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Resource Management in Pervasive Internet of Things: A Survey

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Abstract

Internet of Things (IoT) embodies a vision of merging heterogeneous objects to establish seamless interaction among physical and virtual entities. IoT has given the Internet a shift from connecting networks to interconnecting the physical world. The IoT devices are capable of sensing, processing, communicating and storing the data acquired from the physical world. Most of the applications of IoT are pervasive in nature, the pervasive IoT environment poses many challenges due to constrained resources in these miniature and unattended IoT devices. This paper presents a survey of physical and virtual resource management in IoT systems. The main focus of the paper is on resource management in pervasive IoT environment with limited resources. This paper also presents a use case of IoT based Body Area Network and proposes a model for resource management in personal and community healthcare.

Keywords: Internet of Things, Data Aggregation, Resource Management, Fog Computing, Body Area Networks

1. Introduction

Internet of Things is one of the promising research paradigms in the current epoch, characterized by using smart and self-configuring objects such as sensors, actuators, RFIDs, etc that are connected to the Internet and exchange data by sensing, reacting to events and interacting with the environment. It embodies a vision of merging heterogeneous objects while utilizing the Internet as a backbone of communication to establish interaction among physical

and virtual entities. These seamless interactions among heterogeneous objects make IoT a paradigm that enables ubiquitous and pervasive applications. Thus Internet has seen a pervasive shift from interconnecting end-user nodes to interconnecting physical objects creating a platform of smarter objects capable of informative communication and intelligent processing.

Since a huge number of things connect to the Internet, therefore, it is necessary to have an adequate architecture that permits easy connectivity and control. Extensive work has been done in last few years to find a universal IoT architecture, but IoT encompasses an extremely wide range of applications, as such, single reference architecture has not been used for all concrete implementations Bandyopadhyay and Sen (2011). An IoT architecture should be capable of performing a minimum of three essential functions viz. sensing and aggregation of data, communicating data and utilizing data to provide services at the application level (see Figure 1). The sensing and data collection is done by physical IoT nodes that sense some physical parameters or identifies other nodes in smart environments. Data aggregation, data conversion, and data transmission are performed by network communication nodes such as gateways, responsible for connecting to other smart things, network nodes and servers. The communicated data is then utilized by IoT applications to deliver various services to the users.

IoT comprises of complex environments encompassing many heterogeneous components. The huge amount of data generated by sensor-instrumented objects of the real world in an IoT environment will impose a great demand on processing and storage resources to transform the data into useful information or services. Some applications will be latency sensitive, while other applications will require complex processing including historical data and time series analysis. Therefore, considering the typical resource constraints of IoT devices, it is difficult to envision a real-world IoT ecosystem without including a cloud platform, or at least some powerful devices, for instance, smart gateways or edge/fog devices.

IoT provides a plethora of applications that contribute significantly to en-

hance our daily life throughout many applications that come from different sectors such as remote monitoring of patients by gathering medical data from the patients equipped with medical IoT devices, remote monitoring of soil parameters such as humidity, temperature, etc. in real time to improve crop production, environmental monitoring, monitoring of green energy systems, water monitoring, waste management, road & traffic management, disaster mitigation, etc Ray (2016). Besides these applications, IoT envisions a wide range of applications, but there are limitations in resources which need to be taken care at the software and hardware levels. In addition to the resource limitations, there are many constraints due to characteristics of an individual node (e.g., limited memory and processing), the behavior of the network (e.g., topology change) and constraints at the application level (e.g., latency) Das and Ammari (2009). Although these constraints are application dependent, most of them are common in pervasive applications.

Due to the technological advances and potential for multiple applications, there is a rapid growth on research related to the IoT. The hetergeniety of the devices and systems involved in IoT poses a number of challenges before the research community especially in pervasive applications at the hardware, software, and network levels Liu et al. (2017). Considerable research is being carried out at the device level, and many vendors are providing solutions for different applications, but in most of the cases, there is no standardization at the manufacturer level. Due to the increasing applications at the system level, most of the work is focused on resources management which includes data management, cluster-based routing, energy management, heterogeneity management, process management, memory management, network management, etc. Despite the heterogeneity of IoT devices, the data in IoT applications can be combined, correlated, compared and merged to match the peoples needs and requirements. Virtualization of the IoT data at the device level and network level also play an important role in managing limited resources of IoT environment.

This paper presents a picture of physical and virtual resources in IoT environments, constraints in IoT ecosystems, existing work on resource management

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and explores the possibilities of resource management in constrained IoT devices and its environments. Rest of the paper is organized as Section 2 gives the various resources in IoT environment; Section 3 presents the various constraints in IoT environment; Related work in Resource Management is given in Section 4; Section 5 discusses a resource management architecture for pervasive IoT applications; Section 6 presents the various challenges in IoT resource management; Finally, Section 7 presents the conclusions.
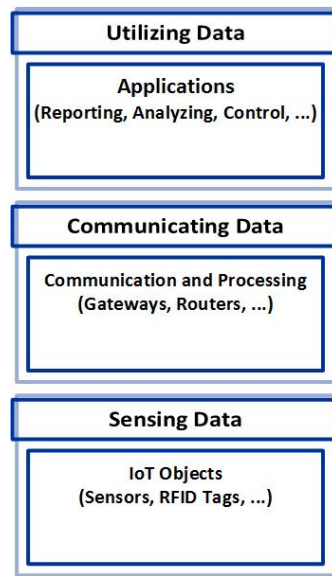
Figure 1: Basic Functions of IoT
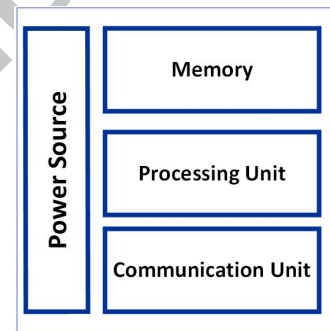
Figure 2: Resources of a Typical IoT Node

2. Resources in IoT environment

IoT is the evolution of Internet designed to collect, analyze and distribute data via IoT devices that forms its core component. An important aspect of pervasive IoT device is its constrained resources. As shown in Figure 2, a typical battery-operated IoT device possesses storage, processing, bandwidth, and energy as its resources. Since these resources are limited in pervasive applications, therefore, various energy-efficient lightweight algorithms and protocols
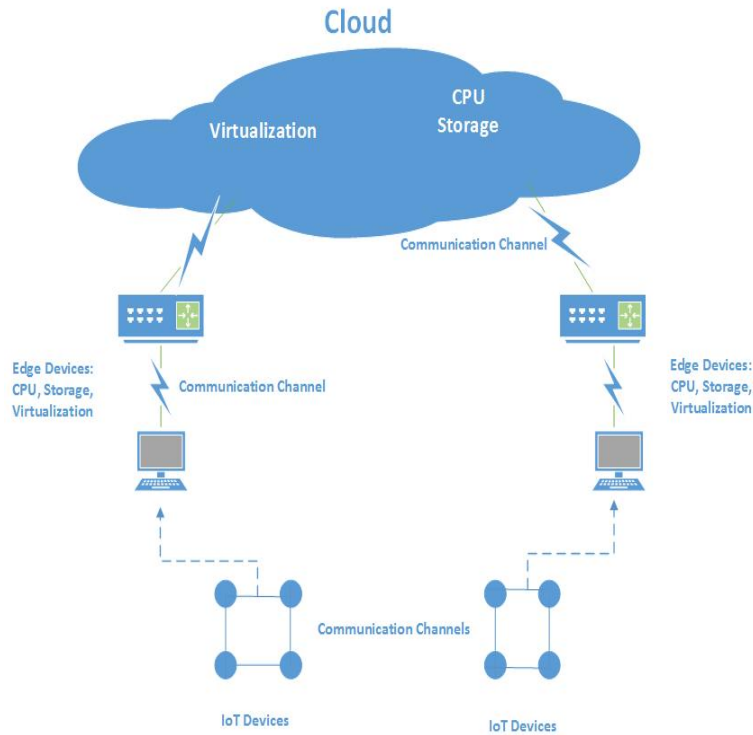
Figure 3: Three-Tier IoT environment

are being implemented to store, process and transfer the data as per application requirements and with an optimized resource management.

