UAV-Aided Data and Energy Integrated Network: System Design and Prototype Development

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Abstract: Terminal devices deployed in outdoor environments are facing a thorny problem of power supply. Data and energy integrated network (DEIN) is a promising technology to solve the problem, which simultaneously transfers data and energy through radio frequency signals. State-of-the-art researches mostly focus on theoretical aspects. By contrast, we provide a complete design and implementation of a fully functioning DEIN system with the support of an unmanned aerial vehicle (UAV). The UAV can be dispatched to areas of interest to remotely recharge batteryless terminals, while collecting essential information from them. Then, the UAV uploads the information to remote base stations. Our system verifies the feasibility of the DEIN in practical applications.

Keywords: data and energy integrated network (DEIN); internet of things (IoT); simultaneous wireless information and power transfer (SWIPT); wireless energy transfer (WET); prototype

I. INTRODUCTION

1.1 Background

The increase of connected devices is a major trend in the next generation communication system. With the development of consumer electronics, these Internet of Things (IoT) devices become smaller but more intelligent. However, power supply to these devices becomes a challenge, since most of them are deployed outdoors. Accordingly, it is necessary to find other sustainable energy sources to extend the life-cycle of devices and even achieve the goal of zero-energy devices in 6G [1]. Energy harvesting [2] is an ideal way to relieve the power pressure for battery-powered communication devices. One kind of energy harvesting technology is to harvest energy from ambient environments. These communication devices live on wind, solar, tidal and wave energy. However, these renewable energy sources may not be suitable for IoT devices in some circumstances. Specifically, IoT devices may be deployed in shadow, where they can't harvest enough solar energy, or their size may be too small to implement wind power equipment. Compared to these natural energy sources, harvesting energy from radio frequency (RF) signals is another promising technology, which has a range of advantages. First, RF signals are more controllable. We can realize on-demand wireless energy transfer to IoT devices. Second, RF signals are capable of carrying energy to far-field, compared to other near-field wireless charging techniques, such as inductive coupling and magnetic resonance. Third, harvesting energy from RF signals only requires antennas and RF to direct-current (DC) rectifiers, which can be readily embedded into a compact device.

Recent works have attempted to coordinate both wireless energy transfer (WET) and wireless information transfer (WIT) in the same RF band, which yields the research of simultaneous wireless information and power transfer (SWIPT) in the physical layer [3, 4] and the research of Data and energy integrated network (DEIN) in the network layer [5]. In a DEIN system, there are hybrid-access stations and terminal devices. Hybrid-access stations are able to transmit energy signals and data signals in the downlink to serve multiple terminal devices [6]. Terminal devices can be remotely recharged by energy signals, and upload their own data.

We implement a DEIN system in the outdoor scenario, which includes a DEIN station carried by an unmanned aerial vehicle (UAV). Due to the mobility and the flexibility of the UAV, it can efficiently deliver both WET and WIT services to terminals by reducing signal propagation distances, while effectively enlarging the coverage of DEINs. These battery-powered or batteryless terminals can be deployed in human-unreachable areas. A DEIN station carried by an UAV can be dispatched to collect these terminals' data whenever we need it without considering the issues of terminals' power exhausted. Therefore, a UAV aided DEIN can be applied for environment monitoring, emergency communications in wide areas lacking of communication infrastructures [7]. To the best of our knowledge, recent works mostly focus on theoretical aspects while few implement a system-level prototype. This paper aims to verify the feasibility of DEIN in practical applications.

1.2 Related Work

Many studies in DEINs focused on theoretical aspects, such as improving WET and WIT performance through rational design in the physical layer [8] and coordinating energy queues and data queues through joint resource allocation in the MAC layer [9]. Lv *et al.* [10] studied the sum-throughput and fair-throughput in a single-cell DEIN system. Yang *et al.* [11] proposed an algorithm to maximize the sum of energy efficiency of all device-to-device (D2D) links in a D2D cellular network by optimizing the resource and power allocation based on a nonlinear energy harvesting model. Dong *et al.* [12] investigated the downlink achievable rates of massive multiple-input-multiple-output (MIMO) enabled DEIN systems. Kowon *et al.* [13] developed a joint design of transmit power allocation, beamforming, and receive power splitting for SWIPT downlink systems in wideband millimeter wave channel. Steven *et al.* [14] proposed a two-tone frequency shift keying modulation scheme for SWIPT system. Wang *et al.* [15] proposed a system operation sequence for SWIPT aided sensor-cloud system.

Recently, UAVs have emerged as an efficient technology for enhancing wireless communication. Yao *et al.* studied the resource allocation for UAV-based emergency wireless communications in [16]. Furthermore, some researchers considered a DEIN system based on UAV. For example, Jiang *et al.* [17] studied the coverage performance of UAV-aided DEIN systems under both linear and nonlinear energy harvesting models. Kang *et al.* [18] proposed a resource allocation algorithm, which jointly designed the trajectory, the transmit-power allocation and the receive-power splitting for a UAV-aided DEIN system. Sun *et al.* [19, 20] studied the physical layer security of a UAV-aided DEIN system in millimeter wave. Hong *et al.* [21] proposed a resource allocation algorithm for secure transmission in UAV-aided DEIN systems. Yang *et al.* [22] studied an efficient trajectory planning method that can minimize a cellular-connected UAV's mission completion time under the connectivity requirement. These work only consider theoretical design without any justification from practical applications. By contrast, our work focuses on engineering implementation which verifies the feasibility of a UAV aided DEIN system in a practical scenario.

