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Data and Energy Integrated Communication Networks for Wireless Big Data

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ABSTRACT This paper describes a new type of communication network called data and energy integrated communication networks (DEINs), which integrates the traditionally separate two processes, i.e., wireless information transfer (WIT) and wireless energy transfer (WET), fulfilling co-transmission of data and energy. In particular, the energy transmission using radio frequency is for the purpose of energy harvesting (EH) rather than information decoding. One driving force of the advent of DEINs is wireless big data, which comes from wireless sensors that produce a large amount of small piece of data. These sensors are typically powered by battery that drains sooner or later and will have to be taken out and then replaced or recharged. EH has emerged as a technology to wirelessly charge batteries in a contactless way. Recent research work has attempted to combine WET with WIT, typically under the label of simultaneous wireless information and power transfer. Such work in the literature largely focuses on the communication side of the whole wireless networks with particular emphasis on power allocation. The DEIN communication network proposed in this paper regards the convergence of WIT and WET as a full system that considers not only the physical layer but also the higher layers, such as media access control and information routing. After describing the DEIN concept and its high-level architecture/protocol stack, this paper presents two use cases focusing on the lower layer and the higher layer of a DEIN network, respectively. The lower layer use case is about a fair resource allocation algorithm, whereas the high-layer section introduces an efficient data forwarding scheme in combination with EH. The two case studies aim to give a better explanation of the DEIN concept. Some future research directions and challenges are also pointed out.

INDEX TERMS Data and energy integrated communication networks (DEINs), energy harvesting (EH), wireless big data, power allocation, information dissemination.

I. INTRODUCTION

An important form of big data is large amount of small piece of data collected from wireless sensors, namely, wireless big data. These sensors are typically powered by battery that drains sooner or later and will have to be taken out and then replaced or recharged. Energy harvesting (EH) has emerged as a technology to wirelessly charge batteries in a contactless way and thus widely used in wireless sensor networks. EH utilizes radio frequency (RF) rather than the traditional induction principle or other energy sources such as wind, vibration or solar to conduct the charging, making it more controller (usually human cannot control wind or sunshine). However this RF-based wireless energy transferring (WET) process is independent of wireless information transfer (WIT) and the latter is by far the major objective of radio transmission nowadays.

Information and energy are two fundamental notions in nature with critical impact on all aspects of life. All living and machine entities rely on both information and energy for their existence. In wireless communications, the relationship between information and energy is even more apparent as radio waves that carry information also transfer energy. Wireless communication systems employ electromagnetic waves in order to transfer information. Up until recently, the information transmission capacity of these signals has been the main focus of research and applications, neglecting their energy content. However, thanks to recent advances in silicon technology, the energy requirements of embedded systems have been significantly reduced, making electromagnetic waves a potentially useful source of energy. For example, recent experiments show that hundreds of microwatts can be harvested from the signals broadcast by a TV station from as far as a few miles away [1]. As a matter of fact, the first use of radio waves was for energy transfer rather than information transmission. However, despite the pioneering work of Tesla, who experimentally demonstrated WET in the late 19th century [2], modern wireless communication systems mainly focus on the information content of the radio-frequency (RF) radiation, neglecting its energy transfer.

Recent research work has attempted to combine WET with WIT, typically under the label of simultaneous wireless information and power transfer (SWIPT). Such work in the literature largely focuses on the communication side of the whole wireless communication networks with particular emphasis on power allocation. In contrast to the state of the art, this paper proposes a new type of communication network called data and energy integrated communication networks or DEIN, which integrates the traditionally separate two processes, i.e., wireless information transfer (WIT) and wireless energy transfer (WET), fulfilling co-transmission of data and energy. In particular, the DEIN communication network in this paper regards the convergence of WIT and WET as a full system that considers not only the physical layer but also the higher layers such as media access control and information/energy routing. There is a lack of systematic understanding of DEIN in the literature. For instance, little is known about how to bring the gains of DEIN from the physical layer to the design of upper layers.

While information and energy transfer are in harmony in nature, an efficient design of DEIN in its engineering sense is challenging. For example, a typical DEIN network consists of many nodes with various capabilities and different constraints from both communications (such as delay, data rate, etc.) and energy (such as battery capacity and battery sensitivity, etc.). These diversities impose difficulties for characterizing the fundamental limits of DEIN networks and result in extra system complexity and may incur more energy and spectral resource [3], [4].

The DEIN concept represents a paradigm shift of future wireless communication networks with its fundamental goals changing from pure information transfer to joint data-energy transfer. For this new type of network as DEIN, fundamental issues regarding information/energy coding, system modelling and theoretical analysis, and the DEIN overall system design need to be considered among many other new research issues. The trade-off between information and energy and their effective interaction necessitate novel designs of almost all layers of the network protocol stack. Efficient cross-layer design approaches will be necessary, for example, to bring advanced physical layer techniques, such as full duplexing and massive multiple-input multiple-output (MIMO), together with dynamic resource allocation algorithms at the data link layer, and even combined with multi-hop data forwarding techniques. As a positioning piece of work, this paper aims to present some high-level concept of DEIN by making the following contributions:

- To present the DEIN system architecture through redefining the traditional network protocol stack by introducing energy processing alongside the traditional data processing. Explanation to each newly introduced components in the stack and their relationship with other system components is also described.
- To give two use cases of DEIN. The first one gives a simple example of the functionalities of the DEIN lower layer, namely, power allocation to maximize the minimum data rate of user devices. And the user devises are powered by the same antenna via WET and their batteries respect the basic energy harvesting rules. The second use case presents a high-level perspective of DEIN, namely, multi-hop data forwarding in combination with energy harvesting.
- To identify some research challenges of DEIN and to point out some future research directions in pursuit of this new and exciting type of future wireless communication networks as DEIN.

