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Original Research Article

Integrating self-powered disaster recovery networks with environmental monitoring for enhanced disaster preparedness and response

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ABSTRACT: This paper investigates a comprehensive approach to enhancing environmental monitoring services within a self-powered Disaster Recovery Network (DRN) infrastructure. The study introduces a variety of solutions aimed at overcoming logistical challenges associated with establishing an environmentally conscious DRN infrastructure. Moreover, the research explores the intrinsic factors governing the system's behavior, defines essential evaluation metrics, and delineates performance measurements. The Wireless Solar Router (WSR) is specifically introduced using the Ubicom IP 2022 platform to realize the Ad hoc wirelessly networked nodes of the DRN infrastructure. To advance the field further, the paper proposes an experimental platform for comprehensive evaluation, assessing network performance, practicality, power efficiency, and resilience to various scenarios. A comprehensive design process is illustrated, and the required values of the system elements, i.e., the number of solar cell panels, the capacity of the battery cells, etc., are adjusted to fulfill the design purposes. In order to reduce the power utilization of the recommended WSR and to lengthen the duration of their batteries, a new distributed power management scheme called Duty Cycle Estimation-Event Driven Duty Cycling (DCE-EDDC) was suggested and installed locally in the WSRs in order to decrease their power consumption and extend the lifetime of their batteries. The suggested method is compared with other duty cycling methods, and the proposed DRN system is also compared with other real-world implementations to show its usefulness in building a green DRN infrastructure.

KEYWORDS: environmental monitoring services; DRN infrastructure; network reliability; wireless solar router; solar energy harvesting; power management; fault tolerance techniques

1. Introduction

Natural disasters, encompassing phenomena like earthquakes, hurricanes, and floods, frequently afflict regions across the globe, resulting in substantial destruction to both lives and properties[1–3]. In the face of these catastrophic events, numerous stakeholders must swiftly make critical decisions related to rescue operations. However, the disruption of terrestrial communication infrastructures and other interconnections, such as power facilities, poses a formidable challenge in facilitating communication between the disaster-affected areas and the outside world[4–6]. In such scenarios, the restoration of the communication system becomes of paramount importance to enable the timely exchange of vital information pertaining to location, events, and the severity of the situation, serving both victims and rescue teams.

Several research articles explore various issues related to emergency communication networks. These articles delve into:

- Content and space analysis of existing networks and big data: Investigating how existing emergency communication networks handle information and its geographical spread[2–4].
- Wireless emergency response systems: Analyzing the specific details and functionalities of wireless systems for emergency response[5–7].
- Emerging communication technologies for disasters: Exploring the potential of technologies like IoT, D2D communication, vehicle networks, cloud and fog computing, UAVs, and WSNs in disaster scenarios[8–10].
- Disaster emergency management networks: Systematically summarizing the overall framework and components of disaster management networks[11–13].
- Advancements in emergency communication technology: Highlighting the latest developments and existing technologies in the field[13–15].
- Communication strategies for mobile Ad hoc networks in emergencies: Classifying different communication approaches within mobile Ad hoc networks for disaster situations[16–18].

Comprehensive environmental monitoring encompasses a spectrum of advanced sensors, from temperature and humidity to pressure, rainfall, wind speed and direction, solar radiation, air quality, and UV radiation. These sensors are strategically deployed to provide real-time, high-resolution data on various environmental quantities. This paper introduces a new paradigm for disaster resilience that centers on the seamless integration of comprehensive environmental monitoring, which includes advanced weather monitoring, with sustainable communication infrastructure, creating a unified system that empowers more effective disaster preparedness and response. The system is self-contained and not reliant on previous models or research, offering a fresh perspective on disaster resilience.

Nonetheless, significant research opportunities remain within this field. This paper aims to address key questions regarding the implementation of a self-powered DRN infrastructure, which is particularly vital in catastrophic scenarios with high probabilities of electrical power source unavailability. These questions encompass:

1) What logistical prerequisites are essential for constructing a self-powered DRN infrastructure?
2) What factors influence system behavior, and how can they be evaluated and measured for performance assessment?
3) How can different environmental monitoring services be effectively integrated with a solar energy-powered system?
4) What criteria should be applied when assessing the entire system in terms of network performance, practicality, and power consumption?

In our work, the distinctive features related to energy conversion and storage in the context of Disaster Recovery Network (DRN) infrastructure set it apart from other works. Here are the key differences:

1) New power management approach: Our work introduces a novel approach to power management by proposing the use of Wireless Solar Routers (WSRs) within the DRN infrastructure. These routers

are designed to harness and store energy from the surrounding environment, with a specific emphasis on solar energy. This innovative approach stands out from conventional methods of power supply and contributes to the eco-friendliness of the DRN.

2) Ad hoc networking for efficiency: Our work emphasizes the use of Ad hoc networking technology within the DRN infrastructure to enhance reliability. Unlike some conventional wireless and wired methods, Ad hoc networks establish connections among nodes without relying on centralized infrastructure or administrative oversight. This results in reduced ownership, installation, and maintenance costs, providing a more efficient and cost-effective solution.
3) Integration of weather monitoring services: Another distinguishing aspect of our work is the integration of a portable self-powered weather station within the DRN infrastructure. This versatile node plays a crucial role in delivering essential DRN and weather monitoring services to various clients. This integrated approach adds a layer of functionality that may not be present in other works focused solely on communication aspects.
4) Extended coverage area through environmental energy harvesting: Our work addresses the limitation of coverage area associated with traditional localized placement of WSRs near wired electricity sources. By proposing energy harvesting from the environment, particularly through solar energy, we overcome this constraint and significantly extend the coverage area of the DRN infrastructure. This approach enhances the adaptability and resilience of the network in diverse geographical locations.