There are also some existing works focusing on prototyping a link-level SWIPT system [23–28]. Specifically, a multi-band rectifier was presented in [23], which can be used for MIMO energy harvesting system. Kim *et al.* [24] presented the design and implementation of SWIPT system modem based on IEEE 802.15.4q standard. Khemar *et al.* [25] designed a rectifier achieving the RF-DC conversion efficiency of 45%, which can be used for ambient RF energy harvesting. Ayir *et al.* [28] study the waveforms and end-to-end efficiency in RF WET using a digital radio transmitter(DAT). Their experiments suggest that when the direct current (DC) input power at the transmitter is constant, high peak-to-average power ratio (PAPR) multi-sines are unsuitable for RF WET over a flat-fading channel, due to their low average radiated power. Moreover, Clerckx *et al*. [26] prototyped an innovative WET transceiver based on software-defined radio (SDR) that can operate in both open-loop and closed-loop (with channel acquisition at the transmitter) modes. Furthermore, they experimentally analyzed the harvested energy and throughput trade-off of a SWIPT system [27]. However, this SWIPT prototype relied upon expensive and heavy lab-based hardware, which are difficult to be implemented in any practical applications. Unfortunately, none of them considered a system-level prototype. Different from these works, we provide a system-level solution to a practical DEIN system, which can be quickly applied for practical environmental monitoring and emergency communications in wide areas.

As far as we know, there are only two exist work provide a system-level DEIN system. Kobuchi *et al*. [29] implemented a SWIPT system operating at 5.8 GHz for spacecraft health monitoring. The transmitter is equipped with a 4*4 active integrated antenna array and all the receives share one 2*2 patch antenna array. The experiment shows that their maximum conversion efficiency is 12% at the charging distance of 1 m. Although this is system-level prototype, the huge size of the antenna and low conversion efficiency make it unsuitable for an UAV application. Therefore, it can only deliver WET service in a small area. Our earlier work [30] provided a hardware design for both the receiver and transmitter of a DEIN system based on ZigBee protocol. At the transmitter, ZigBee signals are used for both WET and WIT. However, its WET coverage is quite limited, due to the low RF-DC conversion efficiency. In this paper, dedicated signals and a link protocol are introduced to improve the WET performance of the system. In addition, we combine the DEIN with a UAV system, which makes the DEIN system with a complete link protocol fully functional in an outdoor scenario. Our novel contributions are summarized as follows:

- A DEIN transmitter with functions of downlink WET in 915 MHz and uplink data collection in 2.4 GHz is prototyped. It is jointly enabled by a DC-RF energy converter, a dedicated communication module and a control unit.
- A batteryless DEIN receiver is prototyped. It is jointly enabled by an RF energy harvester in 915 MHz, a communication module in 2.4 GHz and a sensor. Flexible switching between the wireless recharging mode and active communication mode is controlled by energy management circuits.
- A UAV platform is prototyped to carry and control the DEIN transmitter. Data collected by the DEIN transmitter can be forwarded to a cloud server. The UAV can also take commands from the cloud server.
- We have designed and implemented a fully functioning DEIN system and evaluated its overall performance, indicating its effectiveness and efficiency.

The remainder of this article is organized as follows. In Section II, we describe the system architecture, which is followed by the design of the onboard DEIN transmitter and that of the DEIN receiver in Section III and IV, respectively. In Section V, we evaluate the performance of our UAV aided DEIN prototype in a field-trial. Finally, the paper is concluded in Section VI.

II. UAV-AIDED DEIN SYSTEM ARCHITECTURE

A lot of sensors are deployed for outdoor information collection. When the batteries of these sensors are exhausted, a UAV equipped with a DEIN transmitter can be dispatched to the target area for the sake of remotely charging them via RF signals. In this section, we mainly investigate the system architecture and work flow of the proposed DEIN system.

2.1 System Components

The UAV aided DEIN system includes a UAV, a DEIN transmitter (DEIN_T), a DEIN receiver (DEIN_R) and a cloud server. The DEIN_T is implemented at the bottom of the UAV. Therefore, the UAV can carry the DEIN_T to the vicinity of the DEIN_R. The details of all these components are explained as follows:

UAV: A UAV carrying a DEIN_T collects information from sensors. It also forwards this information back to the cloud server. Apart from the DEIN_T, the UAV is also equipped with Global Navigation Satellite System (GNSS), a Flight Control System, an embedded processor as a control unit and relevant communication modules as depicted in figure 1. Therefore, the UAV is capable of controlling its own motion, such