The remainder of the paper is organized as follows. Based on a brief discussion of existing work, Section II presents high-level architecture of DEINs. Then two important aspects of a DEIN are presented in Section III and Section IV, focusing on the lower layer and the higher layer of a DEIN network respectively. In particular, Section III describes a fair resource allocation scheme whereas Section IV introduces an efficient data forwarding algorithm in a DEIN network. Simulation results are presented in these two technical sections. Some future directions are pointed out in Section V before conclusion remarks are made.

Notations: All lower case and upper case boldface letters represent vectors and matrices, respectively. Let $tr(X)$, $det(X)$, X^{-1} and X^H denote the trace, determinant, inverse and hermitian of a symmetric matrix X, respectively. $\mathbb{C}^{x\times y}$ and $\mathbb{R}^{x\times y}$ denote the set of complex and real matrices of size $x \times y$, and $\mathbb{C}$ and $\mathbb{R}$ denote the set of complex and real vectors of size $x \times 1$, respectively. All letters at the right bottom of different variables can be explained by following: l shows the l-th slot and i is the different users.

II. DEIN SYSTEM ARCHITECTURE

A. DEIN OVERALL PROTOCOL STACK

By extending the traditional network protocol stack, this Section presents the DEIN overall system architecture by adding energy processing stack alongside the information processing layers, as depicted in Figure 1. Researches need to be carried out to characterize the capacity of the DEIN network architecture when receivers have both information and EH constraints. Trade-off needs to be considered between delay, achievable data rate (or throughput), coding method, power allocation in the decentralized DEIN channels.

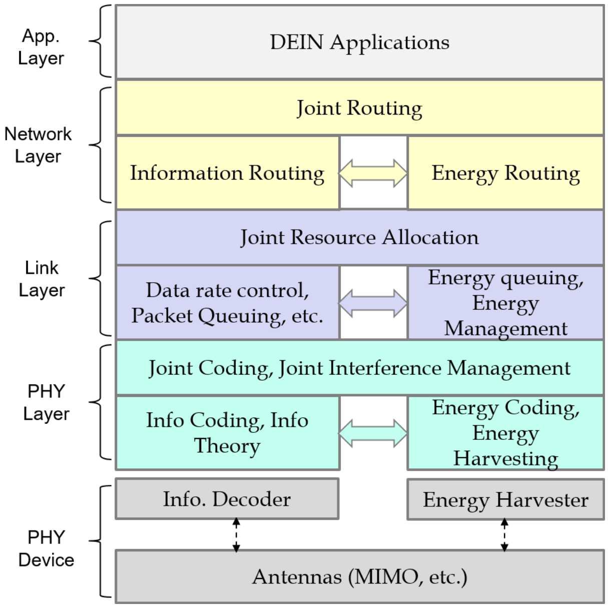

FIGURE 1. DEIN overall protocol stack (UE side).

B. DEIN PHYSICAL LAYER DESIGN

Both information and energy are transferred from the BS in the form of RF and received by antennas at the UE side. Multiple transmit/reception antennas are typically used to improve the performance of the DEIN systems, giving rise to the so-called MIMO (Multiple Input and Multiple Output). Most current literature is limited to small-scale MIMO systems with only a few antennas at the transmitter (e.g. 10 or less). A more promising technology is massive MIMO where hundreds of antennas are deployed at the BS, which can improve the capacity of wireless networks significantly.

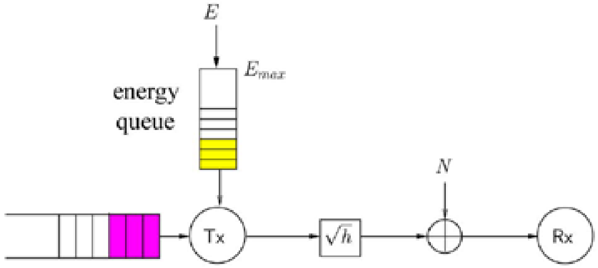

FIGURE 2. System with a finite-sized battery [5].

The amount of energy that can be transferred over the wireless channel is severely limited by fading and path-loss and it is important to design sophisticated physical layer approaches and improve energy efficiency of DEIN. In a way similar to modelling an information communication system, researches have been carried out to investigate energy harvesting from an information theoretical perspective. In this case, References [5] introduces an energy queue on top of the existing communication channel to describe the energy harvesting battery, as shown in Figure 2.

Consider the single-user fading channel with additive Gaussian noise, the transmitter has two queues, the data queue where the data packets are stored, and an energy queue where the arriving (harvested) energy is stored. Consider the classical AWGN channel with input X, additive zero-mean unit-variance Gaussian noise N, and output $Y = X+N$. In the classical result of Shannon, the codewords are average power constrained. The capacity of the energy harvesting channel is known in the cases of unboundedly large battery ($E_{\max} = \infty$), no battery ($E_{\max} = 0$), and for a unit-sized battery ($E_{\max} = 1$) over a binary noiseless link. The goal here is to schedule the transmission of data packets in the data queue using the energy in the battery.

Interference is another important issue of communication systems and thus another DEIN design issue is how to optimize energy and information transfer jointly for MIMO interference channels. Interfering signals not intended for a receiver, impair data transmission, but can indeed be used as a source of energy. Therefore, the increase of interference can become useful for wireless nodes whose batteries are low. Conventional transmission strategies, such as interference alignment (IA) [6], will be tailored to reflect such new interference management, by bringing energy cooperation into the consideration when designing MIMO precoding.

C. DEIN LINK LAYER DESIGN

A DEIN may work in a cooperative manner where there are relay nodes between a pair of source and destination nodes and these relay nodes are powered by energy harvesting. Research issues here include characterization of the performance gain of DEIN with these relays. The performance metrics include data rate, delay, energy efficiency, etc. Furthermore, these relays may work either in a half-duplexing mode or a full-duplexing mode. In the full-duplexing mode, a relay can transmit and receive data simultaneously. From WITs perspective, the loopback interference [7] as a result of full duplex can be harmful to communications. However, the full duplex can be significantly effective when used for energy harvesting since the loopback interference can be exploited for EH at relay nodes. Full-duplex DEIN will be an interesting future research direction.