In summary, our work distinguishes itself through an innovative energy conversion and storage strategy, incorporating self-powered WSRs, environmental energy harvesting, and the integration of weather monitoring services. These elements collectively contribute to a more sustainable, resilient, and mobile Disaster Recovery Network infrastructure compared to other works in the field.

2. Disaster recovery network infrastructure

In this section, we explore the requirements and logistics involved in building a robust and eco-friendly Disaster Recovery Network (DRN) infrastructure. We delve into the challenges of self-sufficiency, power management, and connectivity that such a network must overcome. Moreover, we introduce the concept of a green DRN infrastructure.

In this paper, we propose an approach to enhance the reliability of Disaster Recovery Network (DRN) communication systems by leveraging wireless Ad hoc network technology. Our strategy involves the deployment of a wireless network that becomes active when traditional network services fail or when responding to a disaster event. The envisioned DRN infrastructure comprises a variety of wireless nodes, both fixed and mobile, each tailored to fulfill specific tasks dictated by the requirements of different applications.

A key component of this network is the integration between a Wireless Solar Router (WSR) and a portable self-powered weather station, a versatile node responsible for delivering a range of essential DRN and weather monitoring services to various clients within a designated network area. These services encompass transmitting data and weather sensor signals between critical and industrial facilities, facilitating text messaging, and even supporting multimedia services. WSRs, as integral elements of the DRN infrastructure, receive data packets from diverse sources and subsequently relay them to a local server situated within a Mobile Rescue Office (MRO). These WSRs collaborate to create an Ad hoc network, enabling them to collectively transport data packets to their intended destinations.

Consequently, an efficient Ad hoc routing protocol is required to manage this intricate network, as depicted in **Figure 1(a)**.

Furthermore, within the Ad hoc network, each WSR functions as a router, enabling the forwarding of traffic originating from other WSRs towards their respective destinations. The adoption of Ad hoc networking to enhance the reliability of DRN systems offers substantial advantages over conventional wireless and wired methods. Ad hoc networks establish connections among nodes without relying on centralized infrastructure or administrative oversight, resulting in significantly reduced ownership, installation, and maintenance costs in comparison to other networking approaches.

To meet power supply requirements, WSRs are typically situated in proximity to wired electricity sources. However, this localized placement limits the coverage area of the proposed DRN infrastructure and, consequently, the reach of its services. To overcome this constraint, we suggest the implementation of self-powered WSRs. In this context, we propose that WSRs harness and store the energy they require from the surrounding environment, with a particular emphasis on solar energy, as illustrated in **Figure 1(b)**. This innovative approach enables the deployment of WSRs in virtually any location, independent of power supply availability, thereby extending the coverage area of the DRN infrastructure to a considerable extent.

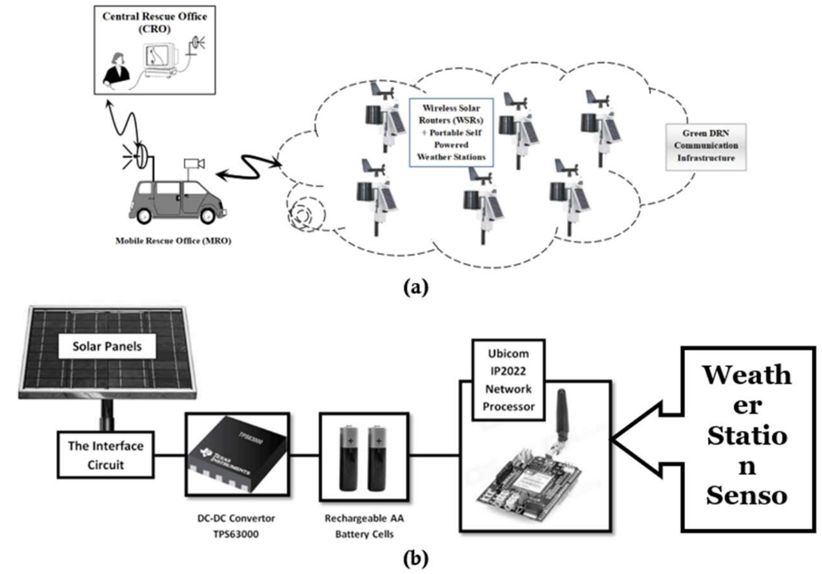


Figure 1. Self-powered DRN infrastructure. **(a)** DRN topology. **(b)** WSR architecture.

Traditional environmental monitoring systems often rely on centralized infrastructure and wired connections, making them vulnerable to disruption during disasters. This can lead to blind spots in data collection and hinder timely responses to environmental threats.

Self-powered DRNs, on the other hand, offer several advantages in disaster scenarios:

- Resilience: DRNs are designed to operate independently of the power grid and traditional communication infrastructure. They use solar panels, wind turbines, or other renewable energy sources to power themselves and communicate wirelessly. This makes them highly resilient to power outages and disruptions caused by natural disasters.
- Real-time data collection: DRNs can be equipped with a variety of sensors to monitor air quality, water quality, radiation levels, and other environmental parameters. These sensors can collect data in real-time, even in remote areas affected by disasters.