The huge amount of data generated by IoT devices increases the demand for processing and storage resources and considering the typical resource constraints of IoT nodes, it becomes necessary to include few high-end nodes in IoT ecosystem e.g., edge devices or smart gateways or cloud platform, to give rise to a Three-Tier architecture (see Figure 3)Delicato et al. (2017). At the system level, there are two types of resources: Physical and Virtual resources. The physical resources include memory, processing, network bandwidth, energy, etc. The virtual resources include protocols and algorithms used in processing, storage, encryption, data fusion. The physical and virtual resources in IoT ecosystem are summarized in Table 1.

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Table 1: Resources in IoT Ecosystem

Platform	Physical Resources	Virtual Resources
IoT Device	Temporary storage, Processing, Energy, Bandwidth.	Algorithms and Protocols used for data aggregation, processing.
Edge Device	Medium Storage, Processing, Energy, Bandwidth.	Algorithms and Protocols used for data aggregation, processing, encryption, virtualization.
Cloud	High Storage, High end Processing.	Algorithms and Protocols used for data aggregation, processing, encryption, virtualization, etc.

3. Constraints in IoT environment

Deployment of IoT devices faces constraints at the node level, network level, and application level. These constraints are in terms of processing, energy, storage and bandwidth, device addressing, standardization, implementation of management protocols, security algorithms, etc.

3.1. Processing, Storage, Energy and Bandwidth Constraints

With the advancements in embedded devices, the processing power of IoT devices is increasing day by day, but this results in increased energy consumption. To overcome that, IoT devices can rely on more powerful devices or servers for processing of data, but it introduces a delay in data processing. Instead, such devices can process the collected data by themselves but it needs storage space for data processing algorithms, which infers that the IoT device with processing capability also need storage capability Elmangoush et al. (2013).

The processing capability and networking is dependent upon the availability of energy. Hence, energy is the major contributor to efficient resource management. Data size, protocols, packet size, processing speed, number of transmis-

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sions and reception operations are some of the aspects of energy management. Also, IoT devices are constrained in terms of bandwidth, the efficient management of bandwidth impose less constraint on energy, storage, and processing requirements in IoT environments Blaauw et al. (2014).

3.2. Device Addressing

In IoT environment, the object(device) needs to be addressed by a unique ID either directly or indirectly. In some cases, the device is connected to the Internet all the time, so it can be addressable and its state can be sensed. In other cases, due to the heterogeneity of devices or security requirements in the IoT, all of the devices are not connected to the Internet directly. In that case, the devices need some technique to be addressed indirectly, adding to the complexity in IoT architecture. Further, it is estimated that the addressing of such a huge number of devices in an IoT environment is beyond the capability of IPv4. Therefore, IPv6 is a better option than IPv4 in terms of providing internal security and end-to-end user transparency in addition to the addressing of IoT objects. But the disadvantage of Ipv6 in IoT is that it requires a large amount of time to be fully functional as a standalone scheme. Thus, there is a huge gap for mobility support which hampers adaptability and scalability in IoT environment Gubbi et al. (2013). In addition to this, there are other addressing issues in IoT environment which includes IPv6 adaptation, automatic identification, and configuration, participatory sensing, etc. Thus, we require modified mechanisms for addressing the huge number of devices in the Internet of Things.

3.3. Standardization

Another constraint in IoT, especially in smart grid networks, is data collection which demands the need for an architecture which will manage data efficiently. Efficient data aggregation, data dissemination, and data distribution techniques supplemented with an efficient architecture can manage data efficiently. The key aspects of IoT environment are the data transmission and

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connectivity of things that need to be taken care at the protocol level. Machine-to-Machine (M2M) communication is a key enabler for various pervasive IoT applications but there is little standardization done in this regard. There is a need for optimized standard interfaces to be made for M2M communication in order to address interoperability and scalability issues related to IoT Klinpratum et al. (2015)Haroon et al. (2016).

3.4. Implementation of Management Protocols

Diversity is an inherited characteristic of the IoT, therefore, there is a need for common protocols and algorithms to provide a middleware base independent of resources and networking function for the connectivity in different environments among various devices. Currently, the Internet is using TCP protocol for transmission at transport layer which is not feasible for IoT environments due to different constraints of IoT devices.

The existing protocols used in pervasive applications such as Wireless Sensor Networks and Mobile Computing are mostly impractical for the Internet of Things. For example, Geographical Source Routing (GSR) use GPS mechanism causing uncertainty and route fluctuation Elrahim et al. (2010), On-demand routing protocol use flooding method to send data to all possible nodes creating congestion problem Perkins et al. (2001) and other existing routing techniques such as Greedy Perimeter Stateless Routing (GPSR)Karp and Kung (2000), Dynamic MANET on demand Chakeres and Perkins (2008), etc have their own limitations. Thus, developing a reliable routing protocol and algorithms are key challenges in IoT due to its constrained behavior.

3.5. Security Algorithms

One of the main challenges of IoT is to ensure data protection and privacy. Since, the components of IoT are RFID tags, sensors, embedded devices, actuators, etc; therefore, the security risk comes predominantly at the manufacturer level. Further, IoT environment poses a great risk to privacy and security by

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integrating all of the digital data into the worldwide network at the application level. Therefore, there is a need to ensure confidentiality, integrity, and authentication of data at the application level as well. At the protocol design level, communication is considered as one of the important aspects of the IoT devices, therefore, we require standard lightweight protocols for low power, reliable, internet-enabled and secure communication in IoT environments.

Thus, security is one of the main constraints in IoT environments Elmangoush et al. (2013)Kumar and Patel (2014); therefore, there is a need to ensure security along with authentication and data integrity at the manufacturer level, application level, protocol design level.

4. Related Work in Resource Management

IoT has evolved as a popular communication system where Internet connects to the physical world. In most of the pervasive IoT applications, a wide range of IoT devices are deployed but these devices are empowered by embedded devices whose resources are scarce and need to be managed efficiently. Due to the resource constraints and complex deployment characteristics of these systems, there are open challenges at different levels of hardware design and development of communication protocols and algorithms. Considerable work has been done in resource management through protocol design, data aggregation, resource management IoT architectures, resource virtualization, resource allocation; the main goal of all is to have maximum resource utilization and minimum resource costs.

4.1. Resource Management and Data Aggregation Protocols

Since the IoT environment faces many challenges such as dense ad-hoc deployment, dynamic topology, and insufficient resources, therefore, the implementation of a large-scale IoT network becomes difficult. Several studies have been made on protocols towards efficient resource management. Some device management protocols include IPv6 over Low-Power Wireless Personal Area

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Networks (6LoWPAN) Ma and Luo (2014), Message Queuing Telemetry Transport Protocol (MQTT) Hunkeler and Truong (2o08), Constrained Application Protocol (CoAP) Bormann et al. (2012), etc. Other management activities include IETF constrained RESTful environments standardization Shelby (2010), protocol mappings to CoAP that evaluates connectivity on different platforms Bergmann (2012), etc. Several solutions have been put forth by researchers, but these independent solutions add extra complexity to resource-constrained devices.

