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Energy optimization of sustainable Internet of Things (IoT) systems using an energy harvesting medium access protocol

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Abstract. The process of modelling the energy expenditure for IoT systems is distinct when compared to Wireless Sensor Networks (WSN), due to a number of factors and metrics. Few of such factors to mention are the IoT layers being different from the Open System Interconnection (OSI) with communication protocols like IPv6 Low power Wireless Personal Area Networks (6LoWPAN), Routing for Low Power and Lossy networks (RPL) and Constrained Application Protocol (CoAP). This leads to the demand for designing efficient Medium Access Control (MAC) protocols to serve the purpose of balance between the performance of the system and minimum energy consumption. The challenge of compatibility of MAC protocols for IoT deployment needs to be addressed. The proposed work is aimed at developing energy efficient framework for optimal balance between energy consumed by connected devices (sensor networks) in a complex and time-critical IoT system through performance monitoring of underlying communication technologies. It also focuses to address the trade-off between energy expenditure and performance of the network for the communicating nodes. An Energy Harvesting MAC protocol is designed and developed after modelling of the nodes using Reinforcement Learning (RL) for time critical IoT systems. The results have shown that the energy expenditure of the IoT devices is considerably minimized and the performance is increased by nearly 80% when compared to the state-of-art energy harvesting solutions for sustainable IoT systems. This research also plays a significant role in matching the energy predictions and the experimentations that validate the IoT systems in a real-world scenario.

1. Introduction and Background study

IoT acts as the connecting bridge between future communication systems and pervasive computing. The vision of IoT is to enable more connected devices through cross-layer protocols. The IoT based systems conjugate the wireless and portable technologies such as WSN, Nanotechnology and Radio Frequency Identification (RFID). Therefore, when multiple technologies are embedded together on a single platform, it is quite factual that energy is the prime factor that is responsible to handle such connected systems [1]. It is vital to pay attention to issues related to energy and power consumption. The process of modelling the energy expenditure for IoT systems is distinct when compared to WSN, due to a number of factors and metrics [2]. Few of such factors to mention are the IoT layers being different from the OSI with communication protocols like 6LoWPAN, RPL and CoAP [6] [7] as depicted in Figure 1. The



network topology for weighted paths is utilized for energy optimization of IoT systems. Regardless of the solution being more reliable and resistive to breaking down of nodes, the drawbacks of fault tolerance and robustness make it harder for dealing with packet transmission, data flow and multi-hop communication [3] [4]. The scale and magnitude of IoT systems with many connected devices intend to maintain the energy consumption of each of the devices. This leads to the demand for designing efficient MAC protocols to serve the purpose of balance between the performance of the system and minimum energy consumption [5]. The need, in turn, poses implications on the design view of energy modelling strategies and energy efficient MAC protocols. The challenge of compatibility of MAC protocols for IoT deployment needs to be addressed. This research is aimed at developing energy efficient framework for optimal balance between energy consumed by connected devices (sensor networks) in a complex and time-critical IoT system through performance monitoring of underlying communication technologies.

An integrated IoT system comprises of sensor nodes that suffer drawbacks such as limited lifetime, area coverage, smaller size and limited processing power. Each sensor node is designed with sensing and data processing components for communicating with its neighbour nodes over dedicated channels. The node transfer data either directly or through relays to the sink node, which is forwarded to the end user or server via a gateway and the internet. Hence, these wireless class of networks poses the challenge of centralized data forwarding, management, control of the sink node's placement and area coverage of access points in an IoT domain. In contrary to the IoT networking devices, which have IP address-based approach, the sensor nodes work based upon node ID or index addressing. Moreover, the energy consumption in sensor networks is inversely proportional to the mesh formation of the nodes. The feature of mesh formation by the sensor nodes can hence play a vital role to improve the lifetime and sustainability of sensor networks. IoT research has the capability to encapsulate the identification potential, sensing technology, artificial intelligence, and interconnection of nano - things, ultimately striving towards the objective of developing seamlessly interoperable and securely integrated systems. These integrated communication networks comprise of many interconnected units such as processor, memory, energy storage unit, radio, micro-controller and so on. The energy consumed by these units is very high during communication. Therefore, the optimization of this energy consumption is a primary necessity to increase the lifetime of integrated systems. This research focuses to enable energy optimization for IoT systems through an energy harvesting protocol. The following sections of the paper describe the background study, methodology of the research and conclusion respectively.