- Early warning and rapid response: By providing real-time data on environmental threats, DRNs can enable authorities to issue early warnings and take rapid response measures to protect people and property. For example, if a DRN detects a sudden spike in air pollution levels caused by a chemical spill, authorities can evacuate nearby residents and deploy emergency response teams.
- Improved disaster preparedness: DRNs can be used to collect data on environmental conditions before, during, and after disasters. This data can be used to improve disaster preparedness planning and response efforts. For example, data on floodplains and landslide zones can be used to identify areas at risk and develop evacuation plans.

Here are some specific examples of how self-powered DRNs can be used in disaster scenarios:

- Monitoring air quality after a wildfire: DRNs can be deployed in areas affected by wildfires to monitor air quality levels and provide real-time data to firefighters and residents. This data can be used to determine when it is safe for people to return home and to track the spread of smoke and other pollutants.
- Monitoring water quality after a flood: DRNs can be used to monitor water quality in rivers and streams after a flood to ensure that the water is safe to drink. This data can help prevent the spread of waterborne diseases.
- Monitoring radiation levels after a nuclear accident: DRNs can be used to monitor radiation levels in areas affected by a nuclear accident. This data can help protect people from exposure to radiation.

Overall, integrating self-powered DRNs with environmental monitoring can significantly improve the ability to respond to environmental threats in disaster scenarios. This can lead to a safer and more resilient system.

3. Sustainable power management

Our paper introduces a cutting-edge power management system, the “Duty Cycle Estimation (DCE)—Event Driven Duty Cycling (EDDC)” technique, to efficiently harness solar energy and sustain network operations. This section provides a comprehensive explanation of this technique, emphasizing its role in green communication infrastructure.

In this study, we have opted for the versatile UBICOM IP2022 platform[16] to realize our envisioned Wireless Solar Router (WSR) due to its multifunctional capabilities. As integral members of the Disaster Recovery Network (DRN) infrastructure, WSRs encounter varying network traffic conditions, significantly affecting their power consumption and operational lifespan. Our primary objective in this research is to provide an alternative power source for WSRs and implement an energy management strategy that optimally governs the utilization of energy stored in the WSRs’ battery cells.

To fulfill the first goal, we introduce a solar energy harvesting module, as illustrated in **Figure 1(b)**. At the core of this module lies the harvesting circuit, responsible for harvesting energy from the solar panels, managing energy storage, and directing power to the intended system. In our setup, we employ a DC-DC converter, specifically the Texas Instruments TPS63000 low-power boost-buck DC-DC converter[16], to ensure a consistent supply voltage to the embedded system.

Concurrently, we introduce a novel duty cycling methodology aimed at efficiently controlling power consumption within the WSR circuitry. Duty cycling involves the periodic transition of embedded nodes between energy-intensive states (active) and low-energy states (sleep) with the intention of conserving energy[17]. During active states, nodes can perform their regular functions, whereas in low-energy states, nodes limit their operations to specific tasks to save energy[17]. We refer to this methodology as “Duty

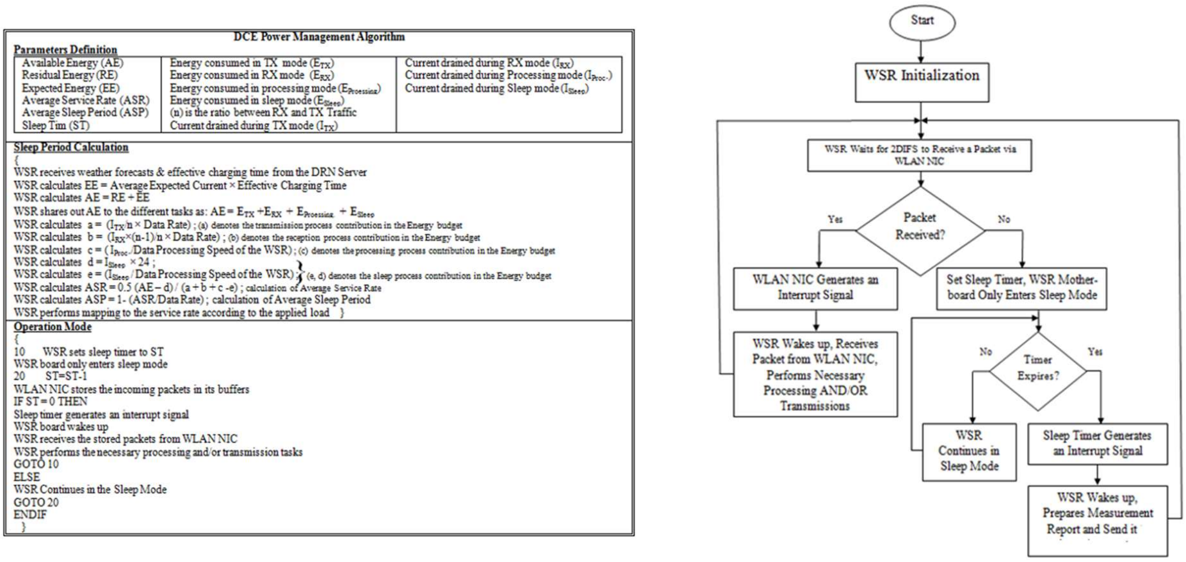
Cycle Estimation (DCE)—Event Driven Duty Cycling (EDDC)," which consists of two key components: dynamic duty cycle estimation and the management of WSR behavior during active periods.