Data aggregation is widely applied and recognized as an effective technique for resource management in pervasive applications. Several comparative studies are being carried out in this such as data aggregation with respect to optimization of energy, latency, network lifetime and data accuracy Rajagopalan (2006), data aggregation mechanisms concerning data accuracy, network lifetime and latency Sirsikar and Anavatti (2015), data aggregation strategies with respect to delay, redundancy, data elimination and reliability Rahman et al. (2016), etc. However, the work reported so far lacks systematic study and has been done in WSNs only. In addition to this, studies have also been made on hierarchical data aggregation protocols such as Power-Efficient Gathering in Sensor Information Systems (PEGASIS), Low-Energy Adaptive Clustering Hierarchy (LEACH), Hybrid Energy-Efficient Distributed clustering (HEED) , Minimum Energy Communication Network (MECN) , Stable Election Protocol (SEP) , Cross-layer protocol, etc that try to optimize the energy efficiency by the use of optimal cluster head selection, forming chains of nodes, by balancing the load on clusters, etc Rani et al. (2009). The main advantage of these protocols is to enhance the network lifetime but the disadvantage is it requires extra time to form clusters.

Data aggregation techniques are of three categories - tree-based, cluster-based and centralized mechanisms. In tree-based data aggregation mechanisms, nodes in the network are in the form of a tree (hierarchical), where intermediate node performs the aggregation of data. Considerable work includes an energy efficient mechanism for building a high-efficiency index tree supported by ex-

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perimental results Dagar and Mahajan (2013), a network lifetime balanced data aggregation in heterogeneous environments Li et al. (2017), a data aggregation approach that aims to decrease data rate, network traffic and extends system lifetime Koike et al. (2016), etc. In cluster-based data aggregation mechanisms, the entire network is in the form of clusters; in each cluster, a Cluster Head is selected to reduce bandwidth overhead and number of packets to be transmitted. Considerable research has been carried out in cluster-based data aggregation in IoT which includes data aggregation guaranteeing less cost of communication between storage and nodes, and less fault tolerance Liu et al. (2014), a Chinese remainder theorem for data aggregation that reduces traffic load, improves efficiency, although it results in a low accuracy of final data aggregation Xie et al. (2015), a cross-layer data aggregation scheme that reduces traffic load and increases energy efficiency Alkhamisi et al. (2016), etc. In centralized data aggregation mechanisms, data moves from each node to a central node (Header Node) that aggregates data and sends the aggregated data in the form of a single packet. Research has been carried out in distributed service-oriented architecture for IoT applications that address heterogeneity and scalability issues, but the limitations of the work are low availability and single point of failure problem Zhu et al. (2016).

Sufficient research has also been done in data distribution and replication, the main goal being the storage of data for efficient resource management. There are two main approaches for data storage: data-centric storage and fully distributed data storage. In data-centric storage, some distinguished storage nodes are responsible for data collection Albano et al. (2011) and in fully distributed data storage, all nodes contribute equally to sensing and storage Omotayo et al. (2007).

Most of the work in Resource Management Protocols and Data Aggregation has been reported in WSN based applications and lacks comprehensive performance evaluation framework which should encompass simulation, analysis, and experiments. Further, limited work exists in the Internet of Things, as such, efforts are needed in IoT resource management.

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4.2. Resource Management and Routing Approaches

Connectivity between the nodes in pervasive environments such as WSN, IoT, etc. where heterogeneous network systems co-exist is a challenging aspect in the design of the network. The connectivity in IoT environments mainly rely on route-finding from source to sink. Several design aspects such as limited energy constraints, short communication range between geo-located objects, low processing power, limited storage, etc need to be incorporated into the routing protocols of WSN or IoT environments. The simple communication models based on the data flooding dissemination cannot be utilized for pervasive and dynamic behavior of IoT applications such as in healthcare and transportation applications Deb et al. (2003) El Salti et al. (2014). Also the unique challenges imposed due to the resource constrained nature of IoT devices prevent the direct adoption of traditional WSN routing mechanisms in IoT environments.

Routing algorithms are recognized as efficient techniques for resource management especially in IoT energy management. To optimize the energy utilization and balance the network load, efficient routing algorithms should be designed in an IoT environment. As in hierarchical cluster based routing scheme where packet transmission from source to the cluster head is mostly by multi-hop, the energy conservation at sensor node is not much effective Singh et al. (2016). Adaptive routing approach is one of the solutions which selectively launch routes of communication between the heterogeneous IoT nodes to optimize the use of limited available resources Al-Turjman (2017).

Several studies suggest shortest path based routing protocols for IoT environments; the energy consumption decreases due to lesser hop-count but other design factors such as communication link conditions and reliability is not taken into consideration. The Cognitive Energy Efficient Algorithm (CEEA) proposes a topology independent protocol which copes up with randomness nature in IoT networks, although the hop count in CEEA is higher as compared to the shortest path algorithm but the overall network lifetime is improved Al-Turjman (2017).

4.3. Resource Management and Quality of Service

The realization of an IoT framework faces many challenges in terms of Quality of Service (QoS) and resource management. The design of QoS parameters such as delay, bandwidth utilization, power consumption, throughput, cross-layer coupling, multi-media in-network processing, fault-tolerance, resource constraints, etc for real-time heterogeneous IoT networks is a challenging task Abazeed et al. (2013). Various multi-path routing approaches are efficient in terms of packet loss probability and QoS parameters in pervasive environments where the link failures are frequent due to topology changes Aburumman (2017). But several studies have suggested that multi-path routing protocols for IoT and other 5G networks face fault-tolerance problems and demand huge processing and storage, energy consumption, etc. One of the approaches suggests a Two-Tier fault-tolerant routing for resourceful IoT devices and resource constrained IoT devices to manage the energy, network delay and throughput in an IoT system Al-Turjman et al. (2018).

In designing the multi-path routing protocol for Wireless Media Sensor Networks (WMSNs) for efficient management of limited resources under heavy traffic conditions, the complexity of the routing protocol increases while determining the optimal path from source to sink Hasan et al. (2017) Hasan et al. (2017). The multi-path QoS based protocols suggest that analytic load and traffic distribution models can help in determining the complexity of the routing in multimedia data delivery Al-Turjman (2018). Some researchers have recommended the use of heuristic algorithms with geographical routing in real time IoT applications to meet the QoS requirements Hasan et al. (2018). To meet the other QoS parameters such as freshness of data and delay in receiving request data, cognitive caching approach is preferred in Fog based IoT applications in which data popularity, cache size, data publisher load and node connectivity are emphasized Al-Turjman (2017).

4.4. Resource Management and Security Approaches

The IoT devices are the sources of sensory ubiquitous data that is utilized

to provide services at the application level Al-Turjman (2017). The IoT applications have influenced our daily lives and the industry as well. However, the diversity of environment and lack of standards have left the IoT exposed to security and privacy threats Kim (2017). The attacks in IoT networks include link attacks such as eavesdropping, leakage of secret information, data tempering, message contamination, denial of service, etc. To address the complex application security issues such as in smart city, smart networks, etc, the design has to consider not only software intrusion at network level, but also local intrusion at the device level Li et al. (2018).

