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Reviewing the Effectiveness of Energy Efficiency Approaches in Cyber Physical System

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Abstract:
Adoption of Cyber-Physical System is inevitable in upcoming times owing to its potential coverage of various physical devices operated by computational algorithms. However, constructing a robust application structure for dynamically supporting the uncertain network is a big challenge to Cyber-Physical System. Out of various forms of inherent problems associated with proper operation of physical devices in such system, one of the biggest impediments towards this can be stated as an energy efficiency problem as the physical devices are basically a low-powered and limited resources sensors and actuators. Therefore, this manuscript discusses about the existing trends of the solution presented in current era in order to address the energy efficiency problem in Cyber-Physical System. The paper has discussed about the various schemes with respect to their strength and flaws that assists in forming up the open research issues required to solve the energy efficiency problem in Cyber-Physical System.

Keywords:*Cyber-Physical System, Energy Efficieny, Internet-of-Things, Physical Device, Constraint*

I. INTRODUCTION

The proliferation of Cyber-Physical System (CPS) is increasing significantly owing to its advantageous features over various machine-to-machine communication system [1][2]. Basically, CPS is formed by joint integration of communication, computation, and controlling approaches [3]. It also acts like a backbone structure for offering higher degree of robustness, stability, and reliability in order to perform communication among varied physical devices. The core goal of using CPS is to incorporate higher scope of operation, interaction among multiple physical devices [4]. With the revolutionary usage of the various nano and micro technologies over the world of fabrication, it is now feasible to develop industry-based application for CPS [5]. Apart from this, advances of software technology enables incorporation of various high levels of abstraction as well as software engineering in order to revolutionize the design of the CPS architecture [6]. However, it should be noted that the basic physical devices used in CPS are mainly actuators, sensors, and processor which is characterized by extremely limited capabilities in terms of operationality [7]. Therefore, it is imperative that it is not feasible for constructing a high end software programs in order to offer advance inbuilt applications. All these sensors have low end memory as well as computational capability and hence they are dependent on higher degree of energy in order to keep them functional [8]. At present, there is various energy efficient as well as energy aware protocols existing in the sensory application that has both advantageous features as well as design flaws [9]. It is due to this reason, that still offering energy efficiency in CPS is quite a challenging situation. Devices that are characterized by the mobility of the user in CPS is highly demanded in existing system as they offer resources

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with significant computational capabilities, supports multiple techniques of communication (e.g. Bluetooth, IEEE standards, 4G, etc). A typical design of CPS consists of 5 discrete layers viz. i) smart connectivity layer, ii) transformation of data-to-information layer, iii) cyber layer, iv) cognition layer, and v) configuration layer. Unfortunately, the hypothetical concept of designing CPS highly differs from existing design practices. Apart from this, the standard concept of CPS always involves combined interaction with the physical devices in presence of a dedicated network and not by using a single physical device. This idea is very much similar to the joint implementation of sensory concept with the robotics along with incorporation of the intelligence. At present, the applicability of the this concept of CPS can be seen in robotic surgery that demands higher precision, avoidance of collision where intervention is anticipated, exploration of human-reachable area that demands sustainability, traffic controlling where coordination is demanded, management of energy in smart building where efficiency is required.

Apart from this, there are various other challenges in CPS with respect to architecture-abstraction, foundation of network and computing, controlling hybrid system, etc. However, energy is the prime challenges out of all these issues in CPS and therefore, this research paper discusses about the recent and most significant approaches towards energy efficiency in CPS. The organization of the paper is as follows: Section II discusses about the essential information about CPS followed by highlights of the energy problems in CPS in Section III. Section-IV discusses about the existing research approaches with respect to the energy efficiency based approaches over CPS and Internet-of-Things. Section-V discusses about the existing research trends while section-VI highlights about the open research issues while Section VII discusses about the conclusive remarks of the proposed review work towards energy efficiency in CPS.