Duty Cycle Estimation (DCE) Algorithm: Within the scope of this paper, we propose that WSRs should adjust their operations based on the available energy, specifically linking the service rate of the WSR to its power budget. In this algorithm, sleep periods are dynamically determined each day, taking various factors into account, including WSR power consumption, weather conditions, and the amount of stored energy. To achieve this, we establish a relationship among Duty Cycling periods, Average Service Rate (ASR), and Available Energy (AE). The key terms in this context include:

- Average Service Rate (ASR): This represents the average of the total traffic (in bps) transmitted and received by the WSR.
- Duty cycling periods: Time is divided into time slots, making Duty Cycle the ratio of sleep periods to the total slot time.
- Available energy (AE): This encompasses the sum of residual energy in the batteries from the previous day plus the anticipated energy for the next day.

Our approach follows the steps illustrated in **Figure 2(a)**. Each time slot is divided into active and sleep periods, with a WSR initially entering the sleep period for a predetermined duration calculated in accordance with AE. When the active period commences, the WSR awakens and processes the stored packets in the WLAN NIC, as depicted in **Figure 2(a)**. At the commencement of each working day, the nodes compute the pre-specified Accumulated Energy (AE). It is imperative to underscore that, throughout the entire workday, the nodes must continuously gauge the current flowing to and from the batteries to facilitate the computation of the Remaining Energy (RE). The measurement procedure involves capturing samples every second, with subsequent computation of average current values on an hourly basis. To enhance forecasting precision, we advocate for the CRO to disseminate weather forecasts and the effective charging period for the region, providing critical inputs for determining the Expected Energy (EE). This forecast encompasses anticipated weather conditions (sunny, cloudy, or rainy) and the approximate charging hours available. Leveraging historically recorded current values under analogous weather conditions, the nodes predict the expected current value. Consequently, the Energy Efficiency (EE) is derived, with nodes storing the average current values for each day categorized by climate conditions (sunny, cloudy, or rainy) in a local database file. Subsequently, the Average Energy (AE) for each weather condition is computed. The subsequent step involves calculating the State of Readiness (SR) of each node based on the determined AE value. The correlation between SR and AE is established by evaluating the power consumed during node activities. Mapping the SR value to varied rates of the applied load constitutes the subsequent stage, necessitating adaptability to fluctuations in the network load. This mapping stage is crucial for accommodating changes in the Service Rate (SR) for medium-load conditions. Anticipating future load based on past behavior is integral to this stage, ensuring responsiveness to variations in network load. The final stage entails determining the Sleep Period (SP) allocated to each time slot. Employing the same mapping process previously discussed, the nodes calculate varying SP values in tandem with fluctuations in the applied network load. This comprehensive process aligns the nodes' energy management with dynamic forecasting, load mapping, and responsiveness to real-world conditions, fostering an efficient and adaptive energy utilization system.

Event Driven Duty Cycling (EDDC): Within our paper, we propose that WSR behavior during active periods is governed by two factors: scheduled tasks and responses to packet reception events targeting specific WSRs. The suggested Event Driven Duty Cycling (EDDC) technique leverages a critical feature known as "Clock Stop Mode". In this mode, the system clock may be disabled, deactivating the CPU core clock and, consequently, the WSR's motherboard. While the system clock is disabled, the interrupt logic continues to function, and a sleep timer remains active. Transitioning from the clock stop mode (sleep mode) to normal execution is feasible through sleep timer interrupts or in response to an external interrupt from the WLAN NIC. Importantly, this method doesn't reset the chip, allowing program execution to resume from where it was paused. This mode shifts only the WSR motherboard to a power-saving mode, turning off its circuitry (except the external interrupt circuits, sleep timer, and program memory). Whenever an interrupt is triggered, such as packet reception by the WLAN NIC or the expiration of the sleep timer, the board promptly awakens within a few clock cycles to execute the necessary actions, as depicted in **Figure 2(b)**.



DCE Power Management Algorithm

Parameters Definition

Available Energy (AE)
Residual Energy (RE)
Expected Energy (EE)
Average Service Rate (ASR)
Average Sleep Period (ASP)
Sleep Tim (ST)
Energy consumed in TX mode (E_{TX})
Energy consumed in RX mode (E_{RX})
Energy consumed in processing mode ($E_{Processing}$)
Energy consumed in sleep mode (E_{Sleep})
(n) is the ratio between RX and TX Traffic
Current drained during TX mode (I_{TX})
Current drained during RX mode (I_{RX})
Current drained during Processing mode ($I_{Proc.}$)
Current drained during Sleep mode (I_{Sleep})

Sleep Period Calculation

```
{
WSR receives weather forecasts & effective charging time from the DRN Server
WSR calculates EE = Average Expected Current × Effective Charging Time
WSR calculates AE = RE + EE
WSR shares out AE to the different tasks as: $AE = E_{TX} + E_{RX} + E_{Processing} + E_{Sleep}$
WSR calculates a = ($I_{TX}$/n × Data Rate) ; (a) denotes the transmission process contribution in the Energy budget
WSR calculates b = ($I_{RX}$×(n-1)/n × Data Rate) ; (b) denotes the reception process contribution in the Energy budget
WSR calculates c = ( $I_{Proc.}$/Data Processing Speed of the WSR) ; (c) denotes the processing process contribution in the Energy budget
WSR calculates d = $I_{Sleep}$ × 24 ;                          } (e, d) denotes the sleep process contribution in the Energy budget
WSR calculates e = ($I_{Sleep}$ / Data Processing Speed of the WSR) ; }
WSR calculates ASR = 0.5 (AE – d) / (a + b + c -e) ; calculation of Average Service Rate
WSR calculates ASP = 1- (ASR/Data Rate) ; calculation of Average Sleep Period
WSR performs mapping to the service rate according to the applied load   }
```

Operation Mode

```
{
10     WSR sets sleep timer to ST
WSR board only enters sleep mode
20      ST=ST-1
WLAN NIC stores the incoming packets in its buffers
IF ST = 0 THEN
Sleep timer generates an interrupt signal
WSR board wakes up
WSR receives the stored packets from WLAN NIC
WSR performs the necessary processing and/or transmission tasks
GOTO 10
ELSE
WSR Continues in the Sleep Mode
GOTO 20
ENDIF
  }
```

(a) **(b)**

Figure 2. DCE-EDDC algorithm. **(a)** DCE algorithm. **(b)** Flowchart of EDDC algorithm.

