

Energy-Governed Resilient Networked Systems

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Abstract—Connected embedded systems in the realm of smart infrastructures comprise ubiquitous end-point devices supported by a communication infrastructure. Device, energy supply and network failures are a reality and provisioned communications could fail. Self-organization is a process where network devices cooperate with each other to restore network connectivity on detecting network connectivity failures. Self-organized networks are envisioned to be hierarchical, implying that a root device is expected to spend more energy to forward the entire network’s data. This leads to battery exhaustion and therefore a single point of failure in the system. In this paper we address this problem by proposing an energy-governed resilient networking framework. Our framework enforces a policy to throttle upstream network traffic to maintain energy drain at the root device. To demonstrate the effectiveness of the proposed policy, we designed our experiment framework using Nano-RK and FireFly; a lightweight operating system and sensing platform respectively.

I. INTRODUCTION

Smart infrastructures comprise ubiquitous devices communicating with each other via a communication network towards a common goal; such systems are called *connected embedded systems* or popularly known as the Internet of Things (IoT). These devices as examples are sensors (temperature, humidity, air quality for example), actuators, mobile phones and network routers. An example connected embedded system in a smart home is shown in Figure 1; home occupants can monitor their home through a cloud service which in turn is connected to various devices. This system is heterogeneous from all aspects of technical capabilities of these devices, making it an interesting and promising paradigm for the future [1].

Devices failures and energy supply disruptions in the connected embedded systems are a reality. Failure of devices supporting store-and-forward network functions disrupts communications and critical data for troubleshooting and monitoring the failure is unavailable. This motivates the need for network self-organization where devices sense failure and autonomously restructure the network topology and use on-board battery to support communications. Thus, self-organization allows for data collection even when provisioned network service is unavailable. To achieve scalability in the self-organized network, hierarchical networks are being proposed [2].

Self-organized hierarchical networks make a tacit assumption that nodes (devices) higher in the hierarchy have capabilities to support higher volume of data communications. Such nodes forward data from devices below them in the hierarchy along with their own data traffic, making traffic supported by network nodes asymmetric. The energy drain on devices in higher layers of the hierarchy will be more than ones below them. This may lead to a single point of failure

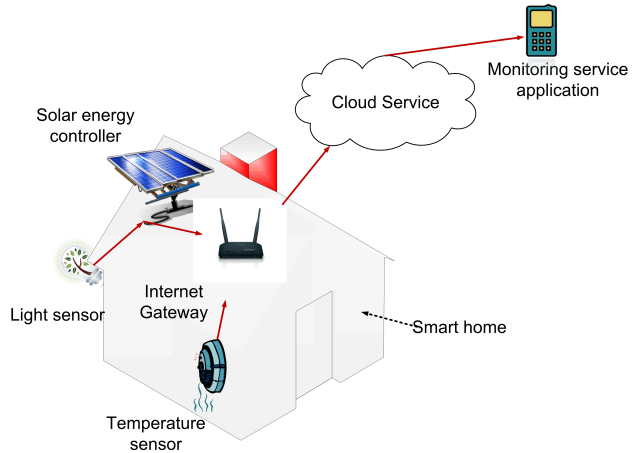


Fig. 1: We illustrate a connected embedded system in a smart home. Home occupants can monitor and control various devices through an internet based cloud service.

in the self-organized network, especially when the root node of the hierarchy fails and no other device is able to reach a functioning internet gateway. We would not want network self-organization itself lead to nodes being disconnected from the communication infrastructure.

A general energy model E for a network device is

$$E = \frac{E_b}{\eta_{PA}} \left(H + \sum_{c=1}^B P_c \right) + E_C + E_S, \quad (1)$$

where the radio frequency (RF) communication cost is expressed in terms of energy cost per byte of data E_b , efficiency of the RF power amplifier η_{PA} ranging between 0 and 1, size of the packet header H in bytes and the payload P 's size of B bytes. E_b is the energy at the RF antenna needed to overcome the energy in the channel to transmit a byte. We observe that computation costs E_C and static energy E_S due to leakage current during device's idle time are constants by modern technology standards. Assuming that E_b , η_{PA} and H are fixed, the RF communication costs will increase linearly with payload aggregation at the root device.