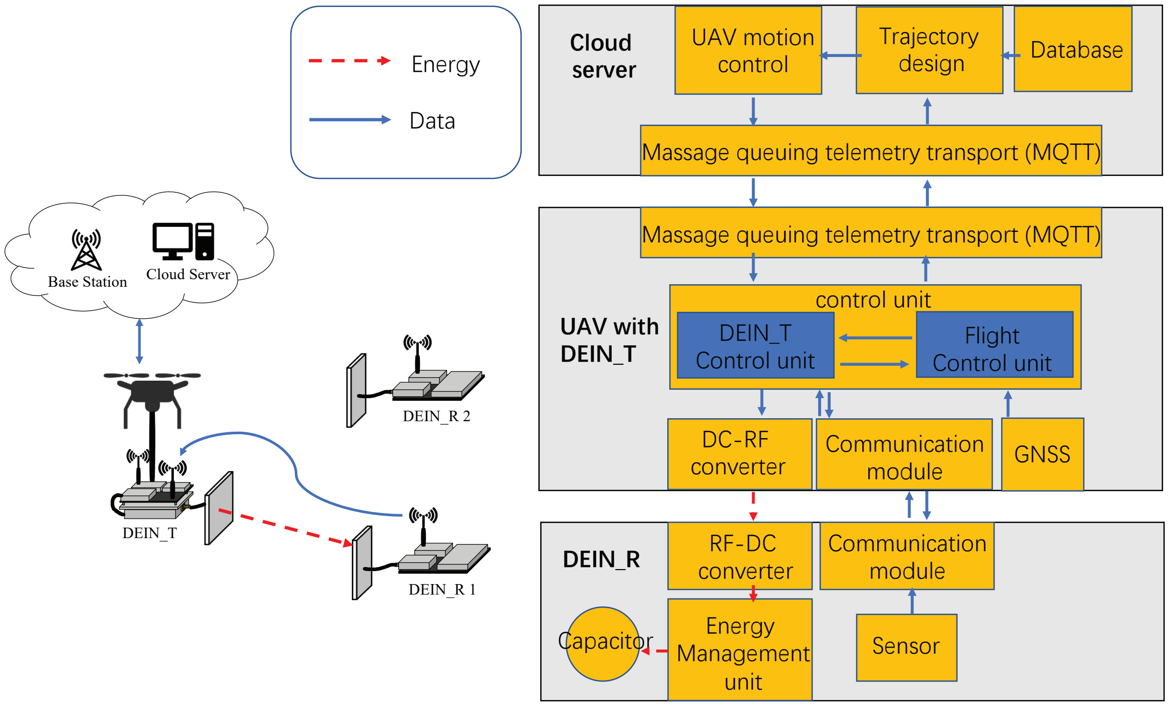

Figure 1. *UAV aided DEIN system architecture.*

as take-off, landing, hovering and flight. In addition, UAV can arrive at a specific coordinate within an error range of a few centimeters by exploiting the on-board D-RTK GNSS system for high precision positioning. Therefore, the UAV may maintain a stable hovering to some extent. Moreover, data collected by the DEIN_T can be forwarded to the cloud server via the UAV's embedded communication module. In practical applications, transportation vehicles equipped with mobile base stations can be used as a gathering point for the take-off and landing of the UAV.

DEIN_T: A DEIN_T has two main functions, namely transmitting downlink RF signals for WET and receiving uplink RF signals for data collection. Therefore, the DEIN_T is mainly composed of three parts: a DC-RF energy converter, a communication module and a control unit as depicted in figure 1. The DC-RF energy converter is invoked for converting the DC energy output from the embedded battery to RF signals. The communication module is relied upon for collecting data uploaded from a DEIN_R. Both the communication module and the DC-RF energy converter are coordinated by the DEIN_T's control unit. In addition, the DEIN_T's control unit exchanges some control commands and application data with the UAV's control unit. Although the control unit of the DEIN_T and the control unit of the UAV are separate, in practice, we can implement both of them on the same microcontroller unit (MCU). After collecting data from the DEIN_R, the DEIN_T relays the data to the communication module of the UAV in order to finally deliver it to the cloud server.

DEIN_R: A harvest-store-then-transmit protocol is adopted by a DEIN_R [31] as depicted in figure 1. A matching network, an RF-DC converter, a battery-charging circuit and an energy management unit are implemented to convert RF energy to DC energy, which can be then stored in a capacitor. The energy obtained should be carefully managed by energy management circuits to prevent the energy storage from being completely consumed by communication modules in an instant. Once the capacitor has sufficient energy, the communication module of DEIN_R continuously collects the environment data from the embedded sensor and uploads it to the UAV until the energy is exhausted.

Cloud Server: The DEIN_T may upload the data via the UAV to the cloud server for remote monitoring. The online and offline status of the DEIN_T is remotely monitored by the cloud server. Moreover, the actions of the UAV (take-off, hovering and landing) are also remotely controlled by the cloud server.

Therefore, the UAV is able to fly to the target position. The server is also capable of calculating the trajectory according to the location of multiple DEIN_Rs, which is pre-stored in the database.

2.2 Working Flow

A single workflow consists of the following five steps:

1. *Initialization*: After the UAV is powered on, its control unit updates an online message to the cloud server. The cloud server then assigns the WET and data collection tasks to the UAV's control unit. The UAV also obtains the trajectory calculated by the cloud server, according to the location of the DEIN_Rs. After the above initialization, the UAV takes off.
2. *Flying*: UAV flies to the location of a DEIN_R according to the pre-designed trajectory.
3. *WET*: The UAV sends a start-up instruction to the on-board DEIN_T, when it arrives at the first specified location. After receiving this instruction, the DEIN_T continuously emits downlink RF signals for WET, while the UAV hovering above the target DEIN_R. The DEIN_R converts the RF energy carried by the received signals into the DC for charging the capacitor. The WET phase is terminated, after the voltage of the capacitor is sufficient to drive all the other functional modules of the DEIN_R.
4. *WIT*: After gleaning sufficient energy storage, the target DEIN_R is powered on for collecting data via the sensor and for uploading the data to the DEIN_T. When the data collection module of the DEIN_T starts receiving data from the target DEIN_R, it means that sufficient energy have been harvested. Then, the UAV flies to the location of the next DEIN_R for WET. During the flight, the UAV may receive the rest of data from the target DEIN_R. Steps 2-4 are repeated, until all the DEIN_Rs upload their data to the cloud server.
5. *Return*: After completing all the tasks, the UAV returns to the starting point, while it reports a mission complete message to the cloud server. During the flying mission, the control unit of the UAV monitors its own energy storage. If insufficient energy storage is reported, the flying mission is immediately aborted, the UAV returns to the starting point and sends a mission abortion message to the cloud server.

