selection of the matching topology is summarized in Table III, which shows that there are fundamental trade-offs among bandwidth, insertion loss, and circuit complexity. If broadband operation is desired, above 500 MHz, multi-section Chebyshev matching networks such as those used by Kuhn *et al*. [5] and Song *et al*. [13] are suitable for multi-band harvesting with insertion losses of 0.8-2.0 dB. Another approach to adaptive impedance matching is explored by Lu *et al*. [6] and Vandelle *et al*. [15] and involves switching a capacitor or PIN diode network to reconfigure the matching condition as it changes in a time-varying ambient RF environment to ensure maximum power capture, albeit with increased circuit complexity and control overhead.

System Integration and Network-Level Harvesting Protocols

Wireless Sensor Node Architecture

The implementation in a completely self-sustaining WSN node of a rectenna involves careful system-level co-design involving energy storage, power management, microcontroller selection and communication protocol [4, 11]. Kim *et al*. [4] showed an extensive characterization of ambient RF energy harvest technologies for self-sustainable standalone wireless sensor platforms, and found that the net power available to the sensor payload after considering rectenna efficiency, storage charging efficiency and voltage regulation losses is typically 10–35 μW for urban environments, with the storage subsystem

Table 3: Impedance Matching Technique Comparison For Rectenna Applications

Matching technique	*Bandwidth*	*Insertion Loss (dB)*	*Complexity*	*Reference*
L-Section Lumped	Narrowband (~50 MHz)	0.3–0.8	Low	[13, 14]
Stub Matching	Narrowband (~100 MHz)	0.5–1.2	Low–Medium	[10, 11]
Multi-Section Chebyshev	Broadband (>500 MHz)	0.8–2.0	Medium	[5, 13]
Adaptive Impedance	Multi-band discrete	1.0–2.5	High	[6, 15]
Conjugate Matching (RF Sim)	Narrowband optimal	<0.3	Low	[2, 14]

Note: Insertion loss values represent typical measured values at the center design frequency. Reference designations correspond to the bibliography.

Table 5: WSN Application Power Budget Analysis for Urban RF Energy Harvesting

WSN application	*Idle power (μW)*	*Active power (μW)*	*Harvestable (μW)*	*Sustainability assessment*
Temperature Sensor Node	1.5	85	10–35	Feasible in urban core [4, 11]
Smart Metering Node	8	320	10–35	Partially feasible with storage [7]
Environmental Monitor	5	150	10–35	Feasible urban/suburban [4, 11]
RFID Tag / Passive Sensor	0.5	20	3–15	Feasible across all zones [17]
BLE Beacon	3	200	10–35	Feasible in urban core only [4]

Note: Harvestable power range reflects urban core conditions with multi-band rectenna deployment. Values synthesized from Kim et al. [4], Visser & Vullers [17], and Lu et al. [7].

using 15–25% of the harvested energy. The use of a low leakage current supercapacitor, which has leakage current lower than 1 μA, was suggested as the best approach to urban RF harvesting, because they have a very high number of cycles (typically more than 500,000) and operate across a broad temperature range while being able to be charged and discharged very quickly, corresponding to the brief durations of RF illumination.

Low-duty-cycle nodes that can perform environmental and temperature monitoring with a power consumption of less than 10 μW can be seen as the most immediate applications for urban RF-WEH, as described in Table IV. Smart metering applications represent a borderline case in which a power budget of 320 μW in active mode can be maintained by duty cycling the active mode (active-duty cycle < 10%) and multi-band harvesting. Popovic *et al*. [11] demonstrated through experimental validation that low-power far-field wireless powering of sensor nodes at distances of 5–15 m from dedicated transmitters is achievable at efficiencies of 0.5–5%, with the primary efficiency limitation arising from the free-space path loss rather than rectenna circuit inefficiency.

Simultaneous Wireless Information and Power Transfer (SWIPT)

In addition to the opportunistic ambient harvesting, significant research effort has been invested in intentional wireless power transfer in communication networks using SWIPT architectures where the same RF waveform is used for both data communication and energy delivery. Zhou *et al*. [19] introduced the basic rate-energy (R-E) trade-off framework for SWIPT systems, showing that there is a fundamental coupling between the rate of information and the harvested power, and that a trade-off boundary exists. Two main receiver architectures were found: the power splitting (PS) receiver, in which the power received by the information decoding circuit and the energy harvesting circuit is split in a ratio $\rho \in (0,1)$; the time-switching (TS) receiver, which switches between information decoding and energy harvesting modes in a time-division manner. As reported in [19] by Zhou *et al*., the gain in throughput compared to pure communication (no EH) mode was found to be 18–34% for typical urban channel conditions in the PS scheme and the energy transfer efficiency was 35–60%. With the energy harvesting phase of the TS scheme, the gains in throughput were slightly lower (12–25%). In a wireless powered communication network (WPCN), the "harvest-then-transmit" protocol was proposed by Ju and Zhang [3] based on this concept, which allows the devices to first harvest energy from the downlink of a hybrid AP and then transmit energy on the uplink for information transmission.