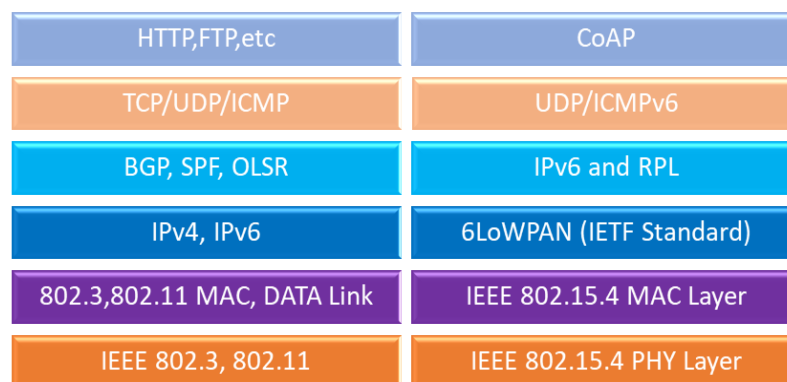


Figure 1. OSI and IoT Layered Stack

The 6LoWPAN is a communication protocol belonging to the adaptation layer and comprises of packet encapsulation and header compression mechanisms with RFC6282 standard definition [8]. It can also be utilized over low powered RF technology. RPL is deployed for networks that consume low power by utilizing information broadcasting through the Directed Acyclic Graph (DAG). The predicted transmission hops and counts are constructed into a tree-based structure to send the updates to its neighbour nodes thereby reducing the overall cost of creating and developing a new object. This protocol relies upon networks that have high energy loss and low data rate through energy from memory and

processing units. RPL utilizes self-configured Dynamic Host Configuration Protocol (DHCP) protocol for network connection and Internet Control Message Protocol version 6 (ICMPv6) message formatting for packet forwarding in fragments. IoT can be broadly classified in two categories, they are Industrial IoT where, in the global internet scenario, IP network is connected to the IoT device and commercial IoT platform. Here, the local communication is either wired or wireless (Bluetooth or Ethernet) and IoT device will be able to communicate with local devices only [9]. One of the key research efforts for IoT includes IoT devices fully relying upon EH as their primary sources of power since novel networking technologies are being developed for the development of low-cost, low-power, wide area networks of small intelligent devices [10]. The applications that focus on the goal of energy harvesting must perform their task in the shortest time possible. This requirement leads to the need for protocol design. The wireless network 6LoWPAN provides techniques for header compression and encapsulation of data acquisition as shown in Figure 2. Many IoT researchers have urged that 6LoWPAN is the key for IoT. IPv6 is considered to be a quintessential requirement if the goal to be achieved is remote controlling of devices or data transmission over global internet platform. 6LoWPAN is considered to be advantageous over Personal Area Networks (PAN) since Peer-to-Peer (P2P) communication is easier to be implemented for devices comprising of global addresses [12]. The authors in [11] have studied and described the primitive case studies and technological considerations for system design in operator-controlled Device-to-Device (D2D) environments. The research article [13] presents a novel IoT based architecture for anonymizing location-based queries in IoT contexts. On the other hand, the researchers in [14] had introduced an architecture that has been integrated with scheduling mechanism based on pipelined time-division for acquisition of sensor data from an adhoc WSN. Integrating the key technologies of IoT such as RFID with WSN, the researchers in [15] have presented a semantic monitoring platform of supply chain management under the semantic IoT-based sensor networks.

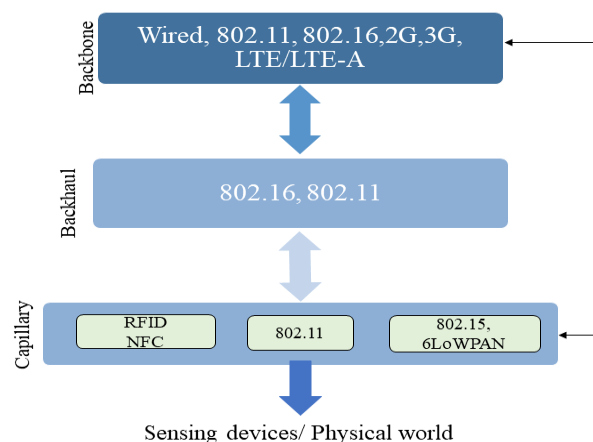


Figure 2. IoT Communication technologies

An outline of vital network infrastructures and enhancement of network performance techniques for development of an energy efficient Wireless Powered Communication Networking (WPCN) has been described in [16]. The work presented in [17] explains the concept of how mobile multi-hop sensor networks overlay on 3G mobile networks and also provides insights into the usability of JXTA as an efficient framework in the mobile environment. The researchers in [18] have introduced a fundamental energy-efficient hybrid distance transmission technology for dynamic networking environment as well as for Internet of Everything (IoE) infrastructure. The authors in [19] have defined the concept of Machine-to-Machine (M2M) communication system, relevant issues, security threats and security requirements and also have proposed a protocol to meet the security attributes against threats of communication. The rapid advancement of heterogeneous devices connected through large scale networks is a transparent indication towards attaining the IoT vision. Many researchers and academicians in the IoT field have put forth their perceived opinion that the fifth generation (5G) cellular systems will take IoT deployment to greater heights. Energy efficient communication plays a vital role

in the interconnection of heterogeneous devices across cross platforms. The research contribution in [4] provides discussion on extensive features of cellular/non-cellular device communications and its essentiality for IoT contexts in 5G networks. The recent contributions have also proposed a hierarchical architectural framework to enable RFID applications for devices that do not have RFID reading capabilities but comprise a wireless interface [4]. Despite the numerous research contributions with regards to designing of energy efficient routing protocols for sensor networks and IoT systems, there is still a need to address many challenges which serve as motivation for this proposed research work.