II. Cyber-Physical System

Cyber-Physical System (CPS) has been evolved up owing to joint operation of physical process, networking concept, and sophisticated computational process. Normally, the controlling of the CPS is carried out using computational-based algorithmic process [10]. At present, there are various wide ranges of applications of CPS viz. medical monitoring, smart grid, robotics, autonomous automobile system, automatic pilot avionics, etc. All these applications are developed by combining mechatronics, design science, and cybernetics [11]. In this aspect, the process control is considered to play a significant role that is also known as embedded system and design where the focus in mainly over computational modeling. It is also essential to know that although there are lots of degrees of equivalence between CPS with Internet-of-Things (IoT) but there have various significant differences [12]. One interesting line of difference is that – the concept of IoT may use CPS devices; however, it is unlikely that all CPS devices should be part of IoT, this is absolutely not necessary at all. Another distinction point is that IoT is more connected to services integration along with physical objects; however, CPS is more inclined towards physical objects [13]. Figure 1 highlights the concept map of CPS applications, where it can be seen that it mainly emphasizes on management of scalability and complexity towards its design methodology while there are various scope of application associated with transportation, military, healthcare, energy, consumer, communication, physical security, etc [14]. Another observation to be made is also that networking over feedback system in CPS is mainly carried out via actuation and wireless system [15]. Sensors are also one of the essential components of majority of CPS application in upcoming times [16]. However, bigger problem is to develop an effective CPS module as it has inclusion of extensive fluctuation of diversified practices connected with different streams of engineering.

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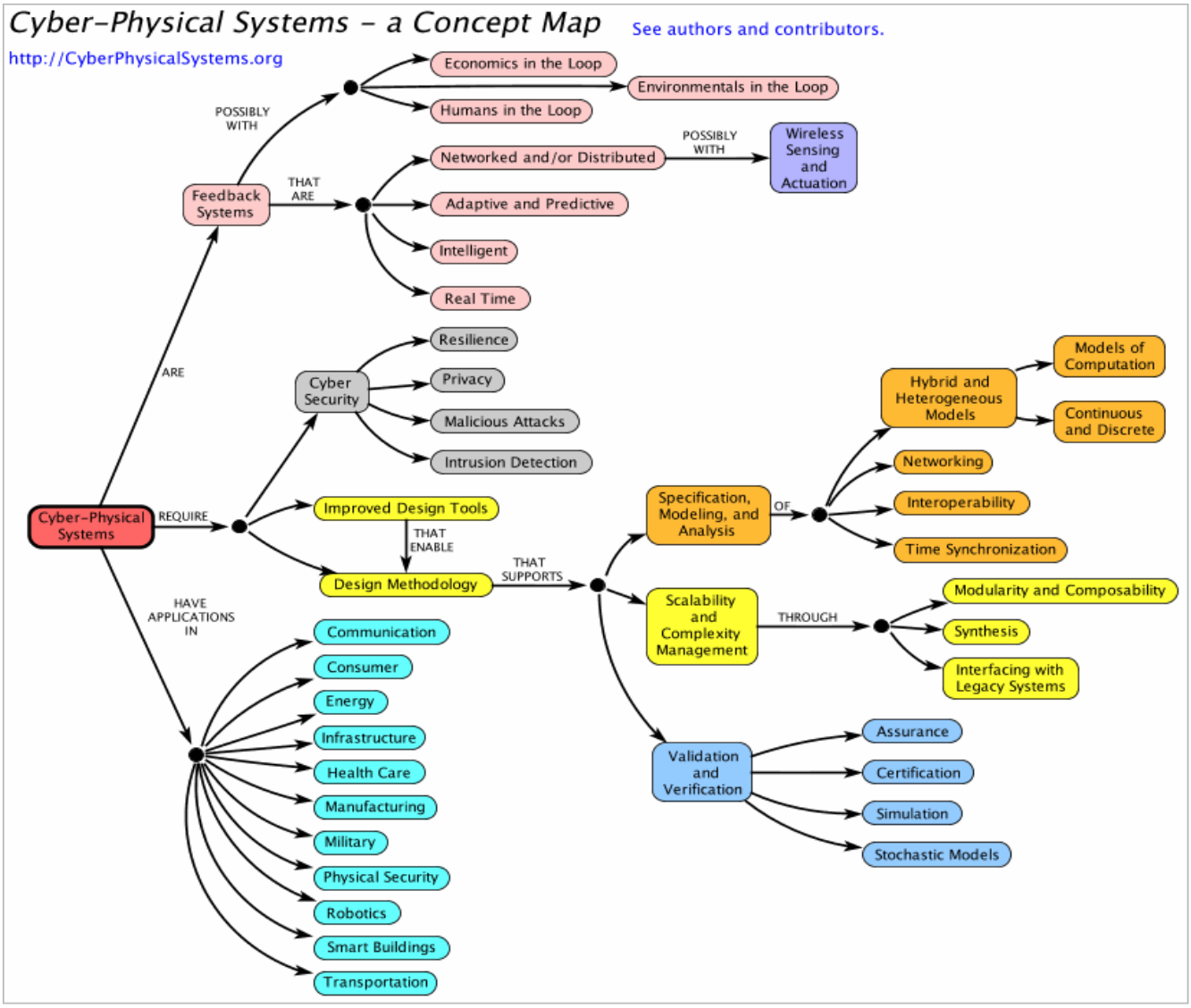