Another important issue for the DEIN link layer design is dynamic resource allocation algorithms that should be fair and efficient in order to improve the overall DEIN performance. Here resource may include spectrum, time slot, power, beamforming vectors, etc. The performance metrics include link data rate (max, min or mean), DEIN network throughput, delay (link or network), spectrum efficiency, energy efficiency, etc. One performance metric that involves EH may be the data rate per unit of harvested energy or per transmitted power. Typically such dynamic resource allocation problems are formulated into certain types of optimization problems with constraints. Constrains here may concern various QoS (Quality of Service) parameters such as task delay, maximal transmission power at the BS or UEs. More importantly, energy constraint such as energy causality constraint and battery finite storage constraints as described in [5] shall be respected in the formulated optimization problems.

Another specific parameter is splitting factor for the energy harvesting side (i.e., UE) to decide the percentage of the harvested energy, denoted by α, to be used for energy harvesting and remaining $1 - \alpha$ is used for information decoding. A use case is given in Section III of this paper to illustrate a simple example of resource allocation in DEIN.

D. DEIN NETWORK LAYER DESIGN

There are two major streams of network design for an EH-enabled network, wireless or wireline. The first one is packet routing or information forwarding powered by EH and the second one is the so-called energy Internet where the basic principle of Internet is applied for energy routing. As far as DEIN is concerned, which is for wireless networks, the harvested energy can be partially transferred to neighbouring nodes through energy cooperation, in addition to the conventional *packet routing*.

Gurakan *et al.* [8] consider a network where there are both data nodes/links and energy nodes/links. Optimal data and energy routings are carried out to minimize networks data transmission delay. In this work, the energy source is not RF as in DEIN but solar and the concerned network is wired rather than wireless networks. For fixed data and energy routing topologies, this work determines the optimum data rates, transmit powers and energy transfers, subject to flow and energy conservation constraints [8]. An interesting observation of the work is that energy is routed from nodes with lower data loads to nodes with higher data loads.

Mobile devices are becoming increasingly powerful nowadays in terms of processing, communication and interaction. Besides, short range communication techniques, such as Device-to-Device (D2D), enable mobile devices to conduct data forwarding and act as relays for others. However, this also introduces another problem: battery runs out very quickly. To address this problem, many recent studies employ Radio Frequency based EH (RF-EH), which can convert RF into electricity. However, a big drawback that limits the application of RF-EH is the large propagation loss of radio signal energy. A promising way to mitigate this problem at the network layer is to deploy multiple energy sources (or energy base bases (eBSs) in the data network. Then one immediate issue is where to deploy these eBSs. For example, through perceiving users mobility pattern, energy sources can be deployed at popular places with many users gathering, and charge a large number of users devices with a small propagation loss. Section IV of this paper gives such a use case.

E. DEIN APPLICATION LAYER DESIGN

In this Section we look into the design of the DEIN application layer from different types of wireless networks, such as wireless sensor networks (WSN), cognitive radio networks (CRN) and mobile cellular networks.

1) WIRELESS SENSOR NETWORKS

A node in a WSN explores its received energy for not only information transmission but also data collection. The data collection process, which usually includes reception, sampling and encoding/decoding, etc., may consume more energy than data transmission. For this reason, specific protocols and algorithms need to be designed for different layers of DEIN. There are some recent works on these aspects of similar concepts. Reference [9] proposed an Energy Harvesting Modeling (EHM) which is suitable for each node in the WSN and shown in Figure 3 [5]. In the modeling, the energy consumption of data collection and information transmission is dynamically allocated by Energy Management Unit (EMU). Reference [10] considered multi-hop network. Reference [11] proposed a delay-constrained-based offline power allocation schedule of multi-hop WSN. Reference [12] compared and analyzed MAC protocol which adopted Carrier Sense Multiple Access (CSMA) and polling designed novel probabilistic polling protocol in single-hop WSN of which some data collection nodes can harvest energy.

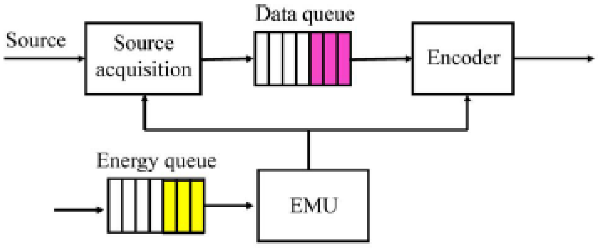

FIGURE 3. **EH modelling of a single sensor node [5].**

2) COGNITIVE RADIO NETWORKS

In cognitive radio networks, secondary users could access the spectrum of primary nodes whenever the spectrum is free [13], [14]. The introduction into the CRN of the technology of EH could improve not only the spectrum utilization but also the energy utilization. The main point of study is the optimization of allocation cognitive energy and the energy consumption of data transmission to maximize the energy utilization under the premise of normal operation of networks [15], [16]. Reference [17] considered energy harvesting cognitive radio networks in which a secondary transmitter harvests energy from ambient sources or wireless power transfer systems while opportunistically accessing the spectrum licensed to the primary network. In reference [18], Gan Zheng considered joint cooperation between information and energy and proposed three schedules of realizing the cooperation. In reference [19], Canhao Xu investigated the robust transceiver design problem in MIMO underlay cognitive radio networks and maximized the sum harvested power at energy harvesting receivers while guaranteeing the required minimum mean-square-error at the secondary information-decoding (ID) receiver and the interference

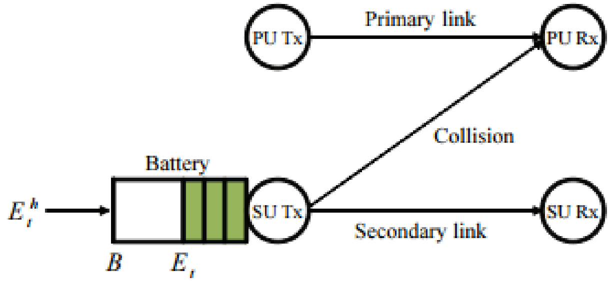

FIGURE 4. **EH-enabled CRN illustration [5].**

constraints at the primary receivers. Figure 4 [5] shows the framework of CRN consisting of a primary user with energy harvesting and a secondary transmitter with energy harvesting.