In this paper we propose an energy-governed resilient networking framework to maintain the energy drain at the new root device in a self-organized network. Our proposed framework employs a three phased cycle. In the first phase, the network is monitored to understand the RF characteristics between each pair of network nodes. Using the RF behavior data among network nodes, the network self-organizes into

a hierarchical communication tree in the second phase. The second phase ensures that nodes only communicate with other nodes which have the best signal quality for better communication reliability. This will reduce energy costs from re-transmissions and other RF characteristics such as interference or noise. This phase also includes other functions such as scheduling communications to avoid transmission collisions. In the third phase, the communication schedule enforces a policy for energy-governance after self-organization. This policy throttles upstream traffic towards the root device such that the net volume of traffic supported at the root device is the same as before self-organization to maintain its energy drain.

The energy-governed policy can be implemented in two ways to throttle upstream network traffic. We propose *packet size modulation* as one method of assigning the leaf nodes a packet size to retain aggregated packet size at the root node as before self-organization. This means that the same communication schedule can be used, but intelligence models needed to decide how data is managed with the new packet size is out of scope for this work. Suppose, we define *data resolution* as the quantity of a specific kind of data to make a meaningful inference. The data resolution using packet size modulation will see graceful degradation as data has to be accommodated within the adjusted packet size. An alternate implementation for this policy is to retain the packet sizes for network nodes, but allow them to transmit with larger time intervals so that net packet traffic at the root node over larger time intervals is still retained. This results in retaining resolution of sensed data, but at the cost of delay. In the system of interest, we believe graceful degradation of data resolution is acceptable due to rapid changes in operating environments leading to continuous monitoring of the smart infrastructure. Hence in this work we implement packet size modulation to enforce our energy-governance policy.

We developed our proposed algorithm using Nano-RK, a lightweight operating system for real-time sensing applications [3]. The proposed algorithm was implemented on FireFly devices, a lightweight sensing platform representative of a broad class of devices in connected embedded systems [4].

The remainder of this paper is structured as follows. Network model and assumptions for this work are discussed in Section II. We discuss related work in Section III. We propose our energy-governed resilient networking framework and algorithm in Section IV. We discuss our implementation, energy model and energy analysis in Section V. We discuss the future energy trends in Section VI. Finally we discuss future work and conclude in Section VII.

II. NETWORK MODEL AND ASSUMPTIONS

Our network model comprises end-point devices communicating with a gateway to the internet. Each cluster of end-devices self-organize to reach a functioning internet gateway during disasters. We use the terms “nodes” and “devices” interchangeably. Following are our network assumptions,

- 1) Nodes use Time Division Multiple Access (TDMA) for medium access. We chose TDMA because it is a deter-

ministic medium access scheme when used in centralized control mode. This leads to accurate energy measurements. We assume local synchronization in the network.

- 2) The energy consumption due to inefficiencies in the RF power amplifier is a constant.

III. RELATED WORK

Self-organization and energy awareness has been studied and applied for specific network applications in the realm of mobile ad-hoc networks, sensor networks, internet of things and smart metering infrastructure in the smart grid [5][6] [7] [8]. These works have centered around proposing clustering techniques, organizing cluster-heads and creating a hierarchical structure among them for end-to-end connectivity and scalability purposes. Cross-layer designs have been used for designing scalable network self-organization algorithms for smart metering infrastructure in the smart grid [2]. Additionally, centralized power control has been implemented in cellular and other wireless network deployments as interference mitigation strategies but not for energy savings [9].

Network monitoring metrics have been studied for various network applications and deployment environments. Under certain conditions of hardware, RF chip being used, transmit power levels, it has been shown that Received Signal Strength Indicator (RSSI) is a good indicator of channel quality [10]. It has been experimentally established that RSSI provides little insight to determining channel quality, rather needing correlations between symbols, packets and packet error rates to establish Link Quality Indicator (LQI) metrics [11].

IV. ENERGY-GOVERNED RESILIENT NETWORKING

In this section we propose our energy-governed resilient networking framework as a three phase continuous cycle.