Figure 1 Cyber-Physical System

III. Energy Problems In Cps

Energy is one of the biggest concern in the offering the functionalities of CPS application and hence the consideration of renewable resources is one of the best option [17]. However, such forms of resources are required to be integrated with the conventional energy system in CPS for seamless energy service dissipation towards the chain of application. The prime agenda of energy efficiency in CPS is basically to control the lines of transmission, manage different demands associated with generation units of energy, promote non-conventional sources of energy, etc [18]. The problems associated with charging phenomenon of storage units can be solved using optimization problems considering various forms of real-life constraint formulation. However, as CPS includes various inclusion of energy-constrained nodes in high numbers; therefore, it is evident than a robust energy efficiency technique is required to run such massive number of nodes in a network. It is also essential to understand that a specialized electric grid is used for running such devices for monitoring and controlling purpose. Such electric power grid system is conceptualized to offer fault tolerant services for all the devices within under it. Basically, conceptual electrical grid for CPS possesses different components e.g. physical layer, actuator and sensor layer, controls of distributed local system, information and knowledge, supervisory sub-control, and higher optimal control system [19]. Fig.2 represents the

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components involved in electric power grid system used in CPS application from conceptual viewpoint.

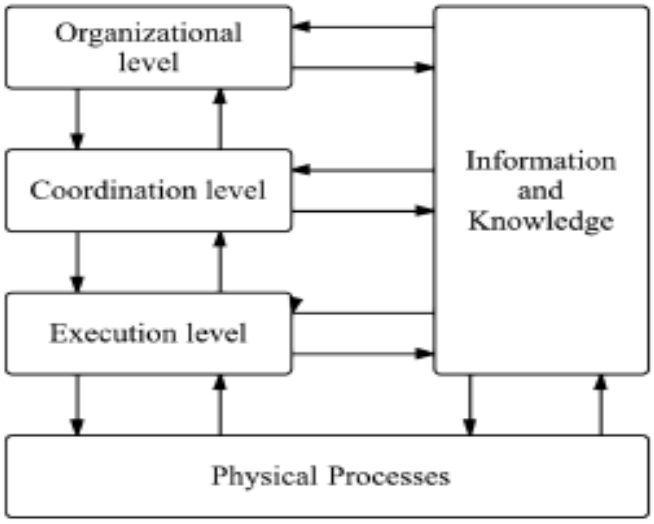

Figure 2 Essential Components of CPS Power Grids

It is to be noted that so called devices in CPS are essentially sensors and actuators that works solely on the standard design (Fig.2) with respect to its execution process followed by an effective coordination process as well as with specific level of organization. However, one of the biggest challenges in this perspective is that this conceptualized standard yet misses the routing phenomenon involved in data transmission in CPS owing to higher inclusion of uncertainty involved in controlling processes of devices. Apart from this, the realization of the control process is carried out extensively as well as scaling operating is also carried out using different forms of mobile networks connecting actuators and sensors in CPS. Another reason of extensive energy usage is that adoption of SCADA in CPS application demands its connectivity with World Wide Web that can cause extensive occurances of transmission thereby demanding more power. It is because SCADA applications uses extensive computational resources as well as it also demands separate application to run its user interfaces on different terminals causing device-based energy consumption. This problem of conventional energy drainage is addressed by using smart grid system [20] it is because conventional energy grid system of CPS is one-directional while that for smart grid system is highly decentralized. The best part of utilization of the smart grid system in CPS is that it is capable of scaling through the completely available networking aspect with each other along with consideration of various inclusions of system dynamics. As per the work of Macana et al. [21], the energy problems associated with the CPS are basically solved by following approach – i) energy control system [22], ii) management of energy resource [23], iii) energy efficiency [24],and iv) developing frameworks for energy system [25]. However, more or less all the work is connected to energy efficiency mainly. The existing approaches of managing energy factor mainly concentrates about minimizing cost of energy, control emission of carbon, maintain sustainability of device, etc [26]. All these approaches also involves tracking of the remnant energy using software where energy dissipated is read from the sensors, meters, etc. These categories of work are associated with the energy evaluation using scheduled metering scheme. However, still there is ambiguity in the measurement system of energy factor using metering system as there are various uncertain attributes included in the evaluation process. Such work doesn't consider the cost factor connected with measuring devices. At the same time, inclusion of different equipments connected to networking also offers security challenges as well as cost [27]. One interesting finding was done in existing system, where cost factor connected with sensory operation is found to be directly contributing in constructing the optimal metering system [28]. However, there was no work to prove this hypothesis till date about these theoretical claims.