3) MOBILE CELLULAR NETWORKS

The research of introducing the technology of EH into mobile cellular networks and reasonable allocation of energy resources is concerned gradually. The 5G wireless communications will also consider energy efficiency and research novel wireless communication architectures and technologies to address spectral efficiency and energy efficiency [20]. In mobile cellular networks, the research of allocation of energy resources is scarce. The reason is that the characteristics of high power of macro base station reduces the sensitivity of energy adjustment. Reference [12] researches the optimal tradeoff between the average grid power and the outage probability in single-cell energy harvesting wireless system. Reference [21] develops a new tractable model for K-tier heterogeneous cellular networks, where each base station is powered solely by a self-contained energy harvesting module. However, due to the unpredictable and intermittent nature of energy source, it is impossible that communication system depends entirely on harvesting energy. So it is significance to mix use of grid and EH in mobile cellular networks. Reference [22] considered a heterogeneous network consisting of one macro base station (BS) powered solely by power grid, and one small base station powered jointly by harvested and grid energy and formulated the problem as minimizing the average power grid consumption by adjusting the radius of small BS and the carrier number of macro BS while satisfying the users QoS (weighted outage probability) constraints for a predefined time period. In addition, the research of the technology of EH in heterogeneous cellular networks also has some concerns [21].

III. A CASE STUDY FROM DEIN'S LOWER-LAYER PERSPECTIVE: FAIR RESOURCE ALLOCATION

In this section, we present a fixed time slotted transmission scheme and analyze the downlink (DL) WET phase and uplink (UL) WIT phase. We formulate problems based on the uplink throughput, with the consideration of fairness. In [23], the massive MIMO system powered by WET adopts slotted transmissions, where each slot is divided into three phases for channel estimation, DL power transmission, and UL data transmission, respectively. The hybrid access point (H-AP) operating in full duplex (FD) mode was studied in [24], where H-AP transmits energy in the DL and receives information in the UL simultaneously. In [25], energy transferring nodes called power beacons (PBs) were used to power UL transmissions, and the relationship between the densities of BSs and PBs and the optimal UL transmission power for a given outage probability were obtained under a stochastic geometry model.

However, none of the above mentioned works has taken into account the power sensitivity of RF-DC circuits. The received RF signals cannot be converted into DC (i.e, energy transfer) if their power level is lower than the power sensitivity of an RF-DC circuit [26]. Thus, actually received energy would be much lower than the theoretically predicted amount, leading to a falsely higher data rate. Besides, none of these works has considered the battery capacity, thus ignoring the possibility of energy oveflow or the opportunities for the user equipment (UE) to optimize the use of harvested energy across UL WIT slots. It has been shown that UE using all available energy for WIT in each slot achieves a lower data rate than uniformly distributing energy between energy arrivals [27]–[29]. To the best of our knowledge, no existing work has studied a WET enabled communication system while considering the power sensitivity of RF-DC circuits. In this paper, we devise a power and time allocation policy for the MIMO UL transmission powered by WET, with the consideration of both finite capacity batteries at the UE and power sensitivity of RF-DC circuits over a block fading channel.

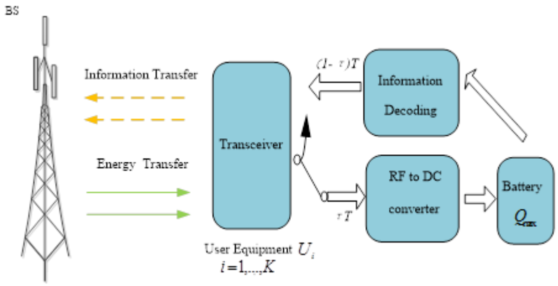

FIGURE 5. **A DEIN communication model for DL WET and UL WIT.**

A. SYSTEM MODEL AND PROBLEM FORMULATION

Suppose a DEIN model consisting of a BS with M antennas and K single-antenna UEs with a finite battery capacity denoted by $U_i(i = 1, \ldots, K)$, as shown in Figure 5. It is assumed that $M \geq K$. Each UE uses the energy harvested in the DL WET phase via beamforming of the BS to power its UL information transmission. The total capacity of battery in each UE is $Q_{\max}$, which is large enough to avoid overcharging the battery.

A fixed time slotted transmission scheme is adopted here. Each time slot has a constant period T, consisting of two phases, namely, the DL WET phase and the UL WIT phase. The duration of the two phases are τT and $(1-\tau)T$, respectively. But for simplicity it is assumed that t=50%. Then, the BS transmits energy to U_i through wireless energy beamforming. The received power level and the energy harvested at U_i in time slot $l (l = 1, \ldots, N)$ are denoted by $P_{l,i}$ and $E_{l,i}$, respectively. It is worth noting that due to the power sensitivity of RF energy harvesting circuits, U_i may not harvest any RF energy if the received signal power $P_{l,i}$ is less than a certain level. Namely, the received power at a UE can be used only if the received power level $P_{l,i}$ exceeds the corresponding certain threshold α(e.g., -10 dBm). This indicates that the WET of every UE follows a Bernoulli process with different probability p_i, where p_i is the probability of delivering energy from the BS. In addition, all UEs conduct UL WIT simultaneously via space-division-multiple-access (SDMA), which is powered by the energy stored in the batteries. The harvested energy is stored in the battery first, and then used for UL information transmission. For simplicity, we assume $T = 1s$ and thus T is omitted in the formula below.

