# ReNEW: A Practical Module For Reliable Routing in Networks of Energy-harvesting Wireless Sensors

V. Rao*, R. V. Prasad*, C. Sarkar†, I. Niemegeers‡
*Delft University of Technology, The Netherlands. Email: {v.rao, r.r.venkateshaprasad}@tudelft.nl
†TCS Research and Innovation Labs, India
‡Eindhoven University of Technology, The Netherlands

***Abstract*—Many Internet of Things smart-* applications are being powered solely through ambient energy-harvested energy. These applications require periodic data collection with low latency and high reliability. Since the energy is harvested in small amounts from ambient sources and is stochastic in nature, it is extremely challenging to achieve low latency and high reliability for such applications. To this end, we propose a distributed, energy-management module called *ReNEW*, for Constructive Interference (CI) based protocols that utilizes the available energy effectively in order to achieve our target of increased reliability in EH-WSN, especially in the low harvesting regimes. We choose CI-based protocols to leverage the low latency guarantees. Specifically, we propose a Markov decision model to maximize the energy utility in the infinite horizon by allocating energy optimally. To this end, we also propose a threshold optimal *policy*. As we find that just a energy scheduler cannot achieve the goal, we also propose distributed techniques to conserve energy on the redundant nodes in the network, and dynamically activate them based on feedback. We also improve the performance of CI by adapting the transmit powers on nodes.**

**We implement and evaluate ReNEW on Indriya testbed for real-world scenarios. We show that in a network of 20 source nodes out of the 30 nodes in the network can perform periodic data collection with an improvement of 2.5 times higher packet reception ratio as compared to LWB. This is one of the worst case scenarios as the harvested energy is as low as 50$\mu$J/s and packets of size 100 B is sent every 30 s. Furthermore, in this scenario, ReNEW saves around 25% higher residual energy on the average as compared to the standard LWB. In a nutshell, by integrating ReNEW with CI based protocols, we enable guaranteed latency and increased reliability for the batteryless EH-WSNs.**

## I. INTRODUCTION

Many Internet of Things (IoT) applications require low latency and high reliability[1] to enable closed-loop control [1]. Low end-to-end latency, high reliability and long lifetime of the network are the parameters that determine the usability and success of the IoT deployment. Batteries limit the lifetime of the devices, and in turn the utility of the network and the applications. Powering all the IoT devices through batteries is not scalable as frequent battery replacement is either labor intensive or impractical due to physical or deployment conditions [2]. Thus many IoT infrastructures adopt Energy-Harvesting Wireless Sensor Networks (EH-WSNs). As batteries are unsustainable, we only consider nodes powered with energy storage buffers such as supercapacitors.

A key problem, is to guarantee high reliability and low latency in EH-WSNs, such that these parameters (reliability and latency) satisfy the application requirements. Given the stochastic nature of energy arrivals, existing networking protocols for EH-WSNs target only reliable packet delivery [3], [4], [5] by adapting to the variations in energy for longer lifetimes rather than also ensuring low latency. Furthermore, they may suffer from Braess paradox [6], wherein the high energy nodes attract more traffic leading to their death. On the other hand, routing protocols have been defined since two decades for battery-powered WSNs that target achieving both guaranteed reliability and latency. Particularly, Constructive Interference (CI) based protocols [7], [8] have been shown to collect and disseminate data in a highly energy-efficient and reliable manner with low latency. However, they fail in EH-WSNs due to the dynamic energy variations. The most plausible conclusion from the current literature is that the EH-WSNs cannot support low latency operations, at least to a reasonably satisfiable extent. Thus, the ambition is to avoid overheads, achieve low latency and high reliability under challenging conditions, i.e., low energy-harvesting conditions.

**Approach**. As CI based protocols offer an energy-efficient platform that guarantees low latency (almost close to theoretical limit), we focus the work only on providing reliability for these protocols. To this end, we propose an energy-management module called ReNEW (*Re*liable routing in *N*etworks of *E*nergy-harvesting *W*ireless sensors) to enable high reliability in EH-WSNs. To prove our point, we use Low-power Wireless Bus (LWB) [7] as the *de facto* routing protocol and develop ReNEW around it. LWB offers guaranteed latency and high energy efficiency without any topological information. While high reliability is also guaranteed by LWB in battery-powered WSNs, or CI based protocols in general, it remains a non-trivial challenge in EH-WSNs as nodes do not have sufficient energy as required by LWB. In particular, in low energy harvesting campaigns, nodes need to be intelligent to use the available energy wisely.