- It is a challenging task for sensor networks in IoT systems to ensure data delivery due to segmented data frames of time-critical applications. The reason for this issue is the unavailability of the node in active state due to improper time synchronization and expired duty cycles for harvesting energy. Therefore, this imposes the development of a well-designed energy efficient transport protocol by taking into consideration the data flow, transmission distance and location of nodes.
- Many existing IoT protocols focus on throughput, delay and lifetime of the network when exploiting the renewable energy resources for Energy Harvesting (EH) of the sensors, whereas the Quality of Service (QoS) optimization is left unaddressed. The impractical assumptions of infinite capacity of energy and data buffers, as well as the synchronization metrics of communication channel for EH systems, should be reconsidered during the design of the transmission protocols.
- The existing EH-MAC protocols are designed to serve the purpose of the single application. Therefore, this leads to an opportunity of designing MAC protocols that can exploit cross-layer resource allocation by consideration of energy consumed not only during data transmissions but also due to other factors such as switching of duty cycles and optimal performance of devices.
- These energy optimization issues for complex IoT systems (due to NP-hardness) need to be mathematically analyzed through numerical methods with lesser time complexity that can aid in the implementation of the same through simulations and real testbed scenarios.

2. Problem analysis and Methodology

When the sensor nodes are deployed in an area, they transfer the data to the sink node via two methods- Primarily, it transmits data directly to the centralized base station through a direct communication protocol. This approach leads to higher energy consumption by the nodes if the distance of transmission between the sensor nodes and the base station is longer, eventually leading to quicker exhaustion of the nodes. Secondly, the nodes act as relays to route the data to neighboring nodes. This is effective for the smaller density of the network since node localization can be computed easily to achieve a faster rate of data collection and forwarding towards the mobile sink node. The requirements to aid the restrained battery power capability of the sensor nodes, for enhanced network lifetime, is indeed vital and imperative. A considerable research contribution which has made conclusive remarks that communication protocols in sensor networks adopt the clustering techniques for mitigation of energy consumed during data collection and aggregation methods. The clustering technique minimizes the higher energy consumption caused due to longer transmission ranges between the node and the sink. It also reduces the range of communications among the clusters in a network, thereby facilitating the duty-cycling mechanisms and assigning packet forwarding tasks to Cluster Heads (CH). The switching of different states in the radio of a sensor node also needs to be controlled for avoiding energy wastages and also for time synchronization between packet transmission and task scheduling. The communication protocols also adopt different transmission mode, based upon the application in which the sensors are deployed. The process of topology control protocol is to find the nearest neighbor to the node which is in the process of active communication, to act as a data channel for packet transmission towards the mobile sink. Therefore, an effective communication protocol with the definitive transmission mode, sink mobility, node localization and application type (event-triggered or query-driven) can have a

considerable and noteworthy impact on the energy conservation and mitigation approaches. The past decades have witnessed the evolution of many energy-efficient MAC protocols as tabulated in Table 1, that are asynchronous with sensor network communication. These protocols utilize the Low Power Listening (LPL) technique for the mismatch of synchronization between the transceivers and radio unit in a commercialized sensor network.

Table 1. Comparative analytics between the MAC protocols of sensor network communications

	S-MAC/T-MAC/DSMAC	Wise MAC	TRAMA	SIFT	DMAC
Time sync needed	No	No	Yes	No	Yes
Comm. pattern support	All	All	All	All	Convergecast
Type	CSMA	Np-CSMA	TDMA/CSMA	CSMA/ CA	TDMA/ Slotted aloha
Adaptive to changes	Good	Good	Good	Good	Weak

1

In the proposed research, the nodes are first mathematically modelled using reinforcement learning followed by using the numerical analysis results to implement the techniques based on simulations and fine-tuning these sensors for IoT systems according to the Q-factor of testbed deployment. A systematic and quantitative review is aimed to be carried out to identify the research gaps and to analyse the data using taxonomies and also to examine the performance metrics, EH design constraints and user-defined assumptions for the existing IoT protocols in order to find a correlation between dependent and independent variables. The further methodology of mathematical modelling and analysis is obtained using an energy-optimized policy where the Markov processes are solved using reinforcement learning to achieve the near-optimal solutions of the system. The implementation of novel cross-layer Multi Renewable Resource Allocation (MRRRA) mechanism based upon Energy Harvesting MAC IoT (EHMACIT) protocol for time-critical IoT systems is currently underway by the authors.