A. Phase 1: Network Monitoring

The internet gateway initiates the self-organization process when it does not receive scheduled data packets from nodes. It starts a new TDMA frame and requests nodes to transmit pilot beacons in a particular slot and frame corresponding to their identification number as shown in Figure 2. Each node transmits the beacon during its slot and sleeps for the rest of the frame. During all other frames, the node is constantly listening for other node’s transmission. For the beacons heard, a node records the quality of the channel using metrics such as RSSI or LQI. Finally, after the frames for beacon transmission are completed, the nodes then report the quality of channel for every other node’s beacons to the internet gateway in their respective frames. The internet gateway constructs a map as a matrix for the channel quality metric as shown in Figure 3, where the nodes reported the RSSI values for beacons from other network nodes and the internet gateway.

B. Phase 2: Self-Organized Network Construction

We construct the self-organized network tree in a way similar to the self-organized network constructed for smart meters in the smart grid [2]. Our network formation algorithm begins

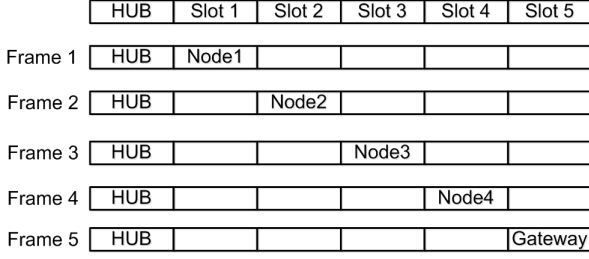


Fig. 2: We illustrate with an example for RSSI collection from network nodes to construct the RSSI map in Phase 1. In each frame, a node transmits in its slot and sleeps during other slots, while other nodes listen to the node's transmission to record RSSI values.

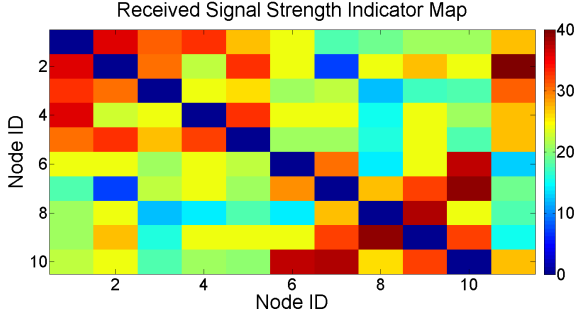


Fig. 3: We illustrate the RSSI values between all pairs of nodes captured as part of the RSSI matrix. The last column is the RSSI values for messages between network nodes and the internet gateway. The variations in RSSI values indicate that not all node to node communication exhibit similar RF behavior. Hence this motivates the need to communicate with neighbors with best RF behavior.

at the node with maximum channel quality to the internet gateway; node with maximum value for metric in the last column of Figure 3. A binary tree is built recursively starting at the root such that for each parent, nodes with highest metric value to the parent become its children. These children are chosen by excluding those nodes which are already connected to avoid loops. Child nodes which do not find any successor nodes will send a message upstream to the root node conveying no further reachability. The root node waits for a period and broadcasts a *tree completion* message. Any node which hears this message and is still not connected requests its neighbor node with maximum metric value to accept it as its child. We leverage the relationship between connectivity and coverage for wireless sensor networks for ensuring connectivity in our network [12]. Thus, it is possible that we may not always have a binary tree while we attempt to connect all nodes. However, this shall not impact our policy's implementation to manage energy drain at the newly chosen root device. The internet gateway learns about the network from the root and computes the schedule using slot ordering for upstream traffic to propagate from leaf nodes to the root [13].

C. Phase 3: Packet Size Modulation for Energy-Governance

We hypothesize that communication energy costs increases with increase in packet size being transmitted as shown in

Equation (1). Our approach to energy-governance is to enforce a policy to throttle upstream traffic. We propose *packet size modulation* to implement the energy-governance policy, where we vary packet sizes for the rest of the network nodes to maintain the packet size of the root node as it was before self-organization. This allows to maintain the same energy drain at the root node even after self-organization, mitigating the chances of an increase in energy drain due to forwarding the self-organized network's traffic.