**Challenges.** The main challenges that ReNEW must overcome are as follows:

1) Nodes do not have energy to participate in all communication slots. This leads to low reliability or packet reception ratio (PRR).
2) An energy-aware scheduler or duty-cycling mechanism on each node is insufficient, the network as a whole may be

---

[1] We define reliability as the Packet Reception Ratio (PRR), which is the percentage of packets that are successfully received at the destination/sink.

wasting resources. The network may suffer when the nodes are harvesting less as they become highly conservative in their participation, which also implies that the benefits of CI to overcome the unreliable wireless channel is lost.

We address these challenges in this paper. Specifically, our contributions are as follows:

- To the best of our knowledge, this is the first work that attempts to provide guarantees on latency and improves reliability considerably in EH-WSNs This practically important aspect is novel and has not yet received its due attention. To this end, we propose a distributed, energy-management module called ReNEW.
- We formalize the energy allocation problem as a Markovian decision problem and we propose a threshold optimal policy.
- We propose a set of protocol optimizations in ReNEW to make better use of the available redundant nodes and increase the performance of CI in the network.
- We implement and evaluate the performance of ReNEW on Indriya testbed with CC2420 radios [9] for real-world scenarios considering different number of nodes and data collection intervals.

We show that in one of the worst case scenarios – where harvested energy rate is as low as $50\mu$J/s with 20 nodes in the network with transmission of 100 B every 30 s – we even get an improvement of 2.5 times higher packet reception ratio, with 25 % higher remaining energy on the average compared to the LWB based greedy algorithm.

**Organization**. We present the related work in Sec. II. Then, we solve the energy allocation problem in Sec. III. Further, we describe the protocol optimization in Sec. IV. Sec. V evaluates and discusses the performance of ReNEW and conclude the article in Sec. VI.

## II. RELATED WORK

The work on routing in EH-WSNs has attracted less attention compared to their battery-powered counterparts. Table I summarizes the most significant networking protocols in WSNs and EH-WSNs. Of these limited works, most of them such as ORiNoCo [5] (opportunistic receiver initiated no-overhead collection protocol) and SP-BCP [4] (solar-powered backpressure collection protocol) target reliably delivering packets to the sink through higher energy nodes. The reasons for not targeting low latency in EH-WSNs are: (a) energy variations make it difficult to get the nodes globally synchronized as traditional synchronization protocols are power hungry; (b) schemes such as Low Power Listening still have considerable amount of overheads before successfully transmitting data; and (c) packet losses on the wireless channel consume significant amount of energy for retransmissions. Furthermore, ORiNoCo and EHOR suffer from Braess's paradox [6], wherein the gradient created towards higher energy nodes turns detrimentally. These higher energy nodes may deplete energy faster leading to lost data packets.

A common strategy employed to make WSN protocol energy-harvesting aware is by using power-management techniques such as adaptive duty-cycling, scheduling tasks and transmission policies. However, directly using them on LWB will not render the desired features. Adaptive duty-cycling techniques [12] determine how long a node should be awake based on residual energy and energy harvesting rates. While these algorithms can be tweaked to determine how much energy to spend, they do not schedule the operation of tasks. We show this in Sec. V as we compare ReNEW to the adaptive cycling mechanism proposed in [13]. Task scheduling [14] algorithms, on the other hand, maximize the number of tasks executed within some specified deadlines by considering the energy remaining in the storage element. However, these algorithms are myopic in their approach.

Markov models representing energy availability have been proposed to determine optimal transmission policies [15], [16], [17]. Each packet to be transmitted is considered to have a certain value, and the node gets a reward proportional to this value if the packet is transmitted. On similar lines, transmission power policies have also been constructed [15]. Higher the energy state, more reward can be accrued. These models target to maximize the average reward over an infinite horizon, which implies that the node will optimize its energy usage and packet transmissions. These works also cannot be used since they either schedule packet transmission in a future time when the energy is higher or do not consider transmission power to improve the performance of CI.