Data aggregation mechanisms in IoT can incorporate special encryption, decryption algorithms and sharing of keys for malicious node detection. In order to offer better services to users in WSN/IoT, security is an important concern as the data transmission is performed over public network with the following restrictions : sensors are easily rendered to failure, topologies of sensor network change frequently, sensor networks render broadcast over point to point communication, sensor nodes are resource constrained in terms of power, computation and storage He and Wang (2015). The IoT network poses a major challenge in terms of resource management as the IoT devices have limited resources such as limited energy, communication and computational capabilities. Protecting privacy in such IoT environment is a serious issue because resources are limited and the number of attacks are apparently much larger Roman et al. (2011). Although the existing network security technologies provide a basis for privacy and security in IoT, but these techniques cannot be used in a resource constrained IoT framework without modifications Da et al. (2014).

To satisfy the security properties of authentication and key agreement protocol, and to mitigate the computation and communication cost of the system, many lightweight authentication schemes have been proposed Lee et al. (2008) Wang et al. (2015). The secure-CSIP mutual authentication framework proposes an authentication for the IoT based healthcare system with less computational overhead to improve the performance efficiency of the system; it also maintains the natural tradeoff between security level and the added communication over-

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head Al-Turjman F. and Alturjman S. (2018). Also to address the potential challenges in security such as data confidentiality, mutual authentication, session key agreement, user anonymity, etc, seamlessly secure authentication and key agreement framework can be used Al-Turjman et al. (2017).

4.5. Resource Management and IoT Architectures

There has been considerable research in IoT architectures, many of which are designed to manage resources in specific application scenarios and takes into account multiple resources especially energy and bandwidth. Various architectural solutions attempt to use the cloud resources to manage resource-constrained environments, such as OpenIoT project Kim and Lee (2014). Other solutions focus to address the real-time constraints of smart city pervasive applications such as fog based architecture to reduce latency and manage energy Al Faruqueet and Vatanparvar (2016), a resilient IoT architecture for smart cities Abreu et al. (2017), a novel scheme for efficient IoT based on WSN Rani et al. (2015), allocation of Virtual Network Functions (VNFs) or Virtual Machines (VMs) on cloud Wuhib et al. (2015), a remote resource management method for transparent computing Gao et al (2012), a novel resource management based on the technologies of the quick emulator (QEMU) virtualization and mobile agent Xiong et al (2014), etc.

In order to cope with a large number of heterogeneous devices and networking protocols, a number of solutions rely on the use of IoT gateway Emara et al (2009) or several sensing servers that connect with different sensor networks Yoon et al (2009). Although these solutions can meet different application requirements, the hardware cost would be too high as most tasks are completed by different sensing servers rather than gateways.

4.6. Resource Virtualization for Resource Management

Nowadays, resource virtualization has become the current trend to manage resources in most of the pervasive applications. Resource virtualization is carried out to solve the issues of abstracting end device functionality leading

to management of resources in application environments where resources are scarce. Considerable work has been done in various fields of computing such as the Internet of Things, Mobile computing, Wireless Sensor Networks, cloud computing and fog computing.

4.6.1. Internet of Things

Recently, there has been a shift in research towards IoT resource management via resource virtualization. Heterogeneity management, improved storage, better processing, energy management, better bandwidth utilization, etc. are some of the benefits of resource virtualization. In embedded IoT devices, the trend is to introduce virtualized environments at the node level or at the network level. Node level virtualization enables multiple applications to run their tasks concurrently on a single resource-constrained node. Most of the work in IoT virtualization has been done in lightweight virtualization at the hardware level, predominantly in raspberry pi boards. Container-based virtualization is a lightweight virtualization technology that has been used on IoT devices for enhanced IoT cloud service provisioning, fast creation and initiation of virtualized instances, high density of applications, reduced overhead as compared to hypervisor-based virtualization Celesti et al. (2016)Scheepers and Mathijs Jeroen (2014). Work has been done in Docker containers for deploying edge computing platform for enhanced resource management, service management, fault tolerance, deployment and termination of servicesIsmail et al. (2015). Work in light-weight virtualization has also been done to analyze the requirements for efficiently designing IoT gateways, however, the limitation of the work is that it considers only limited number of Raspberry Pi boards for performance evaluation and lacks comprehensive power consumption and energy efficiency evaluations Petrolo et al. (2015). There has been work in container edge cloud PaaS architecture based on Raspberry Pi clusters to develop cost efficiency and low power consumption, but the limitations are lack of empirical study with limited hardware devices for performance evaluation Pahl et al. (2016).

In network-level virtualization, a subset of sensor nodes belonging to a de-

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ployed WSN form a Virtual Sensor Network (VSN) to execute given application tasks at a given time, while other sensor nodes remain available for other application tasks. Radio Access Network (RAN) virtualization has the potential to dynamically provide an isolated network in the Internet of Things Li et al. (2015). Some work has already been done in long-term evolution network virtualization using hypervisor software Li et al. (2012).

4.6.2. Mobile Computing

There has been recent work on resource management in mobile computing and most of the work has been done through virtualization in computation offloading frameworks. Various computational offloading frameworks includes: cloudlet allows virtualization of mobile nodes to have virtualized nodes for execution of all computational work and provides resource-rich aid to mobile computing Yang et al. (2013); Mirror Server uses virtualization technique to create a mirror of the smartphone for offloading the computation Shiraz and Gani (2014); CloneCloud uses virtualization techniques to create a duplicate copy of mobile nodes application on the cloud server and allows offloaded components of an application to run in a virtual manner to reduce workload in smartphones Chun et al. (2011); ThinkAir is a framework that exploits the concept of smartphone virtualization in the cloud to perform offloading of computation Kosta et al. (2012); Cuckoo is a dynamic offloading framework that offloads its computation to any resource running a Java VM and hence enhances performance and reduces battery usage Kemp et al. (2010).

4.6.3. Wireless Sensor Networks

Extensive work has been done on resource management in Wireless Sensor Networks (WSNs) that is envisioned to play a dominant role in the Internet of Things. Resource management has been a key feature in the adoption of virtualization technology in WSNs. Considerable Work has been done on resource-constrained nodes in WSN eliminating the memory limitation, and prolonging battery life by abstracting physical computing resources of WSN environment

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into logical units (Tiny virtual machines) Khan et al. (2015). Software Defined Network (SDN) plays a dominant role in network virtualization especially in the field of WSNs. It aims to simplify the provisioning, management, reconfiguration and control of virtualized networks with reduced deployment cost, scalability, versatility and other resource management benefits Omnes et al. (2015). Work has also been done in IoT virtual networks addressing resource management for both constrained and non-constrained devices Ishaq et al. (2012).

4.6.4. Cloud Computing

Internet of Things is supported by virtual unlimited resources of the cloud to compensate its resource constraints (for example, storage, processing, and energy). Various cloud-based solutions would perform real-time processing on-the-go Dash et al. (2010) to implement scalable, real-time, collaborative, sensor-centric applications Fox et al. (2012), to manage complex events Rao et al. (2012), and to implement task offloading for energy saving Yao et al. (2013). Work has been done on security in billing system but it focuses on the consumption of resources and no attention is paid towards the overall resource management, especially for Cloud of Things Park et al. (2013). Some work has been done in resource allocation using virtualization that allocates resources dynamically as per the application requirements, but no attention is paid towards IoT in their study Zhen et al. (2013).

4.6.5. Fog Computing

The computing ability of IoT devices can be pushed to the network edge by incorporating virtualization at fog level Iorqa et al. (2018). Recently, there has been a shift in attention towards fog resource management. With virtualization in fog computing, fog software platforms get several functions into a single node and enable various virtualized nodes to co-exist on multiple supported hardware targets and resolve resource constrained issues in IoT environments.

Research in Fog virtualization is in its very beginning; therefore, no standard solution is available to manage the resources in Fog computing. Some work has

been done in fog computing architectures Flavio et al. (2012), data protection in fog computing Salvatore et al. (2012), etc; But these studies lack practical implications and does not take resource management into consideration.