4. Evaluation and experimentation

To validate the proposed infrastructure, we suggest an experimental platform for thorough evaluation. This section outlines the metrics used to assess network performance, practicality, power consumption, and its resilience in the face of various failure events.

To fulfill the networking and energy-saving prerequisites of the proposed DRN, it is viable to deploy the suggested power management and other algorithms on platforms equipped with specific features[19,20]. These features include: 1) fast wake-up time from sleep to active mode (less than 10 clock cycles); 2) clock stop mode; 3) data saving during the clock stop mode; 4) low power consumption (below 15 mA during sleep mode); 5) sufficient networking and processing capabilities (exceeding 18 Mbps) to meet DRN application demands[19]; 6) support for a wide range of applications and networking protocols in the TCP/IP stack; 7) open-source development and programming environment; 8) reasonable cost. Based on these criteria, the recommended Ubicom IP2022 platforms for the integrated "weather station-WSR".

To assess the power consumption of the proposed Ubicom Wireless Solar Router (WSR) under real-world Disaster Recovery Network (DRN) traffic scenarios, we propose an experimental framework, as illustrated in **Figure 3**. This framework entails the generation of diverse DRN traffic profiles, which are then input into a simulation model. This model serves as a representative depiction of a DRN infrastructure and aids in creating the necessary network traffic. Subsequently, a traffic generator PC utilizes this network traffic to simulate the behavior of the DRN in interaction with a WSR.

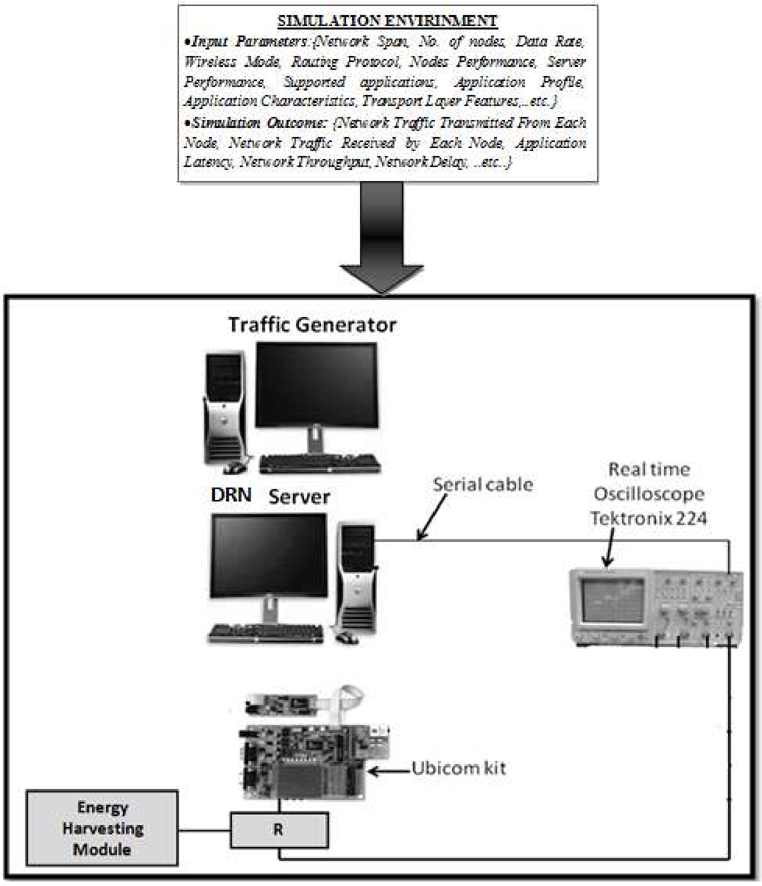


Figure 3. The experimental framework.

The initial step involves the selection of a real-world map for the installation of Wireless Solar Routers (WSRs). This map serves as a representation of a Disaster Recovery Network (DRN) infrastructure, covering an area of 5 × 5 square km and accommodating 40 WSRs[16]. Based on a prior analysis[16], it was determined that Optimized Link State Routing (OLSR) outperforms other Ad hoc routing protocols in a dynamic Ad hoc topology, making it the protocol of choice for our simulation model. The OLSR protocol's functionalities are governed by a predefined set of parameters specified in OLSR RFC 3626[16], which we incorporated into our simulation model, as outlined in **Table 1**. To evaluate the performance of our simulated network, various environmental monitoring services were introduced[2], as detailed in **Table 1**.

Table 1. Simulation model parameters.

Simulation time (min)	60
No. of WSR nodes	40
Network span area (km^2)	25
WSR modeling parameters	Packets processing rate (packet/s) = 2000 Memory = 2 M byte
WLAN settings	Data rate (Mbps): 18 for IEEE802.11a
OLSR settings	Hello interval (s) = 2 TC interval (s) = 5 Neighbor hold time (s) = 6 Topology hold time (s) = 15 Duplicate message hold time (s) = 30

Table 1. (*Continued*).