## III. ENERGY ALLOCATION PROBLEM

In this work, we consider LWB with forwarder selection since it is already an improved version of LWB. Henceforth, when we refer to a node that should participate in a slot implies that the slot is either one of the forwarder selected or its own slot. While the slot schedules are distributed from the sink, each node will have to manage its energy expenditure on its own. Every node must adopt an energy-aware policy to balance the available energy for expenditure in the future and in the current slot. In this section, we address the question: How much energy should be expended in the current time period? Intuitively, if a node aggressively participates in all its forwarder selected slots, the energy gets depleted soon. On the other hand, if the node is too conservative, then the PRR is low because of its non-participation within the network. To this end, we propose to use the Markov Decision Process (MDP) framework. Though there have been several works that propose to use MDP for determining the optimal transmission policies per packet [16], [15], we differ from these works in the following aspects: (i) we cannot 'queue' slots for the future as in some of those models and (ii) we do not decide to transmit in a particular slot but rather allocate energy for the whole communication round.

### A. System Model

We consider an EH-WSN network consisting of $N$ nodes with omni-directional antennas. Every node $u$ in the network has a unique identifier, denoted as $id(u)$. As we target a distributed algorithm, we focus on a single sensor node. We consider that the harvested energy between the communication

| Name | Storage | Working Principle | Basic Idea | Node Wakeup | Reliability | Latency Guarantees |
|---|---|---|---|---|---|---|
| CTP [10] | Battery | Tree-based | Nodes select parents with lower routing cost and ETX | Asynchronous | High | Yes With increased duty cycle |
| Dozer [11] | Battery | Time-slotted | Nodes select parents with lower hop-count and load | Scheduled | High | No, collisions cause delays |
| LWB [7] | Battery | CI based | Every packet is flooded | Scheduled | High | High |
| ORiNoCo [5] | Super-capacitor | Opportunistic with receiver initiated MAC | Nodes send packets to beacons with low routing cost. High energy nodes wakeup more often | Asynchronous | High | No |
| EHOR [3] | Super-capacitor | Opportunistic | Routing metric is a function of residual energy and hop-count | Asynchronous | High | No |
| SP-BCP [4] | Rechargeable battery | Back-pressure | Backpressure calculation is made harvesting energy aware | Asynchronous | Medium to high | No |

TABLE I: Summary of available routing protocols for WSNs and EH-WSNs

rounds $k$ and $k+1$ follows an *i.i.d.* process represented by $Y(k)$ (e.g., [18]). Each node has a supercapacitor as a storage buffer. The sink node is connected to a power grid.

We assume that communication slots for the node is modeled as an arrival process, $X(k)$, and also follows *i.i.d.* Let the number of slots to be allocated in the $k^{th}$ round be $x(k)$. A decision must be made as to how many of these slots will be allocated energy. The remaining slots will be discarded. We model the energy buffer by quantizing it into states $\{E_0, E_1, \ldots E_{max}\}$. Each state holds energy enough for one slot with maximum transmission power (including transmitting for $\eta$ times). The energy for round $k+1$ can be computed as,

$$E(k+1) = \min\{E(k) - A(k) + Y(k), E_{max}\}, \quad (1)$$

$A(k)$ is the energy allocated in $k$. The slot arrival process follows $x(k+1) = X(k)$. We consider a concave, monotonically non-decreasing function, $g$ with $g(A(k))$ indicating the number of slots allocated if $A(k)$ amount of energy is used.

### *B. The Optimization Problem and an Optimal Policy*

Given a state $E(k) \in S$, value $v(k) \in \mathbb{R}^+$, a policy $\pi$ implemented by the node is defined by the probability $\pi(\varepsilon, v)$ of selecting $x(k)$ slots in the communication round $k$. The optimization problem can be formulated as a Markovian decision problem wherein we need determine the optimal policy $\pi_*$ such that $\pi_*(s) = \arg\max_\pi V^\pi(s_0)$, where $s_0$ is the initial state and $V^\pi$ is the value of the policy.