4.7. Resource Allocation for Resource Management

There has been recent studies in resource allocation for efficient IoT resource management. Multiple studies have been carried out to solve it, meeting different resource management goals while balancing the resource constraints. Resource allocation is explored in the field of WSNs, but all such algorithms are mainly centered on energy efficiency. Considerable work includes distributed task allocation that reduces overall energy consumption and task execution time in a heterogeneous WSN Pilloni et al. (2014), a distributed algorithm based on particle swarm optimization Shen and Ju (2011), a game-theoretic approach for reduced network lifetime in Wireless Networks, etc.

IoT environments have more heterogeneous characteristics, therefore, even other resources such as residual memory and processing capacity are considered scarce. Most of the existing studies on resource allocation are focused on service provisioning, the aim is to allocate the resources that enable service execution, however, they do not focus on finding the best configuration that corresponds to an optimal resource allocation Guinard et al. (2011)Silverajan and Harju (2009). Limited work is done on finding the optimal resource allocation in IoT applications. As far as the Internet of Things is concerned, resource allocation is still an open issue.

The summary of literature survey is shown in Table 2.

Table 2: Summary of literature survey

Existing work in Resource Management	Related Work	Performance Metrics	Issues	Research Possibilities
Resource Management Protocols	Standard cluster-based protocols in WSNs such as LEACH, PEGASIS, MECN, MECH, etc Rani et al. (2009)	Network Lifetime, Throughput, Latency, Bandwidth	Adds extra complexity to resource-constrained devices	Provides an optimized solution for IoT resource management with modifications
	Internet Protocols such as 6LoWPAN, Constrained Application Protocol (CoAP), MQTT, etc Ma and Luo (2014)Hunkeler and Truong (20o8)Bormann et al. (2012)	Energy, Bandwidth		
Data Aggregation	Tree based data aggregation Dagar and Mahajan (2013) Li et al. (2017) Koike et al. (2016)	Network lifetime, Throughput, Delay	Each parent node in the tree incurs computational overhead in data aggregation from the child nodes	With modifications can manage resources in Internet of Things
	Cluster based data aggregation Liu et al. (2014) Xie et al. (2015) Alkhamisi et al. (2016)	Energy efficiency, Security	Incur high hardware costs as compared to non-cluster based approach	
	Centralized data aggregation Zhu et al. (2016)	Heterogeneity, Scalability	Single point of failure	

Resource Management and Routing Approaches	Data flooding dissemination Approach Deb et al. (2003), Adaptive routing approach Al-Turjman (2017), Cognitive Energy Efficient Algorithm Al-Turjman (2017)	Hop-Count, Energy utilization, Network load	Traditional WSN Routing Algorithms can not be used directly on IoT platforms	Conservation of resources at Node level
Resource Management and Quality of Service	Two-Tier fault-tolerant routing Al-Turjman et al. (2018), Multipath QoS based routing Al-Turjman (2018) Cognitive caching approach Al-Turjman (2017)	Delay, Throughput, Power Consumption, Bandwidth Utilization, etc	Complexity of routing protocols increases while meeting the QoS parameters	Exploration in resource management at device level
Resource Management and Security Approaches	Lightweight authentication schemes Lee et al. (2008), Secure-CSIP mutual authentication framework Al-Turjman F. and Alturjman S. (2018), Seamlessly secure authentication and key agreement framework Al-Turjman et al. (2017)	Communication cost, Computation, Security, etc	Network security techniques cannot be used in IoT framework without modifications	Security at device level in IoT environments

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Resource Management and IoT architectures	IoT architectures for smart cities Abreu et al. (2017), Fog based architectures Al Faruqueet and Vatanparvar (2016)	Energy, Bandwidth, Latency, etc	No standard solutions available	Application based standardization of architectural solutions for overall IoT resource management
	Lightweight virtualization in Internet of Things Celesti et al. (2016)Scheepers and Mathijs Jeroen (2014)	Storage, Processing Time, Battery life	Limited number of devices for performance evaluation, lacks systematic study	IoT virtualization at system level
	Offloading Frameworks based on virtualization Yang et al. (2013) Kosta et al. (2012)	Storage and Processing capabilities	Introduces delay, bandwidth overhead	Exploration of computational offloading in IoT
	Tiny virtual machines in WSNs Khan et al. (2015)	Memory, Battery life, Computational capabilities	Little work done in WSN virtualization at node level	Exploration of Tiny VMs in IoT
Resource Virtualization for Resource Management	Lightweight virtualization in Internet of Things Celesti et al. (2016)Scheepers and Mathijs Jeroen (2014)	Storage, Processing Time, Battery life	Limited number of devices for performance evaluation, lacks systematic study	IoT virtualization at system level
	Offloading Frameworks based on virtualization Yang et al. (2013) Kosta et al. (2012)	Storage and Processing capabilities	Introduces delay, bandwidth overhead	Exploration of computational offloading in IoT
	Tiny virtual machines in WSNs Khan et al. (2015)	Memory, Battery life, Computational capabilities	Little work done in WSN virtualization at node level	Exploration of Tiny VMs in IoT

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	SDNs and network virtualization Omnes et al. (2015)	Energy, computational capabilities, service provisioning, reconfiguration and control of virtualized networks	Limited work in IoT, manages resources at network level	Exploration of SDN in IoT based networks
Resource Virtualization for Resource Management	Real-time processing on-the-go for sensor-centric applications Dash et al. (2010) Fox et al. (2012) Rao et al. (2012)	Better hardware utilization, task offloading for energy savings	Most of the work has been focused on resource allocation at cloud level only	Resource management at IoT device level
	SDN-based Fog computing solutions Flavio et al. (2012) Salvatore et al. (2012)	Delay, Bandwidth utilization, IoT Network lifetime	No standard solution is available to manage resources in Fog	Fog virtualization for IoT resource management
Resource Allocation	Distributed task allocation, resource allocation based on particle swarm optimization, game theoretic approach Pilloni et al. (2014) Shen and Ju (2011)	Resource utilization, Network lifetime	No focus on optimal resource allocation as per application requirements	Resource management and resource allocation is an open issue in IoT

5. Resource Management Architecture for Pervasive IoT Applications

The pervasive Internet of Things put forth new challenges in the research concerning the development of new application services. To support such intelligent applications, IoT facilities the adoption of embedded computing into every day objects and utilizes its resources to process and manage the application workload. Since, application depends upon the device resources for storage, processing, energy and communication, as such, IoT infrastructure exposes its physical and virtual resources as per application demands.

The IoT devices are usually characterized by limited resources (e.g., memory, processing, bandwidth and energy) that can pose many challenges especially for pervasive applications. Thus to manage such constrained environments, an architecture is required that should be capable of managing these scarce resources. Figure 4 shows Resource Management Architecture for Pervasive IoT applications comprising of five layers: four horizontal layers viz., perception layer, transport layer, processing layer and application layer, and one vertical layer viz., resource management layer.

Perception Layer: The various underlying technologies for identification and addressing of physical devices in perception layer include RFID, Ucode (ubiquitous code), EPC (electronic product code), Ipv6, 6LowPAN, etc. Pervasive IoT applications would have the ability to gather immense data via sensors, smartphones, and various embedded devices, but not all gathered data from IoT environment is relevant in a given application context; only a specific set of data is needed to provide a specific service.