Weather station applications	**Weather sensors**	3 sensors/station Sensors to WSR packet length = (128–512) bit Sensors to WSR packets rate = (20–1000) packet/s
	Text messaging	Message inter-arrival time = 10 s Message size = (200 – 1000) byte [uniformly distributed]
	Environmental file transfer	1024 × 768 pixels (JPEG compression) File size = (0.5–1) M byte Inter-request interval = 180 s [poisson distribution]
	Multimedia streaming	352 × 288 @ 15 fps 197–421 Kb/s H.264/AVC

In our forthcoming experiments, we intend to measure two key parameters:

- Current consumption in normal mode: In this mode, the Ubicom board, along with its associated accessories, operates without any power management strategies in place.
- Current consumption in sleep mode: In this mode, the power consumption of the Ubicom board and its accessories adheres to the DCE-EDDC power management scheme.

To demonstrate the advantages of implementing the suggested duty cycling methods, we plan to conduct a series of tests utilizing the proposed experimental test bed, as depicted in **Figure 3**.

We will assess the impact of the DCE algorithm in various scenarios, with initial settings detailed in **Table 2**. These experiments aim to evaluate the DCE algorithm's adaptability under diverse operational conditions, considering variations in Available Energy (AE) levels. **Table 3** lists the corresponding values of Average Service Rate (ASR) and Average Sleep Period (ASP) from these scenarios, with Residual Energy (RE) representing battery charging levels and (N) indicating the number of paralleled solar panels. Notably, the proposed DCE algorithm exhibits the ability to dynamically adjust duty cycling based on available energy levels, ensuring that the WSR continues to operate in a pre-planned and managed manner.

Table 2. Initial settings of DCE experiments.

Data rate	18 Mbps (IEEE802.11a)
Traffic characteristics	$n = (\frac{RX\ Traffic}{TX\ Traffic}) = 4$
Data processing speed of the WSR	24 Mbps
I_{TX}	150 mA
I_{RX}	120 mA
$I_{Proc.}$	150 mA
I_{Sleep}	1 mA
Battery characteristics	3 v, 2800 mAh
Solar panel	SP1
Average current produced in a sunny day, effective charging time	34 mA 15 h
Average current produced on a cloudy day, effective charging time	20.5 mA 13 h
Average current produced in a rainy day, effective charging time	14.4 mA 11 h

Table 3. ASR and ASP values under different conditions.

RE (% of battery capacity)	N	Weather condition	AE (mAh)	ASR (Mbps)	ASP (s)
100%	1	Sunny	4960	7.75	0.57
100%	1	Cloudy	3801	5.94	0.67
100%	1	Rainy	3482	5.44	0.70
75%	1	Sunny	4260	6.66	0.63
75%	1	Cloudy	3101	4.85	0.73
75%	1	Rainy	2782	4.35	0.76
50%	1	Sunny	3560	5.56	0.69
50%	1	Cloudy	2401	3.75	0.79
50%	1	Rainy	2082	3.25	0.82
25%	1	Sunny	2860	4.47	0.75
25%	1	Cloudy	1701	2.66	0.85
25%	1	Rainy	1382	2.16	0.88
100%	2	Sunny	7120	11.13	0.38
100%	2	Cloudy	4802	7.50	0.58
100%	2	Rainy	4164	6.51	0.64
75%	2	Sunny	6420	10.03	0.44
75%	2	Cloudy	4102	6.41	0.64
75%	2	Rainy	3464	5.41	0.70
50%	2	Sunny	5720	8.94	0.50
50%	2	Cloudy	3402	5.32	0.70
50%	2	Rainy	2764	4.32	0.76
25%	2	Sunny	5020	7.84	0.56
25%	2	Cloudy	2702	4.22	0.77
25%	2	Rainy	2064	3.23	0.82

Furthermore, we aim to assess the efficacy of the suggested DCE-EDDC power management method in defending against unmanaged network traffic conditions, such as those stemming from an Energy Exhaustive Denial of Service (DoS) Attack[15]. Various network traffic rates will be directed at the WSR, both with and without the implementation of the proposed power management method. **Figure 4** will provide insights into how well the properly managed WSR sustains its battery life, irrespective of fluctuations in incoming traffic rates. In contrast, the unmanaged power consumption resulting from varying traffic rates significantly diminishes the battery life of the WSR.

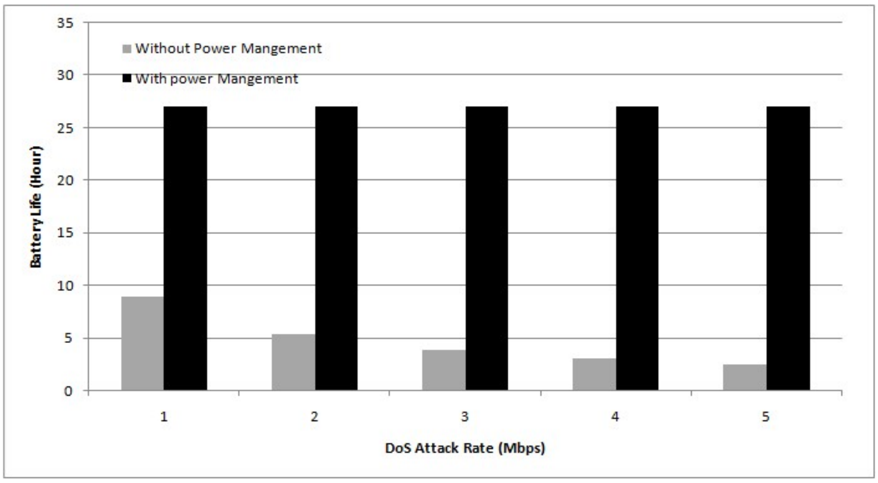


Figure 4. WSR battery life according to different DoS attack rates.