**Optimal policy.** The necessary condition for an optimal policy is: For $\{A(k)\}$ to be asymptotically stationary, a policy that makes $\{x(k)\}$ asymptotically stationary with a stationary distribution $\pi$, it is necessary that $\mathbb{E}[X] < \mathbb{E}_\pi[g(A)] \leq g(\mathbb{E}[Y])$ [19].

We present a policy that satisfies this condition. Let

$$A(k) = min(E(k), \mathbb{E}[Y] - \epsilon), \quad (2)$$

where $\epsilon$ is a small positive constant with $\mathbb{E}[X] < g(\mathbb{E}[Y] - \epsilon)$. This is indeed an optimal policy as a stationary (or a threshold vector) does exist as this satisfies the necessary condition. Asymptotically, as $g$ is concave, $g(A(k)) \to g(\mathbb{E}[Y] - \epsilon)$. Thus, $\{g(A(k))\}$ is asymptotically stationary and ergodic. Thus $\mathbb{E}[X] < g(\mathbb{E}[Y] - \epsilon)$ is a sufficient condition for $\{x(k)\}$ to be asymptotically stationary and ergodic whenever $\{X(k)\}$ is stationary and ergodic [19].

## IV. PROTOCOL OPTIMIZATION

While we saw that the optimal policy outperformed the greedy policy, we notice that only 7 out of 20 slots were assigned to transmit data. This is due to the amount of energy harvested being quite low compared to the consumption rate. To handle such situations, we propose several solutions.

**Dynamic Node Activation.** Since the available energy on the nodes is quite low, a commonly adopted solution is to deploy redundant nodes [20]. This is particularly helpful when there are no secondary power sources such as batteries.

The purpose of redundant nodes is not served if all the nodes, including the redundant nodes are always on. These "helper" nodes must be dynamically switched on when required. Though the authors of [20] propose policies to activate nodes, it is assumed that the redundant nodes can check the neighborhood status. Such an assumption does not hold in our scenario. Therefore, we design a simple distributed policy. A non-source node is activated according to the policy given in Eqn. 3 for a communication round $k$ on a node $i$. A source node is always activated if it has a minimum amount of energy, $E_{min}$ to at least participate in its own slot.

$$\mathcal{A}_i(k) = \begin{cases} \text{no activation} & \text{if } E(k) < E_{min} \\ \text{activate with prob. } p & \text{if } E_{min} < E(k) \leq E_{th} \\ \text{activate with prob. } 1 & \text{if } E(k) > E_{th} \end{cases} \quad (3)$$

**Priority Handler.** Since the nodes may not always have sufficient energy to participate even in all its forwarder selected slots, it is important to quantify the importance of slots. By defining weights, the nodes can then choose the best slots to participate. The priority handler ensures that the energy is spread across the slots and not spent on the first few slots (as in the greedy approach).

A difficulty though is that individual feedback cannot be given to the nodes. We tweak the LWB protocol to make the sink include the information on which slots data was successfully received in the previous communication round. This information, or *ACK*, is piggybacked with the following communication round's schedule. With this ACK information, the node has four cases to deal with:

- The best case is if a node participated in a slot and the packet was received. The priority must be slightly increased in this case so that the node is more likely to participate in the slot again.

- Another case is when the node participated in forwarding data in a slot but was not received at the sink due to failure of CI or an energy outage at another intermediate node. Here, the node cannot do much but try to participate again.
- If a node sees that ACK is received in a slot it did not participate, then the node decrements the priority since its participation is not required for successful data delivery.
- The worst case is when a slot goes unserved i.e., the node did not participate and the data did not reach the sink as well. In this case, the node assumes responsibility by increasing its priority to a higher value.

One method to calculate the weight is to take (1 - PRR) per slot. We increment or decrement priority by 10% of its value.