Packet modulation adjusts the payload size of the leaf node since we assume a constant sized packet header. The new payload size for the leaf P_l in bytes is computed by the internet gateway as

$$P_l = \left\lfloor \frac{P_r}{N} \right\rfloor, \quad (2)$$

where P_r in bytes is the payload size supported at the root prior to self-organization and network size denoted by N . We use a floor function in Equation (2) to obtain integer payload sizes. But the payload size cannot be reduced beyond what is supported by devices. Thus for any given value $P_l \leq H$, the energy cost for goodput will start to increase by observing the first term of Equation (1). Therefore graceful degradation in data resolution is coming at a cost of spending more than half the energy for packet header communication. As devices begin recovering from failure, Phase 1 ensures they are part of the new self-organized network and self-organization ceases when all network nodes are functioning.

We propose three cases of packet size modulation for limiting energy drain in the self-organized network. The cases differ in how the value of P_r is chosen by the internet gateway. These cases also help examine the network's energy expenditure for RF communications for different packet sizes.

1) *Case 1: Root preserving packet size modulation:* The value of P_r is the payload size of the root node as it was before self-organization. We call this root preserving packet size modulation because this scheme makes no energy consideration for other network nodes. It is possible that on self-organization a node which was a leaf in normal operation configuration could be a parent of an intermediate level in the self-organized tree. Thus it is forced to spend more energy to support communications in the self-organized network.

2) *Case 2: Leaf preserving packet size modulation:* The value of P_r is set to the leaf node's payload size prior to self-organization. We call this leaf preserving packet modulation because this scheme makes a consideration for the energy drain for the node which was a leaf in the network configuration under normal operations. Since the root is now supporting only the smallest of the packet sizes from normal operations, it is possible for the entire network's energy consumption to be lower than that of root preserving packet size modulation.

3) *Case 3: Probabilistic packet size modulation:* We treat the payload size supported in the network nodes as a random variable. The payload size takes values between 2 bytes and 80 bytes. Our network structuring mechanism is probabilistic because we cannot always predict the network structure due

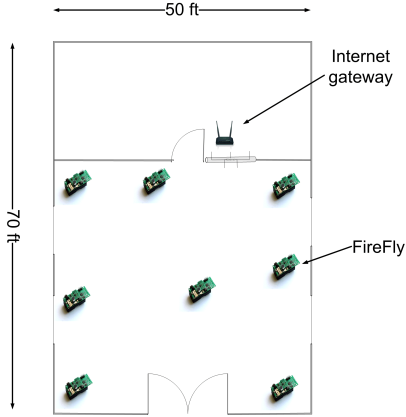


Fig. 4: We illustrate our testbed of FireFly devices at Carnegie Mellon Innovation Laboratory

to temporal behavior of the network monitoring metric. For packet sizes computed by the gateway using Equation (2), the packet size assignment to network nodes is equally likely because of unpredictability in network structure. The probability of the nodes being assigned either of the packet sizes to be supported in the network is $\frac{1}{N}$. If P_i is the payload size in bytes supported by a node $i \in \{1, \dots, N\}$ computed by the gateway, the average packet size P_{avg} of the network is $[\sum_{i=1}^N P_i / N]$. We set P_r as P_{avg} , the statistical average of payload sizes in the self-organized network but not allowing it to be lower than the smallest allowed payload size.

V. EVALUATION AND ANALYSIS

In this section we describe the implementation and experimental results of energy-governed resilient network framework.

A. Network Testbed

We implemented our proposed framework using FireFly as our end point devices and Nano-RK as our development environment for programming the FireFly. FireFly is a lightweight sensing platform with an ATmega128RFA1 micro-controller that is being used for several real-time sensing systems [4]. As a proof-of-concept, we deployed 8 FireFly devices (network nodes) around electrical fixtures at Carnegie Mellon Innovation Laboratory. The network structure is shown in Figure 4, and all the nodes were assumed to be part of one cluster connecting to an internet gateway. The nodes communicate with each other wirelessly using IEEE 802.15.4 protocol with an onboard 2.4 GHz transceiver. Nodes always transmitted at full transmission power in order for us to model the worst case scenario energy consumption for communications. We allowed for node to node communication in Nano-RK allowing for forwarding aggregated traffic in hierarchical networks.