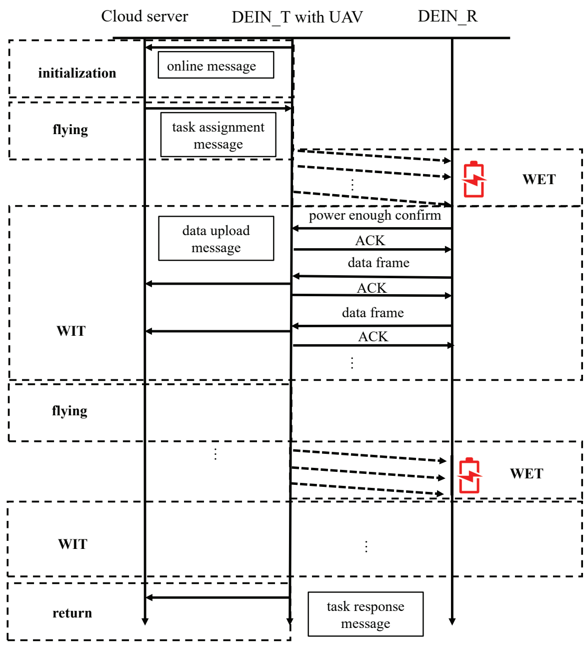

Figure 2. *Link protocol.*

2.3 Link Protocol and Packet Format

The link protocol of the UAV-aided DEIN system illustrated in figure 2. The protocol is designed for a DEIN system with a batteryless DEIN_R. The energy storage of the DEIN_R cannot afford the energy consumption caused by the polling channel search for joining a network. Therefore, a device-to-device (D2D) mode is adopted in the interaction between the DEIN_T and the DEIN_R. When the DEIN_R has harvested sufficient energy, it will send a Power Enough Confirm frame to the DEIN_T. After receiving this message, the DEIN_T terminates WET. The DEIN_R subsequently sends a data frame then. The DEIN_T responds with an ACK for each successfully received frame from the DEIN_R. If the DEIN_R does not receive an ACK of a data frame, it then retransmits this frame. The format of the frame for the interaction between the DEIN_T and the DEIN_R is shown in figure 3.

1. *Data frame*: A data frame is comprised of a physical layer header (PHY), a mac layer header (MHDR), a payload, and a frame check sequence (FCS). In the physical layer header, PREAMBLES are used for symbol synchronization. SFD

is a starting-frame delimiter for frame synchronization. PKL represents the total length of the frame. In the MHDR, MTYPE distinguishes whether this is a data frame or an ACK frame. Seq Num is the frame's identification. DesADDR and SouADDR are the MAC address of the destination and that of the source, respectively. The length of the payload can be calculated by the PKL in the physical layer header.

2. *ACK frame*: An ACK frame has the same physical layer header as the data frame. The mac layer header is comprised of MTYPE and Seq Num. Seq Num should correspond to the data frame. An ACK frame does not have any payload.

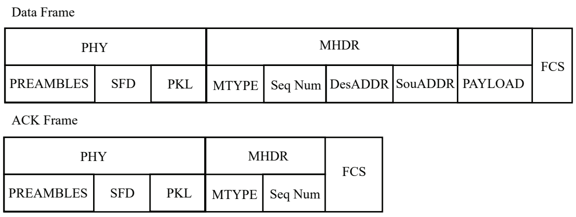

Figure 3. *The format of the frames for the interaction between the DEIN_T and the DEIN_R.*

The interaction between the cloud server and DEIN_T is based on the MQTT protocol, since it is suitable for low power IoT devices. The format of a payload packet of MQTT protocol is shown in figure 4. According to the workflow of the UAV-aided DEIN system, We design four types of packets, namely an ONLINE packet, a TASK packet, a DATA packet and a TASK_RESPONSE packet. Each packet is composed of a packet header (MHDR), a packet body, and CRC check bits. In the packet header, MTYPE represents packet type, which only have four different types right now. PKL represents the packet total length and RFU is a reserved field.

1. *ONLINE packet*: The main body of an ONLINE packet contains four parts. DevEUI records the unique device ID of the DEIN_T. STA indicates the online/offline status of the device. TxPOW in ONLINE packet represents the maximum transmit power of the DEIN_T.

2. *TASK packet*: The main body of the TASK packet is a varied length field, whose actual length can be calculated by the PKL in the packet header. TASKID is a unique task identification. The cloud server assigns tasks with different TASKID every time. DEIN_R1 and TXPOW1 represent the position of the first DEIN_R and DEIN_T's transmit power during it charging the first DEIN_R, respectively.

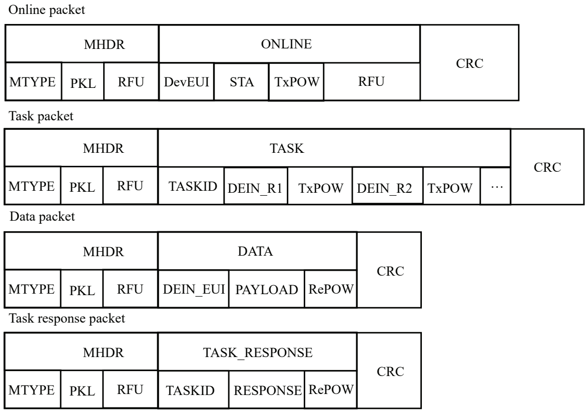

Figure 4. *The format of the packets for interaction between the DEIN_T and the cloud server.*

3. *DATA packet*: In the DATA packet, DEIN_EUI indicates a unique device ID of the DEIN_R to distinguish it from different DEIN_Rs. PAYLOAD is the data payload received from the DEIN_R, while RePOW indicates the remaining energy of the UAV.