Each IoT device would possess a mini-profile consisting of sensed data about the environment and its resources. Thus, a device mini-profile consists of ID, sensed data and resources parameters as shown in figure 5. Each device is characterized by the fields of the mini-profile which makes it similar or different to other devices in IoT ecosystem. This information will help to control how data has to be shared within its cluster groups or outside.
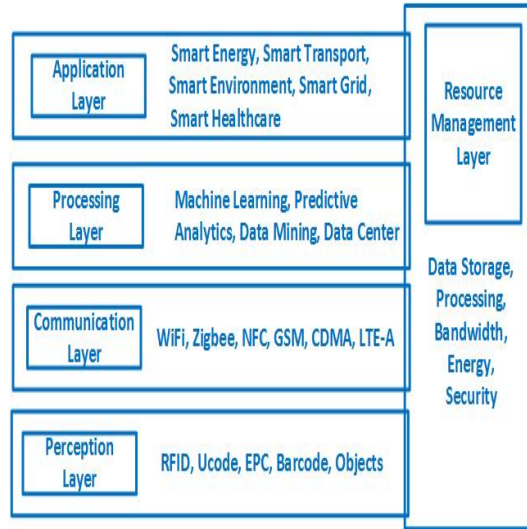
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Figure 4: Resource Management Architecture for Pervasive IoT applications
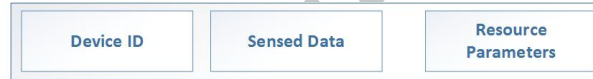
Figure 5: Device Mini-profile

Communication Layer: Pervasive IoT applications require communication technologies to enable interactions among various heterogeneous devices which includes Machine to Machine (M2M), Machine to Person (M2P) and Person to Machine (P2M). The IoT devices use RFID, NFC, WiFi, LTE-A, Bluetooth, etc for such interactions. This layer also takes into account the resource-constrained devices while interacting with other devices.

Processing Layer: Due to the pervasive nature of most of the IoT applications, a gigantic amount of data is being generated from the IoT devices. Processing layer uses necessary machine learning, predictive analysis or data aggregation or data mining algorithms on edge or cloud platforms to process such enormous volumes of data against resource constrained IoT devices.

Instead of working with mere data, this layer works with device mini-profiles and combines them into device profile reflecting more information. For example,

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individual body sensors in body area networks generates individual mini-profiles, aggregated together to form a device profile, reflecting the health data of a particular patient. Moreover, the device profiles can merge to create a patient community yielding more valuable information about the status of the patients in the entire city e.g., patients with same medical profiles, etc. This layer takes into consideration the design and resource constraints of IoT devices while processing huge amount of data in pervasive IoT.

Application Layer: IoT provides a plethora of pervasive applications such as smart healthcare, smart transport, smart environment, smart home, etc that offers a great market for business and provides services to the end users e.g., medicine recommendations and other feedback, etc.

Resource Management Layer: One of the most important layers is the resource management layer which is orthogonal to the above four layers and is responsible for all the activities related to the resource management of the system. This layer takes into consideration the limited resources of IoT devices while sensing, communicating, aggregating, processing and providing services to the users at the application level. It is deployed as protocols and algorithms among different hardware components of the IoT system to provide automatic provisioning of resources as per application requirements.

Discovering resources, estimating resources, allocating resources and monitoring resources are the fundamental activities of this layer, resource allocation being the main activity among all. The goal of resource allocation is to properly accommodate the workload of all the applications currently using the IoT system by allocating the required virtual or physical resources so that it meets the Quality of Service requirements. The main challenge in these resource-constrained IoT systems is an automatic allocation of resources to optimize their use, especially in the pervasive environment.

Therefore, special attention is needed in identifying the specific requirements for every application so that different parameters can be exposed to get tuned for optimization purposes during resource allocations. Data management, virtualization of resources and automatic allocation of resources can be fruitful to

use for resource management in pervasive IoT applications.

5.1. Pervasive IoT Healthcare

The number of IoT devices installed by 2020 are estimated to the tune of 25 billion in different applications. The size of the global IoT industry is estimated to reach 7 trillion US dollars in the market. The growth will be concentrated in four key markets : Connected Home, Healthcare, Cloud-enabled robotics and global aerial drone market. Among the four, the IoT healthcare market is estimated to grow by 94.5 billion dollars in 2020. According to the gartner report, there will be an increase in 18.4% wearable devices, out of which 42% will constitute the medical IoT devices Liu et al. (2017).

The use of Internet of Things in healthcare is still in infancy. Several systems have been developed in healthcare for remote patient monitoring. Emergency healthcare is one of the promising area where the medical IoT can be applied Baker et al. (2017). Remote monitoring can be used for non-critical patients at home rather than in hospital, this will optimize the use of hospital resources.

With the advance of sensor and wireless technologies, there has been penetration of IoT devices in many pervasive health applications. One of the applications is the Body Area Networks which monitors the patients using small wearable IoT devices. Several sensor based wireless systems have been developed which can be used in Body Area Networks (BANs) for patient monitoring e.g., ECG, EEG, Accelerometer, Gyroscope, EMG, Fingertip Pulse Oximeter, Blood Pressure, Body Humidity, Respiration, Inertial Measurement Unit, Temperature IoT deviceS, etc. These devices used in BAN are usually smaller in size as compared to IoT devices used in other applications. The tiny size of these devices put more constraints on resources such as storage, processing and energy as shown in Figure 6.

Since the devices in BAN are mostly wireless and battery-operated (non-rechargeable),therefore smaller the size of a BAN device, lesser the device life
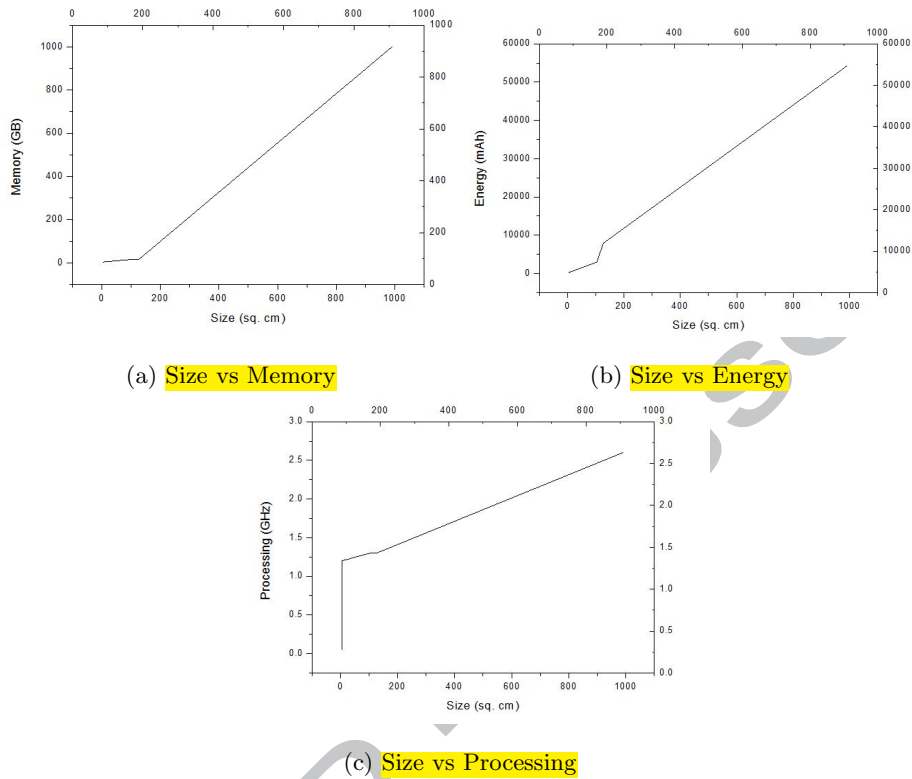
(a) Size vs Memory

(b) Size vs Energy

(c) Size vs Processing

Figure 6: Size vs Resources in IoT

as shown in Figure 7. To improve the lifetime of the devices in BAN, the management of resources such memory, processing and bandwidth is necessary so as to reduce the energy consumption.