We subjected the testbed to send data packets of various sizes among each pair of FireFly nodes. We found little or no temporal behavior in LQI metrics, but found variations in RSSI measured from these data packet exchanges. Hence, in this

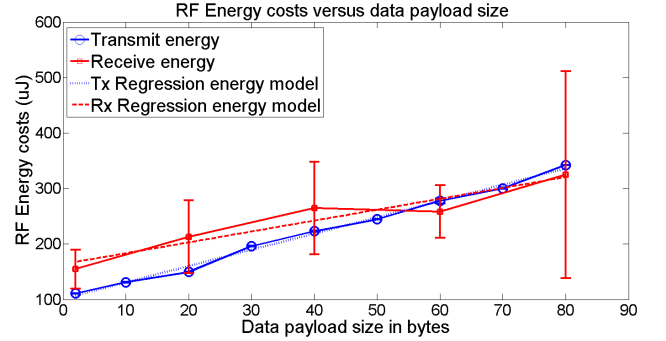


Fig. 5: We illustrate the energy costs for transmitting and receiving data packets of different payload sizes assuming a constant sized packet control header of 40 bytes. We also plot the energy cost model for transmit and receive obtained using linear regression.

work we use RSSI as the metric to monitor the network and construct the self-organized network. The RSSI values range between 0 to 28 for the ATmega128RFA1 micro-controller.

B. Modeling Transmit-Receive Energy Costs

To model the energy costs for communications on the FireFly devices, we allowed one FireFly node to transmit and another node to receive. We varied the payload sizes for transmission from the smallest being 2 bytes to the maximum possible payload size of 80 bytes in intervals of 10 bytes, with each packet size seeing multiple transmissions for collecting training data. We assumed that the packet header is a constant of 40 bytes, with hardware limiting the maximum packet size of 128 bytes. We measured the current drawn by the FireFly node and voltage across it only for the transmission time and the reception time by programming triggers in Nano-RK at the start and end of the transmit-receive cycles. This allows us to compute the energy costs of communication for various packet sizes. Measurements for packet sizes apart from the training sizes were collected to test our model's accuracy.

The energy costs for transmit and receive are plotted in Figure 5. We observed from our measurements that with increase in packet size, both transmit and receive energy costs increase linearly. The energy costs in μJ for transmit (E_{Tx}),

$$E_{Tx}(P) = \frac{E_b^{Tx}}{\eta_{PA}} \left(H + \sum_{c=2}^B P_c \right) \approx 101.4 + 2.93P, \quad (3)$$

and receive (E_{Rx}),

$$E_{Rx}(P) = \frac{E_b^{Rx}}{\eta_{PA}} \left(H + \sum_{c=2}^B P_c \right) \approx 164.9 + 1.96P, \quad (4)$$

are modeled as a function of payload size $P \in \{2, 3, \dots, 80\}$ in bytes. These models represent the communication energy costs discussed in Equation (1) and energy per byte needed for transmission and reception are denoted by E_b^{Tx} and E_b^{Rx} respectively. We observed large deviation in our receive energy model because the receive cycle in FireFly is not a fixed duration and is dependent on the overhead imposed by packet retransmissions and error recovery mechanisms.