4. *TASK_RESPONSE packet*: The RESPONSE field in TASK_RESPONSE packet indicates whether the task is complete or not, which should be returned to the cloud server.

III. DESIGN AND IMPLEMENTATION OF THE UAV WITH A DEIN TRANSMITTER ON-BOARD

The on-board DEIN_T is jointly designed with the control unit of the UAV. The hardware implementation of the DEIN_T is depicted in figure 5, which includes a WET functional module, a data collection module, a Raspberry Pi, a backhaul module, a power amplifier and multiple antennas.

3.1 Control Unit

A Raspberry Pi is invoked as the control unit of the M600 Pro Dajiang UAV. It is connected to the UAV via a USB interface. Therefore, it may control the

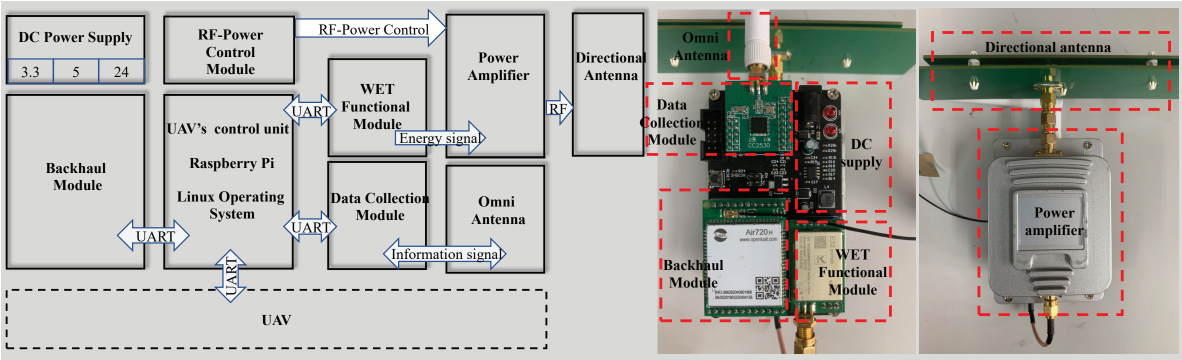

Figure 5. *DEIN transmitter's hardware schematic design and hardware implementation.*

UAV's motion via the UAV's firmware as the UAV's control unit. The Raspberry Pi is also connected to the data collection module and the WET functional module via a Universal Asynchronous Receiver/Transmitter (UART) interface as the DEIN_T's control unit. Therefore, the downlink WET and the uplink data collection can be jointly coordinated by the Raspberry Pi. The Raspberry Pi starts WET when the UAV gets to the target location. When the WET finishes, the Raspberry Pi controls the UAV to fly to the next DEIN_R.

3.2 Wireless Energy Transfer Module

An RF transmitter, a power amplifier and directional antennas jointly enable the downlink WET from the UAV to the ground DEIN_R as depicted in figure 5. The RF transmitter generates RF signals in 915 MHz, which is also the operational frequency of our RF-DC conversion module. For the practical implementation, an SX1278 RF transmitter chip performs as the WET functional module, which is capable of converting the energy packets sent by the Raspberry Pi into the RF signals. Then, a 915MHz power amplifier with an adjustable amplification factor is connected to the SX1278. The power amplifier has a maximum 20 dB gain with a voltage of 24V. As the voltage decreases, the amplification gain also decreases. However, in a UAV aided DEIN system, we always maintain the maximum power amplifying gain, in order to deliver more energy to the DEIN_R. We do not consider multiple antennas, because they need multiple RF chains with more amplifiers, which may significantly increase the energy cost and the weight of the DEIN_T, making it unsuitable for the UAV. In order to counteract the adverse effect of the path-loss, a directional antenna with a 120° vertical radiation angle and a 60° horizontal radiation angle is implemented. Note that the directional antenna on the DEIN_T is mounted vertically downward while the directional antenna on the DEIN_R is mounted vertically upward. Therefore, the antennas between the DEIN_T and DEIN_R are aligned, when the UAV is hovering directly above the DEIN_R.

3.3 Data Collection Module

Since WET has much smaller coverage than communications, the UAV is exploited for reducing the transmission distance between the DEIN_T and the DEIN_R. Therefore, transmission range of the data collection is not our main concern. Since the energy supply of the DEIN_R is scarce, a low-power communication mode should be adopted. A CC2530 chip operating at 2.4GHz is reprogrammed to be suitable in our system. Although we use CC2530 chip, its original networking protocol is abandoned, since it may consume lots of energy. CC2530 is selected in our prototype for data collection as depicted in figure 5, owing to its low-power characteristic while transmitting. Another 2.4GHz omnidirectional antenna is implemented for the uplink data collection.

3.4 Backhaul Module

An AIR720H module, which is widely used in the 4-th generation (4G) mobile communications is implemented for forwarding the collected data to the cloud server as depicted as a backhaul module in figure 5. When the UAV flies, the cloud server can remotely control the on-board DEIN_T by sending commands to the control unit of the UAV via 4G. We use AIR720H as the 4G module and reprogram it to implement a protocol conversion function, which can encapsulate messages from serial ports as the Message Queuing Telemetry Transport (MQTT) protocol and then send them to the cloud. Conversely, MQTT protocol messages sent from the server will also be sent to the UAV's control unit via the serial port. The MQTT protocol is a lightweight IoT communication protocol based on publish/subscribe mode. It works above the conventional TCP/IP protocol, and it is widely used in IoT applications.