To complete our design process, it is crucial to estimate the requisite number of solar panels arranged in parallel, determine the quantity of parallel AA battery pairs, and ascertain their capacities to fulfill the power requirements of the WSR. Our analysis begins by adopting a realistic approach to assessing power needs under demanding conditions:

This study concentrates on three panels of monocrystalline solar cells sharing the same technology but differing in dimensions, resulting in varying values of voltage, current, power, and, consequently, distinct power-generating capabilities (refer to **Table 4**). **Table 5** provides details on various tests conducted at different times of the year in Mosul city/Iraq[13]. Key observations from these experiments reveal that the electrical current generated by the solar cell panels primarily depends on the characteristics of the solar cells, prevailing weather conditions, and the daytime period (effective charging time). The Maximum Operation Period (MOP) without charging battery cells extends to 14 h per day, representing the longest night period. In contrast, the least average charging current is obtained during rainy days, with a minimum day period of 10 h. These findings form the basis of our planning procedure.

Table 4. Solar panels characteristics.

Solar panel class	Dimensions, (height (cm) × width (cm))	Mean voltage (v)	Mean current (mA)	Rated power (w)
Solar panel 1 (SP1)	17 × 10	4	100	0.4
Solar panel 2 (SP2)	23 × 15	4	220	1
Solar panel 3 (SP3)	36 × 29	4	360	1.5

Table 5. Solar panel testing.

Daily average current produced by solar panel 1 (SP1) in Mosul City/Iraq			Daily average current produced by solar panel 2 (SP2) in Mosul City/Iraq			Daily average current produced by solar panel 3 (SP3) in Mosul City/Iraq		
Sunny (summer)	Cloudy (winter)	Rainy (winter)	Sunny (summer)	Cloudy (winter)	Rainy (winter)	Sunny (summer)	Cloudy (winter)	Rainy (winter)
34 mA	20.5 mA	14.4 mA	70 mA	40 mA	30 mA	144 mA	77 mA	62 mA

To calculate the battery capacity, we employ the following relationship:

$$BC = I_{WSR}.\ MOP \tag{1}$$

here, BC represents the battery capacity (in mAh), I_{WSR} is the current drained by an WSR, and MOP is the Maximum Operation Period of an WSR.

To determine the required number of paralleled solar panels, we need to establish their duties in generating the necessary current to supply the WSR for the shortest day period while simultaneously charging the batteries. This is calculated using the Equation (2) below:

$$\text{No. of Parallel Solar Panels} = SP_{WSR} + SP_{BC} \tag{2}$$

where SP_{WSR} is the number of solar panels required to power the WSR, expressed as:

$$\text{SPWSR} = \left(\frac{\text{Current Drained by the WSR}}{\text{Current Produced by a Single Solar Panel}}\right) \tag{3}$$

On the other hand, SP_{BC} is the number of solar panels needed to energize the battery cells, expressed as:

$$\text{SPBC} = \left(\frac{\text{Battery Capacity}}{\text{Minimum Day Period . Current Produced by a Single Solar Panel}}\right) \tag{4}$$

Table 6 highlights that the WSR, when operating in sleep mode, demands a significantly lower number of paralleled solar panels and a reduced battery capacity to support multiple weather station applications. These findings underscore the effectiveness of the proposed power management scheme in extending the lifespan of solar energy-harvested battery-based roadside units, enhancing their reliability and availability, which positively impacts the construction of a dependable DRN infrastructure.

Table 6. Solar panels and battery cells required for various conditions.

Average (daily) network load %	Normal mode					Sleep mode				
	No. of parallel solar cells			Battery capacity (mAh)		No. of parallel solar cells			Battery capacity(mAh)	
	SP1	SP2	SP3	Calculated	Standard	SP1	SP2	SP3	Calculated	Standard
25%	18	9	4	1540	1600	2	1	1	182	200
50%	19	9	5	1624	1800	3	2	1	252	300
75%	21	10	5	1792	1800	5	2	1	371	400
100%	24	12	6	2058	2300	8	4	2	677	750

Next, we will assess the performance of the proposed power management technique in comparison to traditional duty cycling methods, namely Fixed Duty Cycling (FDC)[18] and Artificial Neural Network-based Adaptive Duty Cycling (ANN-ADC)[17]. The evaluation of these methods is based on the following metrics:

- Missed events percentage (ME%): This metric quantifies the percentage of received data lost due to improper sleeping states.
- False wakeup percentage (FW%): Defined as the percentage of slot time spent in the wakeup state without performing any action, indicating unnecessary energy consumption.

The performance of the three duty cycling methods was assessed using the previously mentioned evaluation metrics, as presented in **Table 7**. It is evident that the suggested method exhibits superior performance in terms of data loss and extra power consumption. This enhanced performance is attributed, firstly, to the precise selection of sleep periods based on the timing requirements of scheduled tasks and, secondly, to the fast wakeup mechanism triggered by an external WLAN NIC interrupt, ensuring the reception of all incoming packets without loss. Conversely, the FDC method demonstrates suboptimal performance, with higher energy consumption (indicated by the highest FW% values) and a tendency to lose a higher percentage of received data (indicated by the highest ME% values). The ANN-ADC method displays acceptable performance, which could be further improved through an extensive training procedure. However, it's worth noting that the ANN training is computationally and power-demanding, placing an additional load on platforms with limited resources.