**Energy utilization.** The optimal policy only allocates the energy but does not specify how to use it. With priorities defined to the slots, the problem becomes that of allocating the energy to as many high priority slots as possible. This can be proven to be the classical 0/1 knapsack problem [21]. As the 'weights' of each slot is the same, this problem can be solved in polynomial time ($O(NlogN)$). The slot assignment algorithm is shown in Alg. 1. In order to save energy, we lower the transmission power when the transmissions happen successfully. We modify DIPA [22] to this end. The advantages are two fold: (a) employing different transmission powers across nodes improves the performance of CI [22]. (b) If enough power is saved to serve more slots, then the next higher priority slots are chosen to participate in.

**Algorithm 1** Slot Allocation Algorithm.

```
//txPower indicates the current transmit power
//txTime is the time required to complete one transmission
//We assume the power required for Tx and Rx are equal
//slotEnergy is the energy required to participate in a slot
At the beginning of the communication round $k$:
slotEnergy ← txPower * txTime * $\eta$ * 2;
$A(k)$ ← min($E(k)$, avg_harvested_energy($k$ - slotEnergy);
$n_{\text{slots}}$ ← $A(k)$/slotEnergy;
Sort the slots in descending order of their priority;
Schedule the first $n_{\text{slots}}$ for participation;
```

## V. EVALUATION

In order to evaluate ReNEW module, we implemented it in Contiki OS [23] for WSNs based on our LWB implementation [24] and evaluated it on Indriya [9] testbed that offers realistic results. The experiments were conducted on 30 Tmote Sky nodes.

### A. Evaluation Setup

**Energy modeling.** We implemented the energy-harvesting battery model in software. We consider that each node stores the harvested energy in a supercapacitor of size $E_{max}$ =20 mJ. We performed experiments with a uniform arrival process having a mean rate of 50$\mu$J/s. This is the average amount of energy that can be harvested from indoor lighting [25] which is significantly less than the amount of energy spent in a communication round. For example, a 100 B packet to be sent in a LWB slot with $\eta$=2 consumes almost 900$\mu$J.

**Application.** The nodes need to report their sensed data periodically to a sink node. To evaluate ReNEW, we experimented with two communication round intervals of 30 s and 60 s. For each interval, packets of different length (50 B and 100 B) and different number of source nodes (10 and 20) are also experimented with. We chose these scenarios to test ReNEW for the potentially worst case scenarios.

**Algorithms.** We compare ReNEW + LWB with (a) LWB with no energy-management algorithm. We call this a "greedy" energy allocation policy as the nodes try to participate in a slot if there is energy. (b) LWB with a well-known adaptive duty cycling technique [13] for EH-WSNs as the energy scheduler. The initial battery level is to 65% as considered in the paper. We denote this as "LWB+ADC". Note that all the algorithms employ forwarder selection and therefore participates *intelligently* in the necessary slots only.

**Metrics.** The two metrics used are PRR and average remaining energy in the nodes to infer the lifetime indirectly. The PRR is measured at the sink node. Further, the sink node is considered to be connected to the power grid.

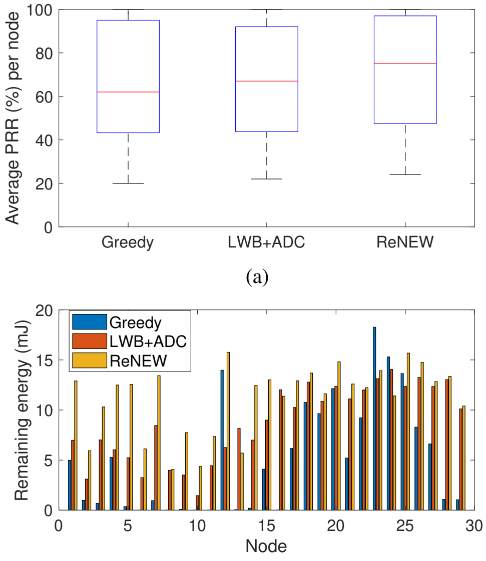
**Realistic evaluation.** The energy consumed on the nodes includes the energy spent on all aspects of the protocol including energy for the actual data collection, overheads for schedule distribution (also ACK in case of ReNEW), and retransmissions ($\eta$). Furthermore, the wireless channel conditions are uncontrolled and the experiments were conducted in the possible presence of WiFi and other interfering sources in the remote testbeds. Therefore, the results depict a real-world deployment scenario.