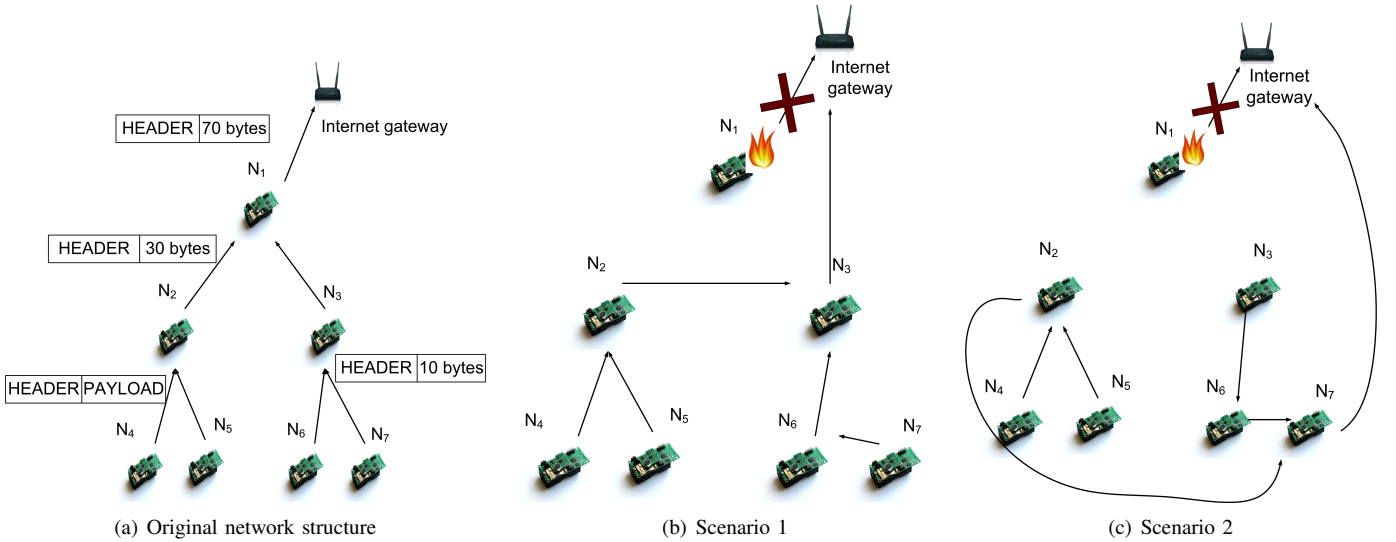


Fig. 6: Figure (a) illustrates a hierarchical network configuration for normal operations and the packet size supported at each level of the hierarchy. Figure (b) illustrates the configuration for Scenario 1, where an intermediate node N_3 in Figure (a) is promoted to be a root node after self-organization. Figure (c) illustrates the configuration for Scenario 2, where N_7 as a leaf node in Figure (a) is promoted to be a root node in the self-organized network.

We use this energy model to predict the cost of self-organization based on packet sizes supported by nodes after self-organization. Our model predicts the energy costs with an average accuracy of 97% and 92% for transmit and receive respectively for the test samples. While there is linearity in energy costs for the entire packet's size, we acknowledge that energy cost of useful byte transmission increases as payload size decreases. Based on our energy models, at least 36 bytes of transmission payload and 85 bytes of reception payload are needed to overcome the cost of transmitting or receiving 40 bytes of fixed size header. However, our hypothesis of nodes needing to spend more energy because of forwarding aggregated traffic resulting in larger packet sizes is valid.

C. Energy-Governance Analysis

We observed changes in RSSI values with high variance for every cycle of our proposed framework. Hence, the network structure was not predictable. For each of the cases discussed in Section IV, we consider two network structures we observed as examples to analyze energy costs after self-organization.

The network structure under normal operations is as shown in Figure 6(a), with each leaf node N_{5-7} sending packets with a payload size of 10 bytes. Each parent node appends its payload of 10 bytes to the payload it receives from its children and forwards the traffic to its parent node. We allowed node N_1 to fail by disconnecting it from the network which was connected to the internet gateway. We describe the instance of two observed topologies as Scenario 1 and Scenario 2 shown in Figures 6(b) and 6(c) respectively. The difference between these scenarios is that an intermediate parent node N_3 is promoted to the root node on self-organization in Scenario 1 and the leaf node N_7 promoted to being the root

node in Scenario 2 on self-organization. We now analyze the RF energy costs for both scenarios and the three cases and compare the energy costs if nodes were still to send packets at the same rate and payload size as for normal operations.

1) *Case 1 (C_1):* The new payload size for *root preserving packet size modulation* is computed using Equation (2). The packet sizes in Scenarios 1 and 2 (S_1, S_2) will be 5 and 2 bytes respectively. In Table I, we see that for all nodes in both scenarios, the energy consumption for communication drops compared to the scenario when there was no energy-governance in self-organization. Thus from our observations we see that root preserving self-organization helps in lowering the energy consumption for communications for the entire network. The energy savings we see for Scenario 1 and Scenario 2 are 17.06% and 27.24% respectively.

2) *Case 2 and 3 (C_2, C_3):* For both the *leaf preserving packet size modulation* and *probabilistic packet size modulation* and the respective scenarios, the packet size at the leaf nodes was 2 bytes as shown in Table I. The energy savings in these cases and the respective scenarios are the same as case 1-scenario 2 ($C_1 : S_2$), which yielded 27.24% energy savings.