In the wired communication of CPS, the usage of Ethernet is inevitable while there are various protocols used in wireless devices in CPS. There is a need of high-end radio technology for futuristic CPS application as they are mainly developed for supporting machine-to-machine communication [29]. The prime objective is to provide service reliability along with capability to support real-time

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dynamics of smart sensors [30]. In this perspective radio network of IoT is claimed to use low powered networking system that bridges the communication problems over higher transmission ranges with lower energy consumption (e.g. Z-wave, 6LoWPAN, Bluetooth, Zigbee, Wi-Fi, etc) [31]. However, all these standards are also associated with the inherent problems leading to disruptive routing in CPS thereby resulting in drop of communication performance. At the same time, the routing scheme associated with energy efficiency is not much to be found in existing scheme which is more inclined towards device-based energy saving approach. The next section discusses about the work being carried out in existing approaches towards energy efficiency.

IV. EXISTING APPROACH

At present, there are various works being carried out towards dealing with energy efficiency of CPS. After reviewing the existing approaches, it is found that existing studies are mainly classified into two types that are mainly focused on CPS and its integral part i.e. IoT. This section outlines the discussion being carried out in this regards:

A. Studies towards energy efficiency of CPS

Most recently, scheduling-based approach was used for controlling energy consumption considering the dynamic aspect of it. The work carried out by Feng et al. [32] have used such approach considering the case study of manufacturing process involved in CPS. A genetic algorithm was used for obtaining the best schedule for energy efficiency. Existing study also explored that a better form of energy management system could also contribute towards energy efficiency in CPS. A review carried out by Guo et al. [33] claimed of tight coupling problems between the communication channel and power network in CPS leading to threats in its operation process (Fig.2). Therefore, a dynamic optimization process of routing over trustworthy communication channel is considered in this work using empirical approach. The investigation showed that presented routing operation leads to resist any form of routing overlapping, prevent directing through error-prone channel, and control routing hops. Unfortunately, the complete scheme is highly device-specific and doesn't emphasize on re-building communication performance over CPS.