We consider frame-based transmissions over flat-fading channels on a single frequency band [30] (i.e., which means the channel remains constant in each slot). Denote $h_{l,i} \in \mathbb{C}^{M\times 1}$ as the UL channel of U_i in the l-th slot and we have

$$h_{l,i} = (\alpha_0 |D_i|^{-\beta} C_i)^{\frac{1}{2}} g_{l,i} \quad i = 1, \ldots, K \tag{1}$$

where α_0 denotes a constant determined by the RF propagation environment, D_i is the propagation distance, β_i is the path loss, C_i is shadow fading and $g_{l,i} \in \mathbb{C}^{M\times 1}$ is the matrix of Rayleigh fading coefficients and $g_{k,i} \sim CN(0, 1)$. By exploiting the channel reciprocity, the DL transmission channel can be obtained as $h_{l,i}^H$. For simplicity, we assume $C_i = 1$ and that CSI is available at both the BS and U_i.

In the DL WET phase, assume that there is just one energy beam to transmit energy from the BS to these UEs satisfying the probability p_i, since we just transmit energy signals in the DL [31]. Besides, ambient channel noise energy cannot be harvested. The DL received signal $y_{l,i}$, received power $P_{l,i}$ and harvested energy $E_{l,i}$ of U_i in the in the l-th slot are expressed as

$$y_{l,i} = h_{l,i}^H \omega_l x_{l0} + n_{l,i} \quad i = 1, \ldots, K \tag{2}$$

$$P_{l,i} = x_{l0}^2 h_{l,i}^H \omega_l \omega_l^H h_{l,i} \quad i = 1, \ldots, K \tag{3}$$

$$E_{l,i} = \epsilon_i \tau_l P_{l,i} = \epsilon_i \tau_l x_{l0}^2 h_{l,i}^H \omega_l \omega_l^H h_{l,i} \quad i = 1, \ldots, K \tag{4}$$

where $n_{l,i} \sim CN(0, \sigma_i^2)$ is the receiver noise, ω_l is the $M \times 1$ beamforming and satisfies $\|\omega_l\|^2 = 1$, x_{l0} is the transmission signal and satisfies $x_{l0}^2 \leq P_{\max}$, where $P_{\max}$ is the transmit power constraint and ϵ_i denotes the energy harvesting efficiency at U_i, which should satisfy $0 < \epsilon_i \leq 1$. For simplicity, we assume $\epsilon_i = 1$.

In the UL WIT phase of each slot, UEs use the harvested energy to power UL information transmission to the BS. For convenience, we assume the circuit energy consumption at U_i is 0. The received signal at the dBS in the l-th slot is given by

$$y_l = \sum_{i=1}^{K} h_{l,i} x_{l,i} + n_l \quad i = 1, \ldots, K \tag{5}$$

where $n_l \in \mathbb{C}^{M\times 1}$ denotes the receiver additive white Gaussian noise (AWGN). It is assumed that $n_l \sim CN(0, \sigma_l^2 I)$. Besides, we assume that the BS employs linear receivers to decode $x_{l,i}$ in the UL. $x_{l,i}$ denotes the transmit signal of U_i and satisfies $x_{l,i}^2 = P'_{l,i}$, where $P_{l,i}$ is the transmit power of U_i. Specifically, let $v_{l,i} \in \mathbb{C}^{M\times 1}$ denote the receive beamforming vector for decoding $x_{l,i}$ and define $V = \{v_{l,1}, \ldots, v_{l,K}\}$. In order to reduce complicity, we employs the ZF based receive beamforming in the normal information BS proposed by [32], which is independent of w_l and τ_l. Define $H_{-l,i} = [h_{l,1}, \ldots, h_{l,i-1}, h_{l,i+1}, \ldots, h_{l,i}]^H$, $i = 1, \ldots, K$, including all the UL channels except $h_{l,i}$. Then the singular value decomposition (SVD) of $H_{-l,i}$ is given as

$$H_{-l,i} = X_{l,i} \Lambda_{l,i} Y_{l,i}^H = X_{l,i} \Lambda_{l,i} [\overline{Y}_{l,i} \widetilde{Y}_{l,i}]^H \tag{6}$$

where $X_{l,i} \in \mathbb{C}^{(K-1)\times(K-1)}$, $\overline{Y}_{l,i} \in \mathbb{C}^{M\times(K-1)}$, $\widetilde{Y}_{l,i} \in \mathbb{C}^{M\times(M-K+1)}$. Thus, the beamforming can be expressed as $v_{l,i}^{ZF} = \frac{\widetilde{Y}_{l,i} \widetilde{Y}_{l,i}^H h_{l,i}}{\left\| \widetilde{Y}_{l,i}^H h_{l,i} \right\|}$. Then, throughput of U_i in bits/second/Hz (bps/Hz) can be expressed as

$$R_{l,i}^{ZF} = (1-\tau_l) \log(1 + \frac{P'_{l,i} \widetilde{h}_{l,i}}{\sigma_i^2}) \quad i = 1, \ldots, K \tag{7}$$

where $\widetilde{h}_{l,i} = \left\| \widetilde{Y}_{l,i}^H h_{l,i} \right\|^2$, and $P'_{l,i} = \frac{E_{l,i}}{1-\tau}$, meaning that we assume using all the energy harvested to transfer information in UL phase.

Let $Q_{l,i}$ represent the amount of energy available in the battery of U_i at slot l after DL energy broadcasting phase and its updating function is as follows:

$$Q_{l,i} = \min(Q_{l-1,i} + E_{l,i}, Q_{\max}) \tag{8}$$

This can be considered as the battery storage constraint indicating that the energy available of U_i cannot exceed the maximum battery capacity at any time.

In order to insure fairness, we maximize the minimum (max-min) average UL WIT throughput of all UEs by optimizing the DL energy beams. The optimization problem can be defined as

$$\begin{aligned} &\max_{\omega_l} \ \min P_{l,i} \\ &s.t. \ \|\omega_l\| = 1 \end{aligned} \tag{9}$$

Please refer to [29] for a solution to this optimization problem.