Our experiments and analysis first validated our hypothesis of communication energy costs increasing linearly with increase packet sizes. Then we proved that energy-governance to maintain energy drain at the root device was possible by throttling upstream traffic. Our analysis shows that energy-governance implemented using packet size modulation can not only energy drain on root device, but also on other network nodes for various network structures with different packet size modulation strategies.

C:S	N_2			N_3			N_4			N_5			N_6			N_7			T_E
	Rx	Tx	E	Rx	Tx	E	Rx	Tx	E	Rx	Tx	E	Rx	Tx	E	Rx	Tx	E	
$NG:S_1$	20	30	392.1	50	60	538.8	0	10	130.3	0	10	130.3	10	20	343.2	0	10	130.3	1665
$NG:S_2$	20	30	392.1	0	10	130.3	0	10	130.3	0	10	130.3	10	20	343.2	50	60	538.8	1665
$C_1:S_1$	10	15	328.55	25	30	401.9	0	5	115.65	0	5	115.65	5	10	304.1	0	5	115.65	1381.5
$C_1:S_2$	4	6	290.42	0	2	106.86	0	2	106.86	0	2	106.86	2	4	280.64	10	12	319.76	1211.4
$C_2:S_1$	4	6	290.42	10	12	319.76	0	2	106.86	0	2	106.86	2	4	280.64	0	2	106.86	1211.4
$C_2:S_2$	4	6	290.42	0	2	106.86	0	2	106.86	0	2	106.86	2	4	280.64	10	12	319.76	1211.4
$C_3:S_1$	4	6	290.42	10	12	319.76	0	2	106.86	0	2	106.86	2	4	280.64	0	2	106.86	1211.4
$C_3:S_2$	4	6	290.42	0	2	106.86	0	2	106.86	0	2	106.86	2	4	280.64	10	12	319.76	1211.4

TABLE I: This table illustrates the energy costs for self-organization under various cases and scenarios. The network's RF energy costs after self-organization is shown in the last column. In all three cases of self-organization, there is savings for total RF energy in the self-organized network compared to scenarios when there is no energy-governance as shown in first two rows. The variables Tx , Rx are the transmit, receive payload sizes in bytes, E and T_E are RF energy at each node and the entire self-organized network respectively in μJ . The variable C indicates the case of energy-governance and S is the scenario. The case with no energy-governance is denoted by NG .

VI. FUTURE ENERGY TRENDS

The computation technology evolves with time and we are seeing the advent of low-power devices where cost of computation is getting lower and lower. We envision that this trend will lead to such constrained devices to have negligible constant computation energy costs. Though RF power amplifiers are not very efficient today, their efficiency has improved compared to their predecessors. Hence, even if we assume that we achieve 100% efficiency in power amplifier technology, the traffic volume component of communication energy cost $E_b/\eta_{PA}(H + \sum_{c=1}^B P_c)$ in Equation (1) will still remain. This is because E_b will still have to spent to overcome the inherent energy in the channel. Therefore even if all other components are fully optimized, policy enforcement is the only other platform-independent solution for energy savings on these constrained devices. How this policy is implemented by applications in this system is an interesting problem for the future. Policy could be uniformly enforced across the network if the high data resolution from all devices provide no additional insights into the current functioning of the infrastructure, thus allowing for graceful degradation in data resolution. The policy can be enforced non-uniformly based on the need for high resolution data from a subset of devices if it justifies the root device's communication cost.

VII. CONCLUSION AND FUTURE WORK

We hypothesized and proved that energy costs for communication for a device increases with packet size. In self-organized hierarchical networks, the root device could fail due to rapid exhaustion of its battery by forwarding the entire network's traffic in addition to its own. We proposed an energy-governed resilient networking framework to mitigate the energy drain on newly promoted root devices by enforcing a policy to throttle upstream traffic. We proposed a packet size modulation technique to adjust packet sizes of other network devices to retain packet size at the root device and thereby maintaining its energy costs even after self-organization. We developed and implemented our proposed framework using Nano-RK and FireFly, which together are representative components in connected embedded systems. Hence, our work can be used as

a platform/hardware independent solution for energy savings in the self-organized networks. On a small scale we achieved about 17% – 27% of energy savings, but we envision larger savings and thus better network longevity in very critical and large-scale operating environments in this system. As future work, we will model the impact on application performance due to energy governance in connected embedded systems.

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