Use case : Body Area Networks (BAN)

Consider a scenario where a patient wears sensing devices that relay medical data to a personal wireless device, thus forming a body area network (BAN). The personal wireless device collects and integrates patient's personal medical data from the body sensors and then transmits the data to the back-end of the network for related diagnostics. The sensing, processing and communication of data in Body Area Network incurs workload such as sense, process and
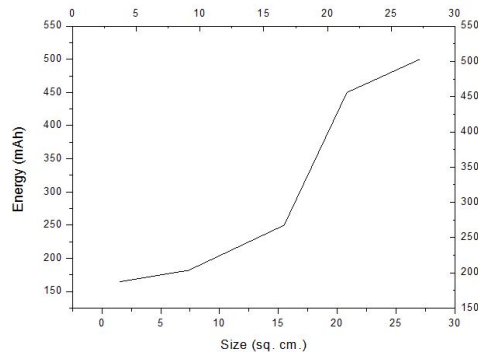
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Figure 7: Size vs Energy in BAN devices

transmission of different body parameters (e.g., heart rate,temperature, blood pressure, etc). This workload can be interpreted as the amount of resources needed to accomplish the specific application tasks.

Assumptions: Let $S_i(1 <= i <= n)$ be the set of dedicated body sensor nodes (IoT devices in our use case) and D be the personal device (edge device in our use case).

A patient (P_1) have a dedicated set of IoT devices $S_1,S_2,S_3,...$,S_n that will transfer data to the edge device(D). The information flow from the IoT devices to edge device is shown in figure 8. These IoT devices (S_1, S_2, S_3, ... , S_n) and edge device (D) will have unique IDs (S_{id1},S_{id2},S_{id3},...,S_{idn} and D_{id} respectively) to ensure secure and dedicated communication in BAN applications. Each sensor in set S_i generates data items (d_i) that forms the mini-profiles (p_i). These min-profiles constitutes the patient profile (P_{p1}) consisting of medical data about the patient. Therefore, each sensor will generate data leading to the creation of min-profiles, represented as:

$$S_i \to d_i \to p_i \text{ where } 1 <= i <= n$$

At the system level, the mappings are given as:

$$\{S_1,S_2,S_3,...,S_n\} \to \{d_1,d_2,d_3,...,d_n\}$$
$$\to \{p_1,p_2,p_3,...,p_n\} = (P_{p1})$$

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The workload of BAN application encompasses memory, processing load, use of energy and network bandwidth. Thus, it is necessary to monitor these resources for efficient resource allocation that leads to better management of resources. Mini-profiles $(R_1, R_2, R_3, ..., R_n)$ are created to monitor the status of resources such as energy $(E_1, E_2, E_3, ..., E_n)$, bandwidth $(B_1, B_2, B_3, ..., B_n)$, processing$(P_{r1}, P_{r2}, P_{r3}, ..., P_{rn})$ and memory $(M_1, M_2, M_3, ..., M_n)$ for IoT devices $(S_1, S_2, S_3, ..., S_n)$ respectively.
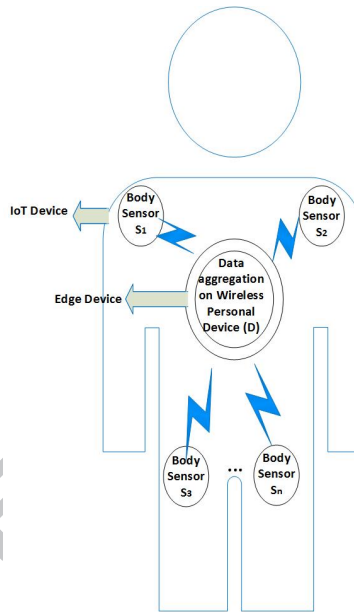

Figure 8: Information flow from IoT devices to Edge device in Body Area Network

Thus for a patient,each body sensor have a min-profile about resources reflecting the status of energy, bandwidth, memory and processing, represented as:

For Sensor S_i,

$$R_i = \{E_i, P_{ri}, M_i, B_i | 1 <= i <= n\}$$

At the system level, the resource parameters of BAN can be represented as:

Total energy (E_{P1}) of all IoT devices of patient, P_1 is given as:

$$\mathrm{E}_{P1} = \sum_{i=1}^{n} \mathrm{E}_i$$

Total processing power (P_{P1}) of IoT devices of patient, P_1 is given as:

$$\mathrm{P}_{P1} = \sum_{i=1}^{n} \mathrm{P}_{ri}$$

Total bandwidth (B_{P1}) of IoT devices of patient, P_1 is given as:

$$\mathrm{B}_{P1} = \sum_{i=1}^{n} \mathrm{B}_i$$

Total memory (M_{P1}) of IoT devices of patient, P_1 is given as:

$$\mathrm{M}_{P1} = \sum_{i=1}^{n} \mathrm{M}_i$$

The total resources (R_{P1}) of all body sensor nodes for a patient, P_1 in a BAN can be represented as:

$$\mathrm{R}_{P1} = \{\ \mathrm{E}_{P1},\ \mathrm{E}_{P1},\ \mathrm{B}_{P1},\ \mathrm{M}_{P1}\ \}$$

Figure 9 gives the abstract view of data gathered about the health of a particular patient and resources of body sensors used in Body Area Network.

The sensed data is communicated to the edge device which integrates, processes and stores the data locally. Lightweight algorithms and protocols are used for communication and storage to manage resources at the device level as well at the system level. The data can also be transmitted to the back-end of the network for related diagnostics to provide services to the patient at the application level.

Running parallel to the sensing, communication and processing activities is the resource management module that discover, identifies and allocates the available resources for maximum resource utilization in terms of storage, processing, bandwidth and energy usage. Initially, each resource will have maximum value. For example, for sensor S_i, the values of resources are:

$$\mathrm{E}_i = \mathrm{W}_i;\ \mathrm{P}_{ri} = \mathrm{X}_i;$$
$$\mathrm{M}_i = \mathrm{Y}_i;\ \mathrm{B}_i = \mathrm{Z}_i;$$
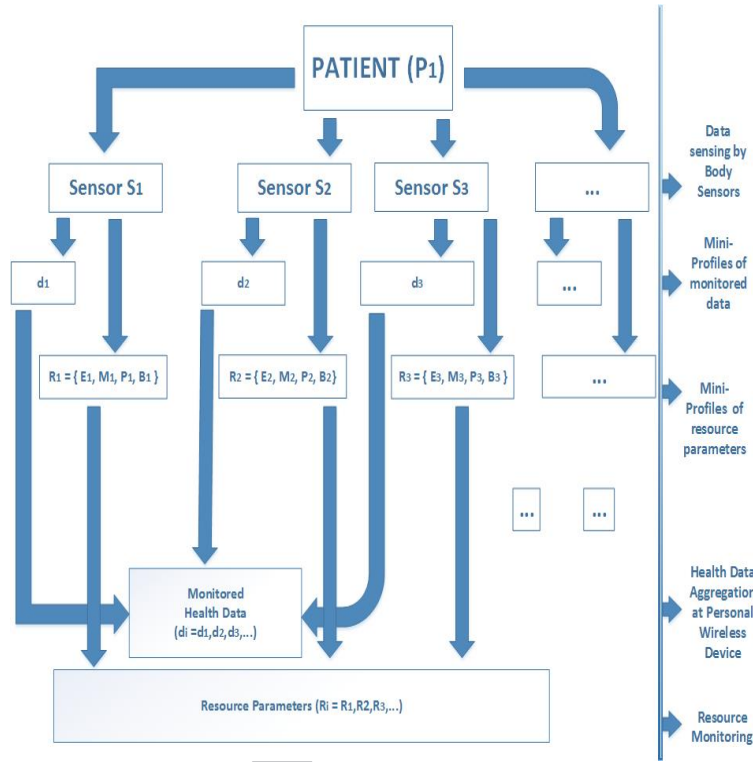$$\text{where } 1 <= i <= n$$

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Figure 9: Abstract view of information in Body Area Networks

where W_i, X_i, Y_i, Z_i represents the maximum value for respective resources.