B. PERFORMANCE EVALUATION AND ANALYSIS

The numerical experiments are performed to evaluate the performance of the proposed algorithm in terms of fairness, sensitivity and throughput. The simulation parameter settings as shown in Table 1 are used unless stated otherwise.

TABLE 1. Simulation parameters.

Parameters	Value
BS antennas number M	3
UE number K	2
Propagation constant α_0	1
Path loss exponent β	2
Shadow fading C_i	1
Propagation distance D_1	10m
Propagation distance D_2	5m
$P_{\max}$	1W
Channel noise power σ^2	10^{-7}W
Battery max capacity $Q_{\max}$	0.005J
Power sensitivity of EH circuits α_1	0.03W
Power sensitivity of EH circuits α_2	0.05W

At the WIT phase, we aim to maximize the minimum throughput among UEs by obtaining an optimal power allocation. The throughput among UEs versus circuit sensitivity can be seen in Figure 6, which indicates that the throughput decreases as the sensitivity grows. This is because as the sensitivity becoming larger, users are less possible to harvest the received energy, causing the throughput at UL phase decreased.

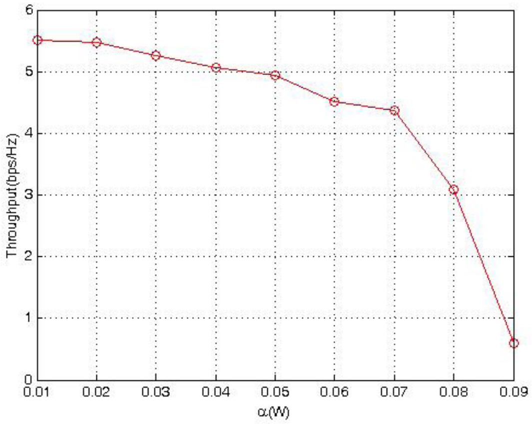

FIGURE 6. **UE throughput versus circuit sensitivity (τ = 0.5).**

We compare different scenarios with different DL slot τ, which can be shown in Figure 7. Its obvious that the throughput will decrease with the circuit sensitivity since more and more users are unable to harvest received energy. Above all, the scenario with $\tau = 0.5$ shows a better performance than any other circumstance, indicating that it is closer to the optimal slot allocation.

Figure 8 depicts the throughput among UEs increases as $Q_{\max}$ grows. The reason is that as a bigger $Q_{\max}$ means a less constrained battery, which helps UEs allocate a more adaptive slot to transmit information. It is also observed that the curve increase more smoothly when $Q_{\max}$ is higher since the energy harvested at UEs will be more difficult to make the battery fully charged, resulting in the battery constraint less an issue.

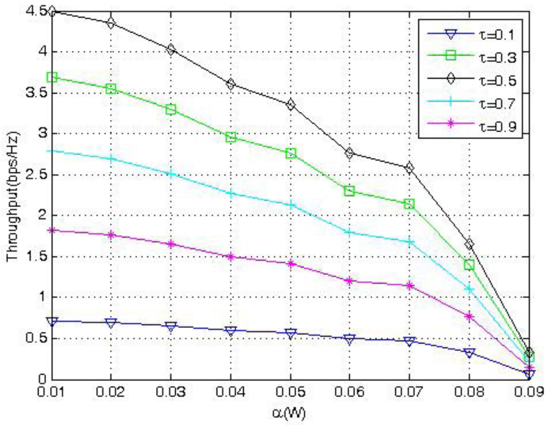

FIGURE 7. **UE throughput versus circuit sensitivity.**

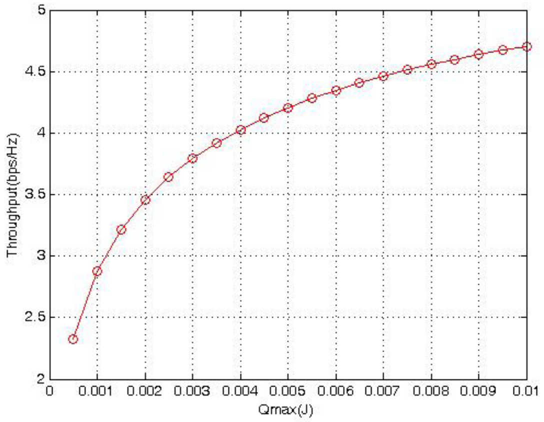

FIGURE 8. **UE throughput versus battery capacity $Q_{\max}$.**

IV. A CASE STUDY FROM DEIN'S HIGHER-LAYER PERSPECTIVE: DATA FORWARDING

A. PROBLEM CLARIFICATION

Wireless big data usually involves data dissemination in a large scale. Given the limited battery and transmission range capacity of UEs, multi-hop relaying is an effective mechanism for large wireless networks. Throwbox deployment is an effective means for data forwarding as it can bridge two UEs that do not encounter each other directly. The seminal work on throwbox deployment in [33] carries out a joint design of throwbox deployment and routing, and proposes three deployment schemes based on different knowledge levels. Work [35] proposes another throwbox deployment approach, which explores the social graph of specific locations and users to determine the deployment of throwboxes. Work [36] conducts throwbox deployment in combination with storage allocation. With a particular number of throwboxes and a specific size of storage, this work attempts to conduct the optimal throwbox deployment and storage allocation jointly, in order to maximize the performance of data forwarding. This paper investigates throwbox deployment in the context of DEIN, namely, the throwbox needs to disseminate not only data but also energy to power up UEs. Thus the throwbox here is named as H-box for hybrid box. The trade-off between data forwarding (DF) and energy harvesting (EH) through throwbox deployment will be looked into in this paper.