3.5 DC Supply

The power of the DEIN_T is supplied by a lithium battery with 24 V. The output voltage of this battery is directly relied upon for supporting the power amplifier. A DC-DC chip MP1584 converts the original output voltage from 24 V to 5 V for powering both the 4G module and WET module. Moreover, another DC-DC chip AMS_1117 converts the output voltage of the battery to 3.3 V in order to support the ZigBee module and other circuits.

IV. DESIGN AND IMPLEMENTATION OF DEIN RECEIVER

Different from the DEIN_T, the DEIN_R does not have embedded batteries. It may only harvest energy from downlink RF signals emitted by the DEIN_T of the UAV to power all its functional modules. This kind of low-cost devices can be quickly deployed within a wide area for realizing environment monitoring. After gleaning sufficient energy, the DEIN_R may collect data from the embedded sensor and upload it to the UAV. The hardware implementation of the DEIN_R is portrayed in figure 6. The DEIN_R mainly includes an RF-DC conversion module, an energy management module and a data uploading module and a sensor.

4.1 RF-DC Conversion Module

An RF-DC conversion module is composed of an RF matching circuit and a rectifier circuit as depicted in figure 6. After passing through the above circuits, the received energy signal is converted to DC signal for charging. The P1110B module is used as the RF-DC conversion module. It has been optimized for operating in the 902-928 MHz band, with the conversion efficiency up to 70%. The maximum output voltage of the RF-DC conversion module is 4.2 V.

4.2 Energy Management

The output DC of the RF-DC conversion module is small and unstable, which cannot be directly used for powering the data collection and sensor modules of the DEIN_R. Therefore, an energy management module is designed, which consists of an energy management circuit and a voltage regulator circuit as depicted in figure 6. The output DC is firstly relied upon for recharging a super capacitor. Only when the voltage of the super capacitor reaches a voltage, it can be discharged for powering other functional modules of the DEIN_R. There are three voltage thresholds for the energy management circuit, namely: an overvoltage threshold (OV), an under-voltage threshold (UV) and a battery-good threshold (VBAT_OKLH and VBAT_OKHL). The workflow of the energy management circuit can be described as a finite-state machine with three states, namely a charging state, a BAT_OK state, and a discharging state as shown in figure 7. A parameter VSTORE represents the voltage stored in the super capacitor. When VSTORE is lower than UV, the energy management circuit works in a charging state. If VSTORE rises to VBAT_OKLH, the energy management circuit is then in the BAT_OK state, which indicates that the super capacitor has gleaned sufficient energy. Once in the BAT_OK state, the circuit will output the super capacitor's voltage directly and set the VBAT_OK pin as a high level. We connect the output-pin to a voltage regulator in order to stabilize the voltage to 2.8 V, while VBAT_OK pin is connected to the voltage regulator's enable-pin. Therefore, the energy management module can always output a stable voltage of 2.8 V in the BAT_OK state. During this period, the energy management circuit continuously recharges the super capacitor until VSTORE reaches OV. Then, the recharging process is terminated. The energy management goes to the discharging state. In the discharging state, VSTORE decreases, while powering the other functional modules of the DEIN_R. When VSTORE drops to VBAT_OKHL, which indicates that the super capacitor cannot supply sufficient energy now, the energy management module returns to the recharging state and repeat the above process. A BQ25504 chip and

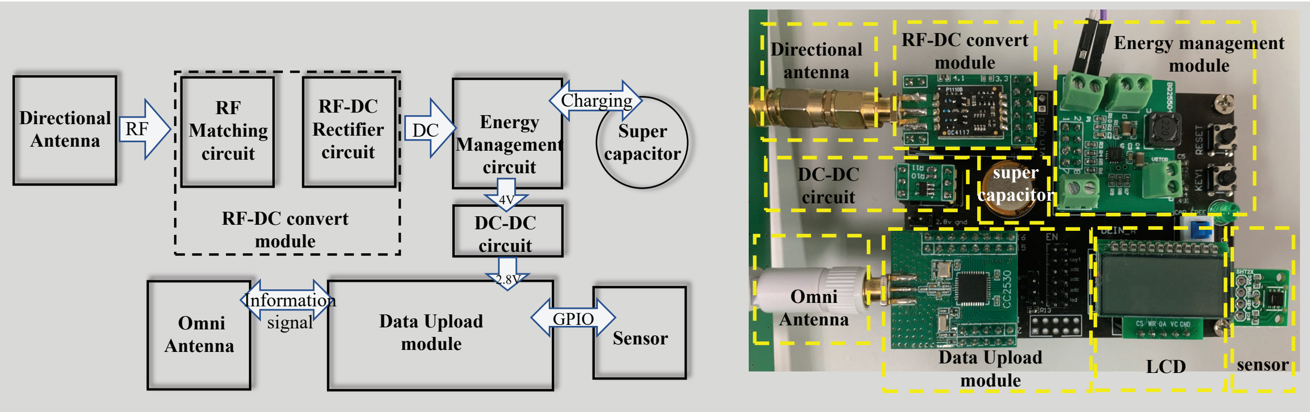

Figure 6. *DEIN receiver's hardware schematic design and hardware implementation.*

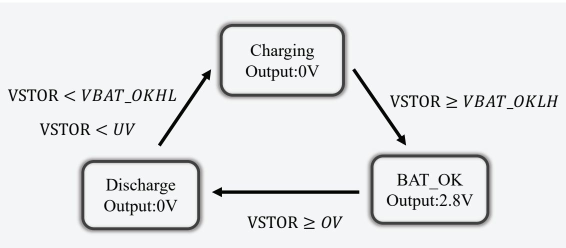

Figure 7. *Finite-state machine of energy management module.*

A TPS7301 chip are implemented to achieve all the above functions of the energy management module.