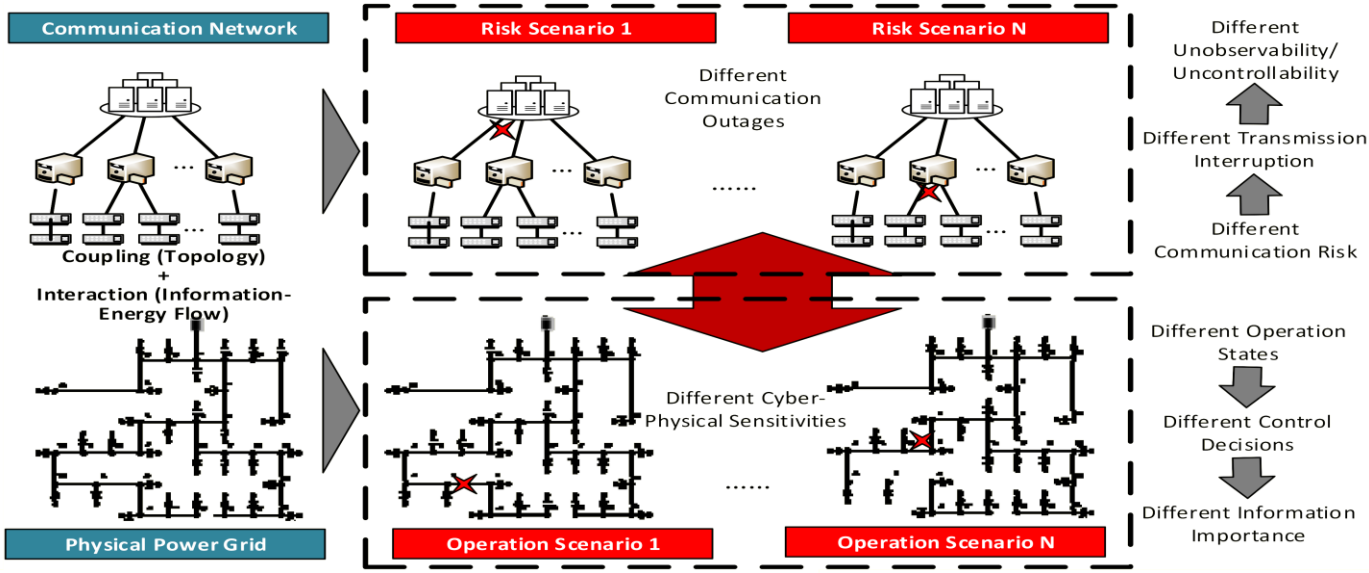

Figure 2 Communication over energy management system (Guo et al.[33])

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Distributed controlling of the energy factor over the smart grid is another point of concern for retaining maximum energy efficiency in CPS. The prime reason is the constraint factor related to it and this issue is addressed by Korukonda et al. [34] where *multiple attributes of constraints* have been considered from networking viewpoint in connection with the design methodology of sensor controller. This approach was claimed to address different forms of fluctuations that could possible take place over physical domain mainly and doesn't consider many essential resources required to be allocated. Study towards connecting *resource allocation* with energy efficiency has been carried out by Li et al. [35]. The authors have considered CPS with IoT services considering industrial application running over 5G networks. The authors have developed a *communication model* for boosting the performing of the central controller system. This model is used for construction transmission link between actuator and multiple sensors considering *resource allocation*, where resources are mainly power and channel. The technique has used game theory as well as *Hungarian model* that are highly iterative in its nature. The study claims of minimizing computationally complexity along with energy efficiency. Apart from this, security is another factor that is also linked with the energy efficiency in CPS. According to the most recent work of Li et al. [36], auditing the energy consumption could not only assists in energy efficiency but also assists in monitoring the security flaws. The authors have used the *deep learning* approach that is capable of understand the state dynamics of the system in order to track the security flaws. Existing studies also discusses about the usage of the context-based adaptive approach in order to conserve energy of components connected with CPS. The work carried out by Lu et al.[37] have used baseline techniques used in IoT using *contextual* factor for energy saving using game theory. According to the study, all the devices of IoT were represented in the form of reconfigurable agents. Therefore, *agent-based approach* is used for energy saving and similar cadre of research was also carried out by Rahman et al. [38]. The researcher has connected agents for identifying the risk towards security factor over the power grids in CPS. The design of agent consists of capturing the information of attacks with respect to power system; however, the work discrete doesn't emphasize about the energy saving. Study towards energy management has been carried out by Wang et al. [39] where the focus of the study was mainly towards using hybrid storage system for energy for operating a vehicle. The study shows that a simplified optimization approach could result in better cost reduction of the storage system. Another interesting part of this study is that it uses *predictive modeling* for energy management. Focus on reliability problems in energy management of CPS is carried out by Xie et al. [40] where *dynamic voltage and scaling of frequency* is used. The study outcome is found to offer minimized time of response as well as offers reliability over constraint factor of time. Study towards data propagation in CPS is carried out by Xin et al. [41] where the agenda is basically to analyze the sensitivity of energy. Using IEEE-14 node configuration, the author have developed a partition-based approach as well as equivalence method considering non-linearity issue over smart grids. Approaches using optimization is also evidenced in work of Zeng et al.[42] where *bio-inspired algorithm* has been used for offering better form of stabilization of energy towards CPS system over a large network. Zhan et al. [43] has used error correction process for energy efficiency while Zhou et al. [44] have used resource allocation scheme for energy efficiency on CPS. Table 1 summarizes the existing study approaches towards CPS energy efficiency.