### B. Results

*A word on notation*: In the figures, 30s and 60s indicate the corresponding period of communication rounds, 30 seconds and 60 seconds, respectively; 10n and 20n indicate 10 and 20 source nodes that periodically send data (out of 30 nodes), respectively. The data size is either 50B or 100B (bytes).

At the outset, we set that all the nodes have a fully charged capacitor. Fig. 1(a) shows the average PRR of a 20 source node network, with 30s interval. Even though it is impossible to deliver all the packets with low harvesting rate, it is clear that ReNEW improves the average PRR as opposed to both the other algorithms; in this case by at least 17% as compared to the greedy approach. The ADC mechanism is better than the greedy approach as it adapts to the available energy, but is not better than ReNEW. This is due to the fact that when the nodes have higher energy, they behave similar to the greedy approach. When the nodes have low energy, the nodes become conservative in their participation, leading to lower PRR.

Fig. 1(b) shows that the greedy approach drains almost all energy to maximize participation in slots whereas, ReNEW is more energy-aware. Thus, even if the harvesting rate drops in the next rounds, the network can sustain for a longer time.



(a)

(b)

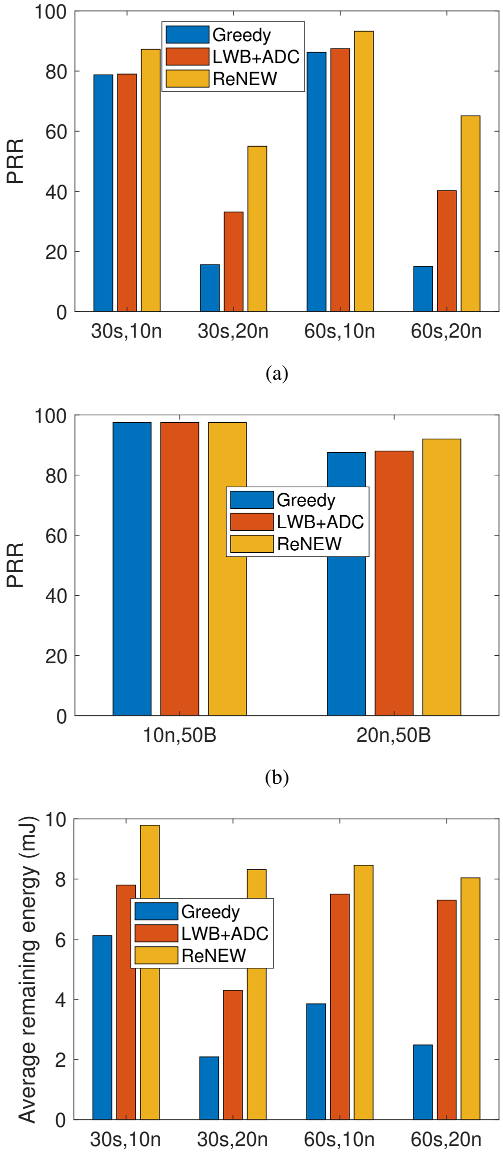
Fig. 1: Scenario 30s, 20n and 50B: (a) Average PRR. (c) Remaining energy per node after 60 rounds.

However, this does not affect (reduce) the PRR of the network as evident from Fig. 1(a).

**Heavy vs. Light traffic**. Fig. 2(a) shows the PRR for data collection over 30s and 60s intervals sending 100 B of data. Evidently, with more time to harvest and lower the traffic, the performance of all the algorithms are almost similar. However, in the worst case (period being 30 s and 20 source nodes), ReNEW shows that it can outperform by *2.5* times the greedy approach, and also LWB+ADC approach significantly. This performance is due to the multi-fold components of ReNEW, particularly dynamic node activation and power adaptation. Fig. 2(b) shows the light traffic scenario wherein 10 nodes transmit data and all the methods perform extremely well. Fig. 2(c) shows the average amount of energy remaining on the nodes for a payload length of 100 B. We see that ReNEW keeps a buffer of more energy on the average. A big part of this is due to the dynamic node activation.