4.3 Data Uploading

The data uploading module of a DEIN_R also adopts a CC2530 chip. However, owing to the scarce energy storage, the DEIN_R should strictly control its power consumption. We then set the data uploading module CC2530 to the sleep mode of level PM3. In this level, the data uploading module switches off its digital core and all the oscillators. Only the external interrupt or reset can wake the module up from the deep sleep. Therefore, the power consumption of the CC2530 enabled data uploading module can be minimized. DEIN_R is equipped with a SHT20 sensor to collect temperature and humidity information in the environment. After the capacitor has sufficient energy, the CC2530 wakes up every 5 seconds and uploads the data collected from the sensor.

V. PERFORMANCE EVALUATION

We evaluate the performance of our UAV aided DEIN prototype in a field-trial. As depicted in figure 8, two DEIN_Rs are placed 20 m away and raised by tripods. Under the cloud server's control, the UAV takes off from the ground and rises to an altitude of 3 m. The UAV hovers on top of the DEIN_R to carry out the downlink WET and uplink data collection via the onboard DEIN_T. The average distance between the UAV and the DEIN_R is 2 m, and the capacitance of the super capacitor is 0.22 F. After about 2 minutes and 5 seconds, the voltage of the first DEIN_R's super capacitor is recharged from 0V to 4V. And the cloud server totally received 52 kB data from the first DEIN_R. After collecting data from the first DEIN_R, the UAV flies to the next DEIN_R for both the WET and the data collection. After finishing all the assignments, the UAV returns to the origin.

We first evaluate the WET performance from the on-board DEIN_T of the UAV to the ground DEIN_R. Specifically, we studied the effect of the transmission distance on the voltage level of the super capacitor in figure 9 by setting the capacitance of the super capacitor to 0.22 F, setting the target voltage to 4.3 V. Observe from figure 9 that increasing the distance may greatly increase the charging time to reach the target voltage 4.3 V. For example, when the transmission distance is 1 m, the super capacitor's voltage of the DEIN_R reaches 4.3 V within 67 seconds. By contrast, when the transmission distance increases to 3 m, the voltage of super capacitor reaches 4.3 V after 360 seconds. This is because a longer transmission distance may result in higher path loss during the signal propagation. When the UAV hovers, the antenna alignment and charging distance can be highly affected, which

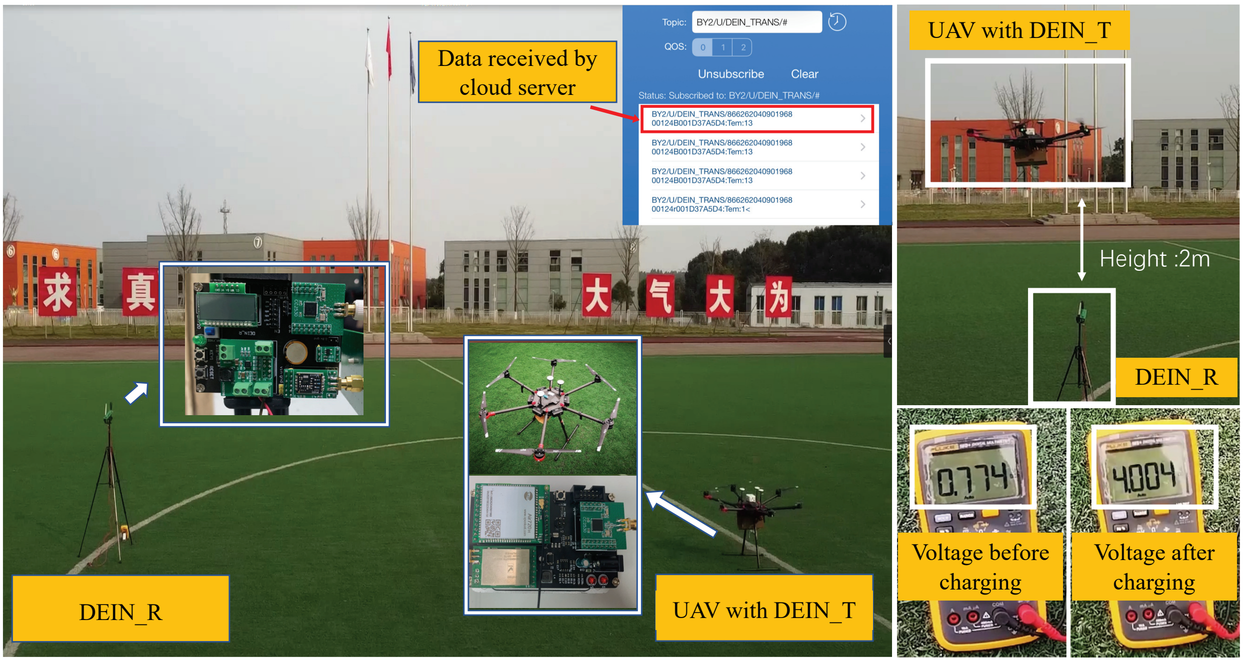

Figure 8. *UAV-aided DEIN system prototype.*

Table 1. *Wireless energy transfer performance comparison with other prototypes.*

	Prototype style	Tx power	Maximum Charging distance	Charging time	End-to-end efficiency	Operating frequency	Coverage
SDR SWIPT prototype [26]	Link-level	20 dBm	2 m	-	-62db	863-873 MHz	2 m
5.8GHz SWIPT prototype [27]	System-level	35 dBm	1 m	-	<12%	5.8 GHz	1 m
DEIN prototype [28]	System-level	35 dBm	0.45 m	About 650s	-	2.4 GHz	0.5 m
UAV-aided DEIN prototype (this work)	System-level	40 dBm	3 m	About 360s	-	900 MHz	20 m

fluctuates the charging efficiency.