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Table 1 Summary of Work Carried out for Energy Efficiency in CPS

Authors	Problems	Technique	Advantage	Limitation
Feng et al. [32]	Energy conservation of manufacturing process	Dynamic scheduling	9.35% of energy saving	Application specific, no benchmarking
Guo et al. [33]	Tight coupling	Routing optimization	Benefits routing	Doesn't address communication-based issues
Korukonda et al. [34]	Variation in energy system of CPS	Constraint-based controller design	Effective stabilization of bus voltage	Device-specific solution
Li et al. [35]	Resource allocation	Game theory, Hungarian method	Extensively benchmarked	Highly iterative
Li et al. [36]	Energy, security	Deep learning	Effective energy prediction	No benchmarking, attacks generalized
Lu et al.[37]	Energy saving	Context, game theory, reconfigurable agent	16.21% of energy saving	Computational complexity evaluation for device w.r.t. network is missing
Rahman et al. [38].	Security over power system	Multi-agent	Fault tolerant	Doesn't emphasize on power saving
Wang et al. [39]	Energy management of vehicle	Predictive modeling	Cost reduction of energy storage	Accuracy not benchmarked
Xie et al. [40]	Improving reliability	Dynamic voltage and frequency scaling	16.66% improved reliability	Doesn't emphasize over energy saving
Xin et al. [41]	Data propagation in CPS	Graph partition, equivalence method	Extensive analysis capability of power	Doesn't emphasize over energy saving
Zeng et al.[42]	Cascading failures in CPS	Swarm intelligence	Effective topology control	Doesn't emphasize over energy saving
Zhan et al. [43]	Energy consumption in CPS	Error Correction	Support heavy data transmission	No energy modeling
Zhou et al. [44]	Energy efficiency	resource allocation, Channel state information	Controlled power consumption	Network factor not considered

B. Studies towards energy efficiency of IoT

From the prior section, various new approaches towards energy efficiency concerning to CPS has been briefed. However, there is certain discrete section of literature that has emphasized on energy efficiency of IoT which is also a jointly studied by various researchers. Moreover, IoT is also an integral part of the CPS system irrespective of its differences with CPS. It is known that majority of the IoT applications are built over Wireless Sensor Network (WSN) and there are various studies being carried out toward energy efficiency in it. The most recent work of Behera et al. [45] has presented a *clustering* mechanism that is responsible for energy efficiency for the sensors when deployed in an IoT environment. The study presents a discussion of selection process of the best clusterhead that could contribute to energy efficiency. The outcome showed that it offers 66% of energy saving. Existing study has also connected routing with energy saving in WSN in IoT environment. The approach presented by Lin et al. [46] have also used clustering-based approach for energy efficient data transmission which ensures that defective clusterhead should be resisted to participate in data aggregation process. The technique uses *graph modeling* in order to develop the fault tolerant routing. *Scheduling* is another approach for object

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monitoring application in IoT for energy efficiency. The work carried out by Mostafa et al. [47] using *vertex cover problem* over multi-objective function. The energy problem has been modeled using *travelling salesman path* where the outcome shows that it is effective for maintaining error free operation over an IoT environment. It was also seen that mobility also affects the energy efficiency in IoT application especially where there are uses of conventional routing protocol. The work of Murali and Jamalipour [48] has presented a solution towards overhead problems of control packets due to mobility. The study uses a *trickle timer* that is responsible for selecting the best node in order to reduce energy consumption over mobility condition. *Energy harvesting* is another mechanism for energy conservation in IoT environment studied in existing system. Study towards this direction is carried out by Nguyen et al. [49] have presented a routing scheme that claims of energy efficiency considering heterogeneous communication environment in IoT. The study uses *stochastic* attributes that ultimately performs prediction of energy to be harvested as well as the study also supports IEEE 802.15.4 standard. The study also contributes towards computing cost factor required for constructing an energy efficient route. Pan et al. [50] have developed an approach that focuses on energy efficiency of low-powered devices running over edge devices operating in an IoT. The work has introduced a computational-based approach where two significant modules has been constructed i) to regulate power for increasing extraction of power from energy harvester in compliance with a specific routine and ii) modulating the frequency of it. The study outcome was proven to over approximately 9% of energy efficiency. Routing-based strategy for energy management has been presented by Shen et al. [51] where apart from energy; overall performance improvement was also investigated. The study presents three essential contributions i.e. i) distributed clustering approach using distributed mechanism, ii) adaptive clustering approach for energy distribution in evenly order, and iii) energy reduction for long-overhaul communication. The work of Xu et al. [52] has integrated both routing and clustering approach for energy efficient data aggregation over massive network size of WSN. The concept has been implemented using timer as well as *gradient-based routing* in order to offer better topology control as well as energy efficiency using multihop communication scheme. Adoption of conventional routing scheme e.g. RPL routing is frequently used in IoT network for data communication. The work carried out by Zhao et al. [53] have emphasized jointly over energy efficiency as well as reliability together. A region-based routing scheme has been presented in this work. The proposed system contributes to a unique form of routing scheme where all the nodes are not required to be participating in the process of route discovery process. The work carried out by Zhou et al.[54] has presented routing protocol for retaining maximum energy efficiency considering the case study of underwater things of IoT. The study is about the selection of the best relay node for a given time limit for the static environment. Hence, there are various schemes towards energy efficiency for IoT based environment. The summarization is tabulated in Table.2