**Payload length.** The payload length also significantly influences the performance, as larger the payload, more is the required energy to transmit. Fig. 2(a) and Fig. 2(b) shows the results when 50B and 100 B were sent by the source nodes for 60 s periodicity. It is again evident that more payload length has an influence on the performance. Again, ReNEW outperforms the other approaches.

**Density.** Fig. 2(a) clearly shows that higher the density of redundant nodes, better is the performance. Furthermore, due to the dynamic activation of redundant nodes, ReNEW performs better than the other approaches. In ReNEW, a node with energy less than 75% of its maximum capacity, will choose with a probability, $p = 0.5$, to participate or not. This reduces the number of redundant nodes wasting their energy. As not all nodes exhaust energy in all participatable slots and due to this, there is a higher chance for ReNEW to find at least one forwarder to send its packets. This is future work as to how much this helps.



(a)

(b)

(c)

Fig. 2: (a) Average PRR for different traffic intensities and source nodes (100 B). (b) Average PRR for payload length 50 B at 60 s periodicity. (c) Average remaining energy for different number of sources, and payload length of 100 B.

## VI. CONCLUSIONS

The Internet of Things (IoT) is changing our daily life bringing better and improved quality of life. However, these myriads of IoT devices powered by batteries cannot scale. Thus, we sought ambient energy-harvesting in WSNs to be used in IoT applications. However, these devices must provide the similar performance in terms of latency and reliability as their battery-powered counterparts.

In this paper, we focused on providing high reliability to EH-WSNs. We proposed to use a recent data collection protocol LWB based on Constructive Interference, which can provide the guarantees on latency. However, in EH-WSNs setting LWB cannot guarantee reliability because of the stochastic nature of energy harvesting. To this end, we proposed a module called ReNEW. We proposed an *optimal policy* and also found the necessary condition for designing an optimal policy. We also show that it is indeed an optimal policy by showing the existence of a stationary (or a threshold vector). Furthermore, we proposed several enhancements and fine-tuned the protocol to improve the reliability offered by ReNEW. ReNEW is completely distributed and a practical module. We implemented ReNEW on TMote Sky nodes. We used Indriya and FlockLab testbeds, which are standard experimental facilities, to evaluate our algorithms. We found that ReNEW outperforms LWB even with an adaptive duty-cycling mechanism. A key reason for this performance improvement is the redundant nodes. Finding the critical density that can provide guarantees on reliability in EH-WSNs is an important challenge, which we will investigate in our future work.

## ACKNOWLEDGMENT

SCOTT (www.scott-project.eu) has received funding from the Electronic Component Systems for European Leadership Joint Undertaking under grant agreement No 737422. This Joint Undertaking receives support from the European Unions Horizon 2020 research and innovation programme and Austria, Spain, Finland, Ireland, Sweden, Germany, Poland, Portugal, Netherlands, Belgium, Norway.

## REFERENCES

[1] M. Burns et al., "NIST: The IES-City Framework Draft Version 1.0," 2018, accessed: 30 July 2018. [Online]. Available: https://s3.amazonaws.com/nist-sgcps/smartcityframework/files/ies-city_framework/IES-CityFrameworkdraft_20180207.pdf

[2] R. V. Prasad, S. Devasenapathy, V. S. Rao, and J. Vazifehdan, "Reincarnation in the ambiance: Devices and networks with energy harvesting," *Communications Surveys & Tutorials, IEEE*, vol. 16, no. 1, 2014.

[3] Z. A. Eu, H.-P. Tan, and W. K. Seah, "Opportunistic routing in wireless sensor networks powered by ambient energy harvesting," *Computer Networks*, vol. 54, no. 17, pp. 2943–2966, dec 2010.

[4] S. Yang, X. Yang, J. A. McCann, T. Zhang, G. Liu, and Z. Liu, "Distributed networking in autonomic solar powered wireless sensor networks," *JSAC*, vol. 31, no. 12, pp. 750–761, 2013.

[5] C. Renner, S. Unterschütz, V. Turau, and K. Römer, "Perpetual Data Collection with Energy-Harvesting Sensor Networks," *ACM Transactions on Sensor Networks*, vol. 11, no. 1, pp. 1–45, Sep. 2014.