We then set the distance to 2 m and set the capacitance of the super capacitor to 0.47 F. We test the voltage variation of the DEIN_R's during a recharging operation. This evaluation aims for estimating the hovering time of the UAV above each DEIN_R in order to obtain a constant amount of data collection. For the energy management circuit of the DEIN_R, VBAT_OKLH is set to 4.1 V, while VBAT_OKHL is set to 3 V. Observe from figure 10 that after the DEIN_T starts WET, the voltage of the super capacitor rises from 0 V to 4.1 V in 365 seconds. After reaching 4.1 V, the DEIN_T stops transmitting energy packets. The data uploading module of the DEIN_R then starts transmitting the collected data to the DEIN_T. During the data uploading process, the voltage of the DEIN_R's super capacitor continuously reduces. After 47 seconds, the voltage drops to the threshold of VBAT_OKHL = 3 V. The DEIN_T may activate the downlink WET again. During this period of the data uploading, the DEIN_R uploads 128 kB data in total. As shown in figure 10, after 92 seconds, the voltage of the DEIN_R rises back to 4.1 V. Note that the data uploading module of the DEIN_R cannot operate during the charging period. Obviously, the charging time now is much shorter than the first period.

Finally, the comparison between our prototype and the other SWIPT/WET counterparts are summarized in Table 1. Comprised with these works, our prototype can achieve charging a terminal in a tolerable time. Moreover, with the help of UAV, the DEIN system can deliver both WET and WIT service in a wide area.

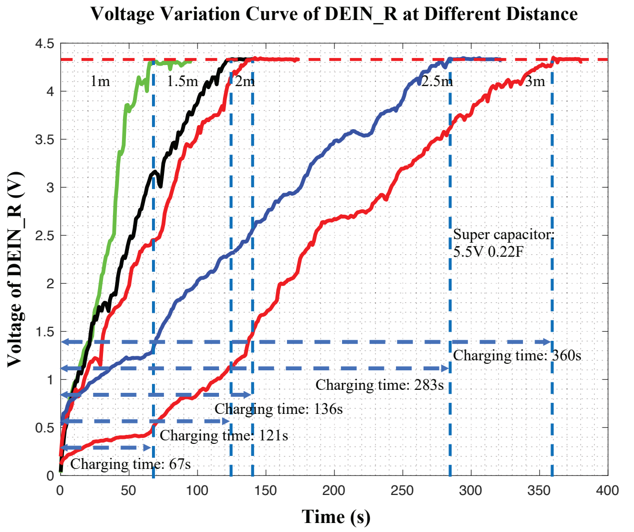

Figure 9. *Variation of capacitor voltage of DEIN receiver at different distances.*

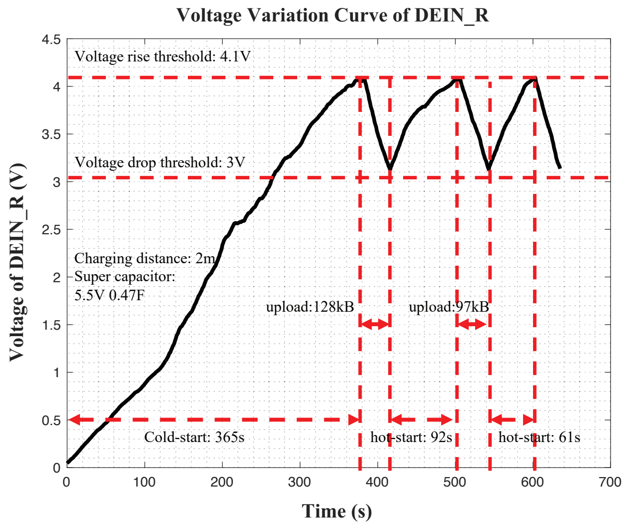

Figure 10. *Voltage variation of the DEIN receiver's recharging operation.*

VI. CONCLUSION

In this paper, a system-level solution to a practical DEIN system with UAV has been prototyped. The UAV with a DEIN_T onboard can be dispatched to the target area to charge the batteryless DEIN_R and then collect data from them. Our system can finish the task of charging a single DEIN_R and that of receiving approximately 50 kB data in less than 3 minutes, while the average charging distance is 2 m and the capacitance of super capacitor is 0.22 F. This UAV aided DEIN system can be applied for environment monitoring, emergency communications in wide areas lacking of communication infrastructures.

The balance between the charging time and data uploading time is important for designing the UAV-aided DEIN system. A larger capacity of the DEIN_R's super capacitor may support a longer data uploading time. But it also results in a longer charging time, which may consume more energy of the UAV. Moreover, the total weight of the DEIN_T should be carefully designed since the load weight also affect the operational time of the UAV.

In order to achieve a better performance, our UAV aided DEIN system can be further improved. For example, we may enable active charging protocol in the system, so that the terminals may monitor its own energy storage and actively request for a wireless charging service. Therefore, the UAV may only need to fly to the vicinity of the terminals with the charging requests, which may substantially reduce its own energy consumption. Furthermore, accurate antenna alignment technologies may be carefully investigated in order to overcome the shiver of the UAV during the wireless charging process, because misalignment between an antenna pair may substantially reduce the wireless charging performance.

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