Given a set of application tasks and the set of resources, resource allocation aims to allocate these resources to complete these tasks under some predefined conditions. Once the workload is accommodated by proper allocation of physical and virtual resources of a sensor S_i, the value of resources for the sensor S_i will become:

$$E_i = W_i \text{ - } w_i; P_{ri} = X_i \text{ - } x_i;$$
$$M_i = Y_i \text{ - } y_i; B_i = Z_i \text{ - } z_i;$$
$$\text{where } 1 <= i <= n$$

where w_i, x_i, y_i, z_i represents the consumed values for respective resources.

This resource monitoring will keep track of allocated resources, non-utilized and available resources so that the system will be able to reclaim such non-

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utilized resources, returning them to the pool of available resources. The data obtained through the monitoring activity estimates the number of resources to be used for successful completion of the application.

Considering the constraints at the node, network, and application level, it is clear that resource allocation is an optimization problem which aims to maximize the avaialiability of resources of IoT devices such as energy, processing, memory and bandwidth.

At the node level, it can be modeled as:

$$\text{Maximize } E_i P_{ri} M_i B_i$$

Subject to constraints

$$E_i <= W_i; \qquad P_{ri} <= X_i;$$
$$M_i <= Y_i; \qquad B_i <= Z_i;$$

At the system level, it can be modeled as:

$$\text{Maximize } \sum_{i=1}^{n} E_i \sum_{i=1}^{n} P_{ri} \ \sum_{i=1}^{n} M_i \sum_{i=1}^{n} B_i$$

Subject to constraints

$$\sum_{i=1}^{n} E_i <= \sum_{i=1}^{n} W_i; \qquad \sum_{i=1}^{n} P_{ri} <= \sum_{i=1}^{n} X_i;$$
$$\sum_{i=1}^{n} M_i <= \sum_{i=1}^{n} Y_i; \qquad \sum_{i=1}^{n} B_i <= \sum_{i=1}^{n} Z_i;$$

Thus, the aim of resource allocation will be managing resources, which will help in efficient management of resources as per application requirements. And the data related to patient's health and resource parameters both play an important role in resource management, which implies resources can be managed through the management of data.

The body area network can be extended to community level as shown in Figure 10. In a city, BAN patients push the data from their wireless personal device (edge devices) to the local cloud (fog), where further processing of data can be done. A number of big data tools and techniques can be employed at the fog level to provide services to the patient community. This can result in the creation of BAN grids, favorable in smart city pervasive IoT applications.
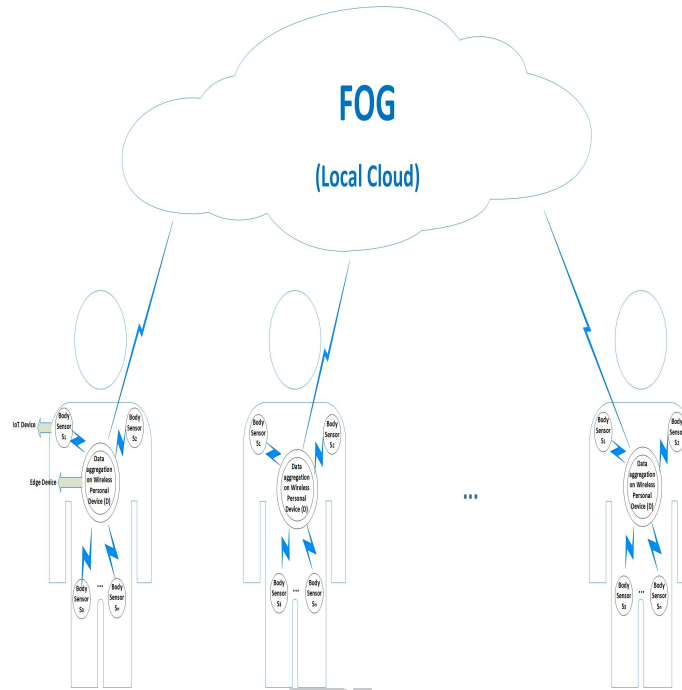
Figure 10: Patient Community

6. Open Challenges in IoT Resource Management

Most of the IoT applications are pervasive, so the collection of data, initiation, and execution of services, etc are possible with minimum human intervention. However, the devices/things in IoT are resources constrained, as such the main tradeoff is to have automated applications against limited resources. Resource management handles the workload of pervasive applications by the optimized allocation of physical and virtual resources but it encounters a number of hurdles as discussed below:

- Heterogeneity Management: Pervasive IoT environment is a very complicated heterogeneous network platform which enhances the complexity of various types of devices using various communication technologies. Management of heterogeneity at the architectural level and protocol level are major challenges in resource management of pervasive IoT.

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- Communication and Connectivity: IoT environments are constrained in terms of communication and connectivity. As the number of devices increases, the probability of the number of transmissions and receptions (communication) increases which in turn demands more connectivity. Thus, limited communication and connectivity are major challenges in resource management.

- Computational Power: IoT devices have limited computational capabilities such as limited processing power and storage; therefore, processing and storing the voluminous data generated in pervasive IoT becomes a challenge in resource management.

- Energy Management: IoT devices are limited in power, so deploying these devices for a very long time becomes the main hurdle in resource management. Further, power efficient and low power consumption hardware, sleep modes, etc are critical design elements in resource management.

- Device Management: Number of IoT devices is an important aspect in pervasive applications. As the number of devices increases in a network, a unified information infrastructure is required to manage them in such environments. In addition, identifying, naming, and addressing the IoT devices becomes main challenges in resource management.

- Data Management: The pervasive IoT produces data of different type, size, and formation. Handling such complex data is a major challenge in IoT resource management.

- Resource Allocation: Resource management handles the workload by resource allocation. But having optimal resource allocation as per application requirements is a major challenge in resource management.

7. Conclusions

The basic functions of an IoT device includes sensing and data aggregation, processing, storage and communication of data from the physical world to the

virtual environment. For a particular application, a huge number of IoT devices are used especially in pervasive and unattended IoT applications. The pervasive IoT environments pose multiple challenges due to the resource limitations. To address the issues arising out of the resource constraints, adequate architecture is needed that permits easy connectivity and control. Considerable research has been carried out at the device level, but lack of standardization still prevails.

Virtualization is one of the promising techniques which will help to optimize the available limited resources in an IoT environment. In order to optimize the resources utilization, resource allocation can play an important role in terms of distributed task allocation and work offload. Fog computing can also improve the resource management in pervasive IoT environment by local data aggregation minimizing latency, Bandwidth utilization, etc.

As the number of applications is increasing, more focus has to be on the resource management with main attention on data management. Various aspects such as what to store (data size), how to store (data structure) and how to communicate the data (number of transmissions/receptions) will directly impact the management of resources in IoT environment. From the above discussions, we conclude that to optimize the use of available resources, data management and efficient resource allocation shall play a key role in pervasive IoT environments.

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