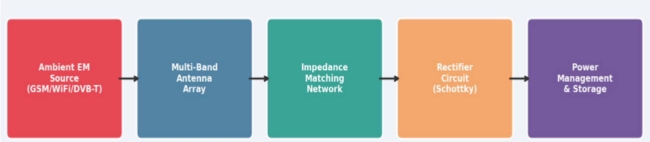

Fig. 5: Block diagram of a complete wireless energy harvesting system architecture from ambient EM source to load. Synthesized from Kim *et al*. [4], Costanzo *et al*. [2], and Vandelle *et al*. [15].

Coordinated Multipoint and Cooperative RF Harvesting

Coordinated multipoint (CoMP) transmission strategies provide a way to improve the RF energy availability at harvesting terminals in heterogeneous wireless networks

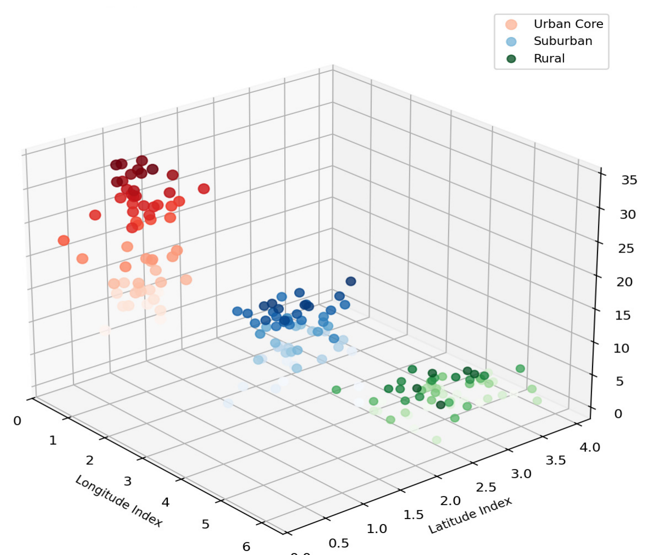

Fig. 6: Spatial distribution of harvestable RF power (μW) across simulated urban, suburban, and rural WSN deployment zones. Synthesized from Piñuela *et al*. [10] and Visser & Vullers [17].

Table 6: SWIPT and Cooperative Harvesting Network Protocol Performance Metrics

Protocol/Architecture	*Throughput Gain (%)*	*Energy Efficiency (%)*	*Coverage Radius (m)*	*Reference*
SWIPT (PS Scheme)	18–34	35–60	50–200	[19]
SWIPT (TS Scheme)	12–25	28–50	50–200	[19]
WPCN (Harvest-then-Transmit)	22–41	40–65	30–150	[3]
CoMP-RF Harvesting	28–45	45–70	100–500	[20]
Solar + RF Hybrid	—	60–85	50–300	[9]

Note: Throughput gain expressed relative to pure-communication (no energy harvesting) baseline. Data synthesized from Zhou et al. [19], Ju & Zhang [3], and Zhu et al. [20].

Table 7: Technology Readiness Level (TRL) Assessment for RF Energy Harvesting Subsystems (2008–2020)

Technology aspect	*TRL (2008)*	*TRL (2013)*	*TRL (2016)*	*TRL (2020)*	*Key milestone*
Antenna Design	4	6	7	8	[13, 15]
Rectifier Circuits	3	5	7	8	[5, 6]
Power Management	3	5	6	7	[8, 11]
Multi-Source Integration	2	3	5	7	[9, 15]
Network Protocols (SWIPT)	1	3	5	6	[3, 19]

Note: TRL scale: 1 = basic principles observed; 9 = operational system proven. Assessments synthesized from the reviewed literature.

(HetNets) by combining the energy of multiple base stations. Zhu *et al*. [20] analyzed an integrated solution based on CoMP for RF energy harvesting in a two-tier HetNet comprised of macro base stations and small cell access points and showed that the harvested energy of a mobile terminal can be enhanced by 28-45% by using cooperation among various transmission points in the network, in addition to increasing the energy harvesting range of the mobile terminal. The energy efficiency of CoMP-RF harvesting was quantified at 45–70%, representing a substantial improvement over non-cooperative scheme. Niotaki *et al*. [9] extended the analysis to hybrid solar and RF energy harvesting platforms, demonstrating that solar and RF sources exhibit partially complementary temporal profiles—solar harvesting peaks during daylight hours while RF harvesting peaks during evening communication activity—and that their combination achieves 60–85% overall energy availability compared to 35–60% for RF-only systems.