Rather than research in relaying among UEs, which are well investigated, this paper considers the following scenario in DEIN: the base station first forwards data to multiple H-boxes, and then the UEs that need the data can receive data from the H-boxes when they visit the hot spots with H-boxes. As this is in a DEIN network, in addition to receiving data (i.e., to carry out WIT), UEs can also harvest energy from the throwboxes (i.e., to conduct WET). For simplicity and easy illustration, we assume the transmissions of data and energy use different wireless channel.

Suppose the concerned DEIN network is composed of M UEs, denoted by $\mathcal{M} = \{0, 1, \ldots, M-1\}$ and N potential deploying places $\mathcal{N} = \{0, 1, \ldots, N-1\}$, called *hot spots*. There are Y H-Box in total to be deployed. Vector $\mathbf{Y} = [y_0, y_1, \ldots, y_{N-1}]$ ($y_j \in \{0, 1\}$) indicates the number of H-Boxes deployed at each hot spot. If $Y \geq N$, the deployment is quite simple as each hot spot can have an H-Box equipped. In this paper, we consider the situation where $Y < N$. Here the technical task is to select certain hot spots for the given number of throwboxes.

Mobility pattern of each user is explored, from which the average sojourn time of each user at each place can be attained. The average sojourn time can be computed by calculating the ratio of time the user spent at the place in the past. Consider a whole time T, the average sojourn time is the product of the ratio and the whole time. Specifically, we denote by τ_j^i the average sojourn time of user i at hot spot j during the whole time T.

B. EFFICIENCY OF DATA FORWARDING AND ENERGY HARVESTING

H-Box deployment aims at maximizing the efficiency of data forwarding and energy harvesting. As for data forwarding efficiency, instead of data transmission rate, the success ratio of data forwarding is more concerned, because data forwarding in MSN is usually unreliable. Therefore, we define data forwarding efficiency by the success ratio of data forwarding. For instance, if 10 different data are expected by 10 different UEs, the total number of data copies expected to be received is 100. If 90 copies are received in total, then the data forwarding efficiency is 0.9.

Energy harvesting efficiency can be denoted by the average capacity of energy harvested from the hot spots by each UE. Similarly, it is determined by the average sojourn time of UEs at the hot spots. However, it does not always increases with the sojourn time. When the average sojourn time reaches a threshold, the battery will be fully powered and no more energy will be harvested. Consequently, we define the following threshold function to denote the increase of energy harvesting efficiency with the average sojourn time.

$$\psi_\alpha(x) = \begin{cases} x, & \text{if } x < \alpha, \\ \alpha, & \text{otherwise} \end{cases} \tag{10}$$

Denoting the capacity of UE device battery by Q, and the power of the received energy signal (i.e., the energy harvested per unit of time) by P, we define the threshold by $\frac{Q}{P}$. With such a threshold, the maximum energy harvesting efficiency is Q. In other words, the battery capacity of a UE can be doubled at most via energy harvesting. Such a threshold turns out to be reasonable since the doubled battery capacity is usually enough for the daily requirement of most mobile UEs.

C. H-BOX DEPLOYMENT SCHEME

We propose the *Hybird-Deployment* (*D-deployment*) to realize the above two goals. As the two goals cannot be achieved simultaneously, we make a tradeoff between them.

Firstly, we consider how to maximize energy harvesting efficiency. According to the threshold function defined in Eq. (10), energy harvesting efficiency can be maximized by

$$\begin{aligned} &\text{Max. } \mathcal{E}(\mathbf{Y}) = \sum_{i=0}^{M-1} P \cdot \psi_{Q/P}(\sum_{j=0}^{N-1} \tau_j^i \cdot y_j) \\ &\text{s.t. } \sum_{j=0}^{N-1} y_j = Y, \ y_j \in \{0, 1\} \end{aligned} \tag{11}$$

where $\mathcal{E}(\mathbf{Y})$ denotes the energy harvesting efficiency of the network. Q and P are the capacity of UE device battery and the energy harvested per unit of time, respectively. τ_j^i is the average sojourn time of UE i at hot spot j and y_j is the number of H-Box deployed at hot spot j.

Then, we make the tradeoff by considering energy harvesting efficiency while maximizing data forwarding efficiency. Since the base station send the same data to each H-Box, data arrive the H-Boxes with the same speed. Define the average speed by μ. Then, the total number of data copies expected to be received is μMT and the number of data copies actually received is $\sum_{i=0}^{M-1} \mu(\sum_{j=0}^{N-1} \tau_j^i y_j)$. Hence, data forwarding efficiency can be denoted by

$$\mathcal{D}(Y) = \frac{\sum_{i=0}^{M-1} \sum_{j=0}^{N-1} \tau_j^i y_j}{MT} \tag{12}$$

We make the tradeoff by maximizing data forwarding efficiency at the constraint of energy harvesting efficiency. Specifically, we first compute the maximal energy harvesting efficiency $\mathcal{E}_{max}$ that can be achieved by Eq. (11). Then, considering a degradation of energy harvesting efficiency $\beta \mathcal{E}_{max}$ ($0 \leq \beta \leq 1$), we make the tradeoff by

$$\begin{aligned} &\text{Max. } \mathcal{D}(\mathbf{Y}) \\ &s.t. \quad \mathcal{E}(\mathbf{Y}) \geq \beta \mathcal{E}_{max} \\ &\qquad \sum_{j=0}^{N-1} y_j = Y, y_j \in \{0, 1\}. \end{aligned} \tag{13}$$

β is a parameter to control the importance of the two goals. The larger β is, the more important energy harvesting will be. When $\beta = 0$, energy harvesting efficiency is thoroughly ignored. On the other hand, if β increases to 1, the scheme will totally focus on energy harvesting efficiency. Eq. (11) and Eq. (13) can be easily solved using heuristic methods.