Table 7. Performance of different duty cycling methods.

%AME	%FW	%AME	%FW	%AME	%FW
43%	255%	0%	2.9%	0%	0%

A comparison of the main features between the current work and other DRN solutions is presented in **Table 8**. The suggested system offers a broader array of solutions, encompassing all necessary elements for constructing a dependable and secure DRN infrastructure.

Table 8. Comparison with other DRN solutions.

	Current work	OEMAN[14]	TeamPhone[2]
Network type	Wireless mesh network (WMN)	Multihop access networks	Cellular networks, Ad hoc networks and opportunistic networks
DRN node	Wireless solar router (WSR)	Smart phone, laptop PCs	Smart phone
Power source	Solar energy, battery cells	Battery cells	Battery cells
Routing protocol	OLSR	Simple routing in tree-based topology	AODV, DTN2
Power management	DCE-EDDC	None	Wake-up scheduling
Research methodology	Simulation, experimental work	Experimental work	Experimental work
Supported applications	Text messaging, field measurements, file transfer, multimedia streaming	Internet access	Text messaging

Finally, **Table 9** compiles the statistical findings derived from a range of experiments, taking into consideration the influence of the proposed power management techniques and the DRN clustering algorithm. The data presented in **Table 7** underscores the substantial reduction in the number of paralleled solar panels and the decreased battery capacity required for WSRs when operating in sleep mode to support multiple environmental monitoring applications. These results underscore the remarkable effectiveness of the suggested power management scheme in extending the lifespan of solar energy-harvested battery-based WSRs and enhancing their reliability, ultimately contributing positively to the establishment of a dependable and available Disaster Recovery Network (DRN) infrastructure. Additionally, the network's performance, installation time, and cost have all met the stipulated requirements within the acceptable range for DRN operations[10–12].

Table 9. Evaluation metrics of green environmental monitoring DRN infrastructure.

Network type		**Wireless mesh network (WMN)**
Ad hoc routing protocol		Optimized link state routing (OLSR)
WSR node		Ubicom IP2022 network processor platform, 120 MHZ CPU, 2 Mbyte memory
Wi Fi standard		IEEE802.11a, 18 MHZ
WSR transmit power (W)		25 dBm
Antenna type		Omni antenna 2.4 GHz/5 GHz dual band Gain: 1.5 dBi (2.4 GHZ)/4.5 dBi (5 GHZ)
WSR radial transmit range (m)		300
Average installation time/WSR		30 min
Estimated Cost/WSR		$150
Quality of service (QoS) support		Yes
Remote WSR management		Yes, via simple network management protocol (SNMP)
Network performance	Average network access delay (s)	0.00169
	Average file transfer latency (s)	6
	Average video streaming latency (s)	0.5
Requirements of solar system	Solar panel dimensions (height (cm)×width (cm))	36 × 29
	Mean voltage (v)	4
	Mean current (mA)	360
Requirements of solar system	Rated power (w)	1.5
	No. of paralleled solar panels required [normal mode]	6
	No. of paralleled solar panels required [sleep mode]	2
	Battery capacity (mAh) [normal mode]	2300
	Battery capacity (mAh) [sleep mode]	750
Power consumption analysis	Average drained current (mA) [normal mode]	150
	Average drained current (mA) [sleep mode]	70
	Battery life (h)/normal mode [2800 mAh battery cells]	15
	Battery life (h)/sleep mode [2800 mAh battery cells]	29

5. Conclusion

This paper introduces an effective approach to deploying a self-powered and dependable Disaster Recovery Network (DRN) infrastructure designed to support various environmental monitoring applications. Our work distinguishes itself through an innovative energy conversion and storage strategy, incorporating self-powered WSRs, environmental energy harvesting, and the integration of weather monitoring services. These elements collectively contribute to a more sustainable, resilient, and mobile Disaster Recovery Network infrastructure compared to other works in the field. The paper explores a range of methodologies and algorithms to facilitate the realization of such an infrastructure. Several valuable insights can be gleaned from this study. Foremost, the pivotal determinant for the successful execution of an "energy harvesting-battery-based" embedded system is the intelligent power management algorithm's capacity to adapt to diverse DRN operational scenarios. The adoption of the suggested "Duty Cycle Estimation (DCE)—Event-Driven Duty Cycling (EDDC)" method offers numerous advantages, including simplified implementation, optimized utilization of energy resources, and heightened network performance. Notably, this approach also bears substantial economic benefits, requiring fewer solar panels and a suitable battery capacity. Furthermore, it's imperative for management strategies to strike a balance between a highly reliable and a well-performing system, considering the embedded nature of a Wireless Solar Router (WSR). Additionally, the network's performance, installation time, and cost have all met the stipulated requirements within the acceptable range for DRN operations. To the best of our knowledge, the integration of these disaster recovery algorithms and techniques with a solar energy-powered system represents a novel and unexplored frontier in prior research endeavors. This innovative combination holds the promise of advancing the fields of disaster recovery and environmental monitoring, offering enhanced reliability and performance while also addressing sustainability and economic considerations.

Author contributions

Conceptualization, QIA and NAI; methodology, QIA; software, QIA; validation, QIA and NAI; formal analysis, QIA; investigation, QIA; resources, QIA; data curation, QIA and NAI; writing—original draft preparation, QIA and NAI; writing—review and editing, QIA; visualization, QIA; supervision, QIA; project administration, QIA; All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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