[6] T. Roughgarden and É. Tardos, "How bad is selfish routing?" *Journal of the ACM (JACM)*, vol. 49, no. 2, pp. 236–259, 2002.

[7] F. Ferrari, M. Zimmerling, L. Mottola, and L. Thiele, "Low-power wireless bus," in *ACM SenSys*. ACM, 2012, pp. 1–14.

[8] A. Escobar, C. Gonzalez, F. J. Cruz, J. Garcia-Jimenez, J. Klaue, and A. Corona, "Redfixhop: Efficient ultra-low-latency network flooding," in *IEEE SECON*. IEEE, 2016, pp. 1–2.

[9] M. Doddavenkatappa, M. C. Chan, and A. L. Ananda, "Indriya: A low-cost, 3d wireless sensor network testbed." in *TridentCom*, vol. 90. Springer, 2011, pp. 302–316.

[10] O. Gnawali, R. Fonseca, K. Jamieson, D. Moss, and P. Levis, "Collection tree protocol," in *SenSys '09*. ACM Press, Nov. 2009, p. 1.

[11] N. Burri, P. Von Rickenbach, and R. Wattenhofer, "Dozer: ultra-low power data gathering in sensor networks," in *ACM/IEEE IPSN*, 2007.

[12] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, "Power management in energy harvesting sensor networks," *ACM TECS*, vol. 6, no. 4, sep 2007.

[13] C. M. Vigorito, D. Ganesan, and A. G. Barto, "Adaptive Control of Duty Cycling in Energy-Harvesting Wireless Sensor Networks," in *IEEE SECON*. IEEE, jun 2007, pp. 21–30.

[14] C. Moser, D. Brunelli, L. Thiele, and L. Benini, "Real-time scheduling for energy harvesting sensor nodes," *Real-Time Systems*, vol. 37(3), 2007.

[15] N. Michelusi, K. Stamatiou, and M. Zorzi, "Transmission Policies for Energy Harvesting Sensors with Time-Correlated Energy Supply," *IEEE TOC*, vol. 61, no. 7, pp. 2988–3001, jul 2013.

[16] J. Lei, R. Yates, and L. Greenstein, "A generic model for optimizing single-hop transmission policy of replenishable sensors," *TWC*, vol. 8, no. 2, pp. 547–551, feb 2009.

[17] V. S. Rao, R. V. Prasad, and I. G. Niemegeers, "Optimal task scheduling policy in energy harvesting wireless sensor networks," in *2015 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2015, pp. 1030–1035.

[18] P. Poggi, G. Notton, M. Muselli, and A. Louche, "Stochastic Study of Hourly Total Solar Radiation in Corsica Using a Markov Model," *International Journal of Climatology*, vol. 20(14), 2000.

[19] V. Sharma, U. Mukherji, V. Joseph, and S. Gupta, "Optimal energy management policies for energy harvesting sensor nodes," *arXiv preprint arXiv:0809.3908*, 2008.

[20] K. Kar, A. Krishnamurthy, and N. Jaggi, "Dynamic node activation in networks of rechargeable sensors," in *INFOCOM 2005.*

[21] M. R. Garey and D. S. Johnson, *Computers and intractability*. wh freeman New York, 2002, vol. 29.

[22] V. S. Rao, M. Koppal, R. V. Prasad, T. V. Prabhakar, C. Sarkar, and I. Niemegeers, "Murphy loves CI: unfolding and improving constructive interference in WSNs," in *INFOCOM 2016*, apr 2016.

[23] A. Dunkels, B. Grönvall, and T. Voigt, "Contiki-a lightweight and flexible operating system for tiny networked sensors," in *LCN 2004*. IEEE, 2004, pp. 455–462.

[24] C. Sarkar, "Lwb and fs-lwb implementation for sky nodes using contiki," arXiv preprint - https://arxiv.org/pdf/1607.06622.pdf, 2016.

[25] M. Gorlatova, M. Zapas, E. Xu, M. Bahlke, I. J. Kymissis, and G. Zussman, "CRAWDAD dataset columbia/enhants (v. 2011-04-07)," [Online] http://crawdad.org/columbia/enhants/20110407/energy.