D. PERFORMANCE EVALUATION AND ANALYSIS

Performance of the H-box deployment (H-deployment) scheme is studied by Matlab based simulations. An existing throwbox deployment scheme [35] is employed for comparison. For the convenience of discussion, we call it *S-deployment*. S-deployment focus on maximizing data forwarding efficiency, but fails to consider energy harvesting efficiency. Moreover, instead of computing the sojourn time of UEs, it simply selects the hot spots with the largest centrality for deployment. We consider a scenario with 100 UEs and 15 hot spots. The average inter-contact time between any UE and any hot spot is randomly set according to a uniform distribution $U(1, 10)$. The main parameter settings are listed in Table 2.

TABLE 2. Simulation parameters.

Simulation parameters	Default Value
Number of hot spots N	15
Number of UEs M	100
Number of throwbox Y	4
Total time considered T	12 hours
Capacity of UE device battery Q	10 J
Power of the received energy signal P	0.6 mW
Parameter β in the tradeoff	0.9

Two performance metrics, i.e. Data Forwarding (DF) efficiency and Energy Harvesting (EH) efficiency, are studied. DF efficiency is the ratio of data copies received by the UEs successfully. EH efficiency indicates the average energy harvested by each UE. Performances of the two deployment schemes are compared with different number of H-Box Y.

The number of H-Boxes decides the chance for UEs to receive data and harvest energy, and hence affect the DF efficiency and the EH efficiency. As shown in Fig. 9 and Fig. 10, Both DF efficiency and EH efficiency increase with the number of H-Boxes. Differently, DF efficiency increases all the time indicating that it can be further improved with more H-Boxes. While, EH efficiency increases and approximates to an upper bound, which is the capacity of the UE device battery Q, according to the threshold function. Such an upper bound is reasonable as it allows UEs to double their battery capacity via energy harvesting and such an energy capacity is usually sufficient for the daily requirements of most UEs.

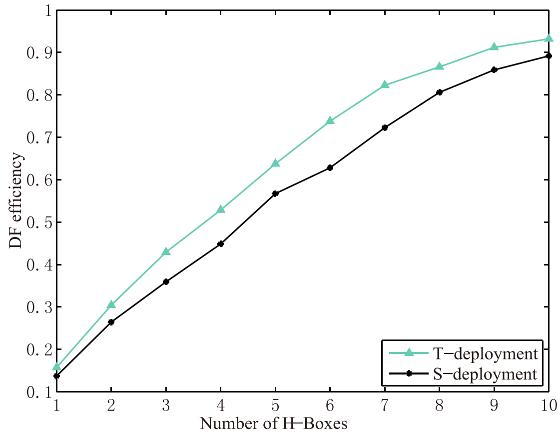

FIGURE 9. DF efficiency under different number of H-boxes.

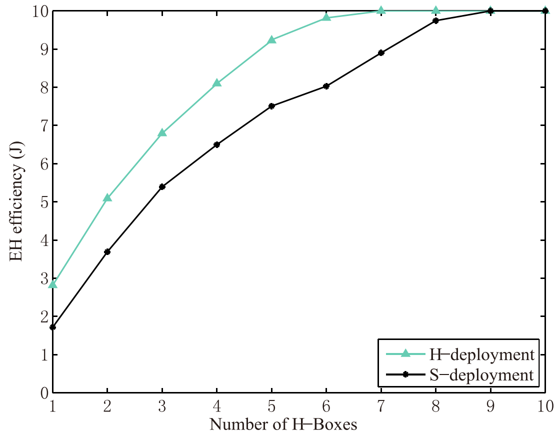

FIGURE 10. EH efficiency under different number of H-boxes.

In addition, H-deployment outperforms S-deployment in terms of both DF efficiency and EH efficiency because, in S-deployment, H-Box is directly deployed at the hot spots with the largest centrality. Such a deployment principle is quite simple. Nevertheless, the centrality adopted is simply derived from the visiting frequency of UEs which is not as valid as the total sojourn time to evaluate DF efficiency and EH efficiency.

V. CONCLUDING REMARKS AND FUTURE DIRECTIONS

This paper proposes a new network architecture/protocol stack called DEIN where traditional information transmission is fully or partially powered by RF EH. The cooperation between WIT and WET in DEIN is described. Two DEIN use cases are then presented focusing on the lower layer and the higher layer of a DEIN network respectively. The lower-layer use case is about a fair resource allocation algorithm whereas the high-layer section introduces an efficient data forwarding scheme in combination with EH. Some research challenges have been briefly discussed when describing the DEIN system architecture in Section II. More future research directions are identified below:

1) Research into the information theoretical foundation of DEIN, including the relationship between energy coding and information coding, joint coding of information and energy and its criteria.

2) Interference management in DEIN, in particular how to turn interference, which is regarded as harmful in traditional wireless communications, into a useful source for energy harvesting.
3) DEIN system architecture, including multi-hop relays that are powered purely via RF EH. In a relay-assisted DEIN network, the cooperation among nodes requires knowledge of the battery status of other nodes in the network. This leads to more signaling among nodes and thus increased DEIN overhead and more spectrum wastage and more interference to other nodes. Moreover, the diversity of network topology imposes more complexity to the problem.
4) Protocols and resource allocation. Both WIT and WET use the limited radio spectrum. How to design efficient and fair resource allocation algorithms while satisfying requirements from energy/battery, networks and end UEs is a challenging issue.
5) Hardware design and implementation of DEIN. One example is the design of new receiver architectures that will have the capability to optimally decode and harvest energy simultaneously.
6) Cooperation and integration with other energy sources such as solar, wind, vibration, etc. Research issues include energy source selection, distributed energy storage, energy charging/use scheduling, etc. and these shall be conducted jointly with data transmission.

Other equally important issues include energy security, how mobility making impact on EH. Furthermore, the majority of the current research focuses on single UE cases. How to expand this to multi-user scenarios is also a future direction.

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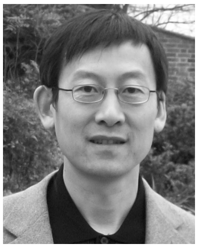

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