3. Results and Discussion

The network lifetime is defined as the total operational time taken by the network to remain in the active state to perform the dedicated task. It is also described as the duration until the primary sensor node or cluster of sensor network nodes of the network go to dead state or run out of energy. The depiction that is shown in Figure 3 states that EH and modelling based upon reinforcement learning provides improved network lifetime by nearly 80% with respect to packet generation. The network lifetime (T_N) is directly proportional to energy consumption (E_p) by the data packets p belonging to network N , which is expressed as in equation 1.

$$T_{N=} = \frac{E_p}{p}, \text{ for all } p \in N \quad (1)$$

The calculated energy expenditure during transmission and reception operations by IoT nodes/transceivers also indirectly monitor and record the overhead caused by control packets of a routing protocol.

¹S-MAC-Sensor-MAC; T-MAC-Timeout MAC; DSMAC- Dynamic Sensor MAC; TRAMA-Traffic Adaptive MAC protocol; SIFT- MAC protocol for event-driven WSN; DMAC- Data gathering MAC; CSMA- Carrier Multiple Access; Np-CSMA- Non-persistent CSMA; TDMA- Time Division Multiple Access; CA- Carrier Access

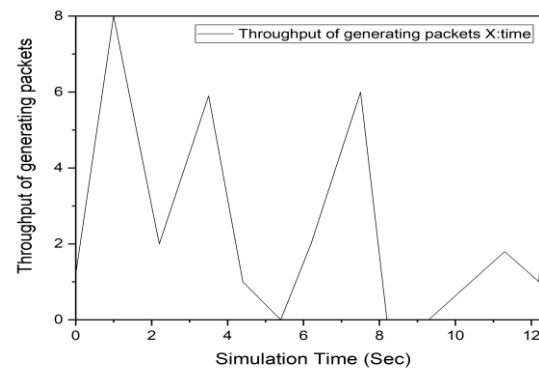


Figure 3. The throughput of generating packets with respect to time after energy harvesting

4. Conclusion

IoT can be considered as an integral part of everyday life where the whole idea is to change the scope from internet of people to the IoT. IoT is envisioned to activate more population of prior devices that are not connected to each other for making them to share information and communicate on a cross-layer platform. The services that have been envisioned for the future of IoT include areas such as healthcare, agriculture, smart cities, transportation, energy saving, so on and so forth, with the goal of providing significant benefits to the consumers and for the sustainable development of the society. Therefore, this research work that aims to focus on how to reduce energy consumption when millions of such devices are connected and communicated in a cost-effective and efficient manner, can have significant importance to the society. The research gaps such as compatibility of existing MAC protocols in IoT deployments and optimal performance in presence of multiple harvesting technologies are to be addressed according to the methodology of this research and such significant findings can considerably lay the future roadmap for IoT communication systems. Nowadays, where IoT research innovations have reached to a point where life without mobile phone and internet can never be imagined, the proposed solutions can be foreseen as a promising directive towards potentially beneficial outcome to the academicians and IoT researchers as well.

The primary focus of this research is to solve and address the issue of energy consumption. Firstly, it focuses to address the uncertainty behind the traditional IoT systems which completely rely upon the energy that is stored in batteries and capacitors. Rather, energy harvesting using renewable energy resource such as RF signals has been utilized for powering the circuitries of the sensor node, followed by employing the methods of energy harvesting MAC protocol in the proposed scenario. Therefore, a two-way approach of handling the issue of energy consumption in this research is that – improving the lifetime of the network (by not completely and primarily relying on energy stored in batteries/capacitors) through ambient energy harvesting followed by proposing energy saving techniques to handle the high energy consumption when enabling technologies of IoT is employed for time-critical systems. The problem analysis carried out in this research has major findings that higher energy consumption in IoT networks is the primary matter of concern to ensure reliability and longevity of a network. The state-of-the-art research contributions have seldom focused upon the issue of energy management. Therefore, it was also analysed that the major causes for higher energy consumption in IoT networks are – communication protocol, network topology, routing mechanism and energy transmission/storage techniques. The impact of each of these mentioned causes and factors have been studied and analysed for systematic qualitative review of energy management in IoT systems. The issues such as node failure, interference management, the lifetime of the network and time delay are focused upon and addressed. Thereafter, to solve each of the said drawbacks, the research objectives with regards to energy harvesting, energy transfer and controlling/handling of the energy levels of the IoT nodes have been proposed and achieved in this research.

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