Comparative Analysis, Challenges, And Optimization

Technology Readiness and Evolution

The development of wireless RF energy harvesting technology over the 2008-2020 time period demonstrates a gradual maturation from laboratory proof-of-concept demonstrations to applications-ready, field-deployed systems. Table VI summarizes the technology readiness level (TRL) assessment of principle subsystems categories based on the literature reviewed. The most developed technologies are antenna design and rectifier circuit technologies, which have progressed to TRL 8 by 2020 (system prototypes in operational environments), due to commercial availability of high-quality Schottky diodes and maturity of substrate-integrated antenna fabrication techniques [5, 13]. Energy harvesting electronics have reached TRL 7, with commercial energy harvesting integrated circuits (eg Linear Technology LTC3588) being available for practical deployment [4,8]. Multi-source integration, SWIPT network protocols are still at TRL 6-7, where the systems have been tested mainly in controlled laboratories and not in full operation in urban environments [3,9,19].

Key Technical Challenges

Although important steps have been taken, there are still some basic technical issues that hinder the implementation of the ambient RF-WEH systems practically. The major challenges that were identified from the literature reviewed and the proposed mitigation are summarized. The greatest restriction is that the ambient power density is low and fluctuates, causing the harvested power to be limited to 10–35 μW in urban cores and less than 5 μW in suburban areas with single-band rectennas [10, 16]. It can be partially overcome by multi-band rectenna architectures that combine the contributions from several frequency bands, resulting in a corresponding increase of the available power of 2.5–4× [5, 6] but introducing more circuit complexity and possible inter-band interference effects. In practice, RF-WEH systems suffer from many hardware non-idealities that are often overlooked and are a substantial factor in degrading system performance. Luo *et al*. [8] analyzed the power loss due to various hardware impairments – phase noise in a voltage controlled oscillator, in-phase/quadrature imbalance in direct-conversion receiver, and quantization noise in the analog-to-digital converter – and found that these impairments combine, resulting in a 15–30% power loss when compared to ideal circuit simulations.

Quantitative Performance Benchmarks and Comparative Assessment

When comparing the principal rectenna architectures described in this paper, several interesting quantitative results come to light. The multi-band stacked design of Kuhn *et al*. [5] has the highest peak efficiency of 84%, but it needs a relatively high input power level (above −5 dBm) to maintain this efficiency, so it is best suited for the near source harvesting scenario. The Assimonis *et al*. [1] electrically small design also compromises on peak efficiency (65%) for ultra-low power operation (−30 dBm minimum sensitivity), thus being well suited for ambient harvesting of distant sources. The Song *et al*. [13] broadband design is a compromise for 75% efficiency over a 100 MHz bandwidth, and the Lu *et al*. [6] four-band adaptive design is the most efficient (70%) over the wideest spectrum, but it is not as broad as the Song *et al*. [13] design. CoMP-RF harvesting protocol of Zhu *et al*. [20] achieves the largest throughput enhancement (28–45%) and energy efficiency (45–70%) out of all the cooperative protocols discussed in this paper, but it introduces an overhead in coordination between base stations, which may be difficult to achieve in current deployments. A simpler alternative, with throughput gains of 22–41%, is the WPCN harvest-then-transmit protocol [3] which is compatible with standard cellular infrastructure modifications.

Conclusion

The purpose of this paper is to provide a thorough review of the research advances on wireless energy harvesting from urban electromagnetic pollution over the last 12 years (2008-2020). The literature reviewed confirms that the ambient power densities measured in urban RF environments, with contributions from all the bands (GSM 900, GSM 1800, UMTS, WiFi and DVB-T), reaches up to 0.227 μW/cm², making the urban RF environment a viable and constantly available energy source for ultra-low-power wireless sensor nodes. The most sophisticated rectenna designs that have been realized during this period have been multi-band stacked designs with 84% RF-to-DC conversion efficiency, and electrically small designs with −30 dBm sensitivity.

In the network level, SWIPT frameworks with power splitting and time switching receivers, with WPCN harvest-then-transmit strategies, and with cooperative harvesting strategies based on CoMP have shown improvements of 12–45% in terms of throughput over communication only baseline networks, and also significant energy transfer efficiencies of (28–85%). Depending on the architecture and deployment scenario. Complementary PV sources are successfully used in a hybrid system with RF harvesting, demonstrating that the total energy delivered by these systems is 60-85% for diurnal operation cycles, which is the most effective solution for standalone IoT deployment. Ambient power density fluctuations, nonlinear rectifier performance at low input powers, hardware non-ideality losses (15–30% efficiency reductions), harvester aperture limitations from regulation, and power density mismatch across multi-band operation have all been systematically characterized and strategies for mitigating these challenges have been synthesized from the literature. Advances in adaptable impedance reconfiguration, energy-aware network protocols and monolithic MMIC rectenna integration would put the field "on track" to move from TRL 6-8 demonstrations to large-scale urban deployments as of 2020. From the synthesis, several directions for future research emerged: Firstly, spectrum sensing for rectenna arrays could be co-optimized with machine learning techniques, and secondly, standardized methodologies for ambient RF power density mapping for urban planning could be developed for the millimeter-wave frequency bands as 5G deployment grows in momentum.

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