Table 2 Summary of Work Carried out for Energy Efficiency in IoT

Authors	Problems	Technique	Advantage	Limitation
Behera et al. [45]	Increasing residual energy	Clustering	66% of energy saving	Constraints of physical devices not considered
Lin et al. [46]	Fault tolerance	Clustering	Increases network lifetime	Constraints of physical devices not considered
Mostafa et al. [47]	Energy efficiency, fault tolerance	Scheduling-based approach	Minimize energy consumption	Scalability no assessed

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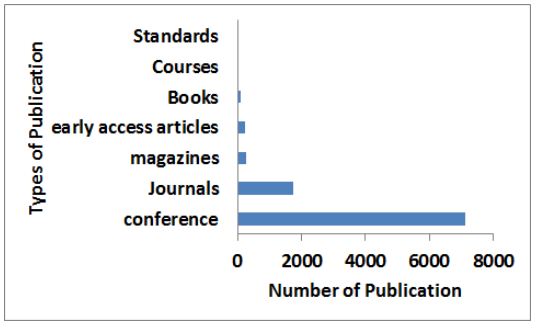
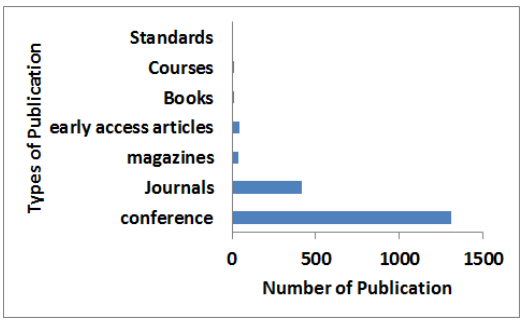
Murali and Jamalipour [48]	Energy issues in mobile nodes	Trickle timer	90% retention of battery of mobile nodes	Constraints of physical devices not considered
Nguyen et al. [49]	Energy efficiency, quality of service	Predictive modeling	83% of energy saving	Work specific to solar energy
Pan et al. [50]	Energy efficiency for low-powered device	Energy harvesting, routine management	8.8% of energy saving	Scalability and energy efficiency are not balanced
Shen et al. [51]	Energy efficiency	Distributed/adaptive clustering	20% improvement in life cycle with good scalability	Constraints of physical devices not considered
Xu et al. [52]	Energy efficiency in large scale WSN	Clustering, routing, multi-hop, topology control	50% network lifetime prolonged, scalable	No optimization
Zhao et al. [53]	Energy efficiency	Traffic model using P2P	Maintains lower delay and better energy efficiency	Applicable for static network only
Zhou et al.[54]	Energy efficient routing	Channel aware communication	Significant cost reduction	Constraints of physical devices not considered

V. Research Trend

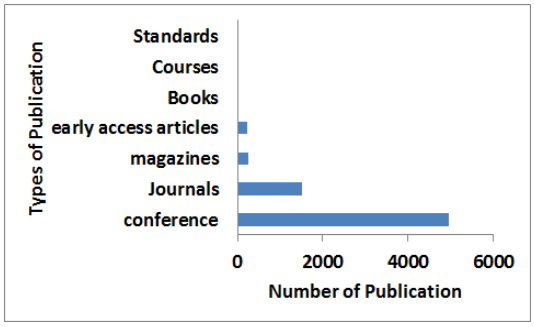
From the existing frequencies of research towards energy problems, it can be only seen that there are highly scattered work trends towards this problem in CPS. Fig.3 visually shows the original data of publication between 2010 to till date.



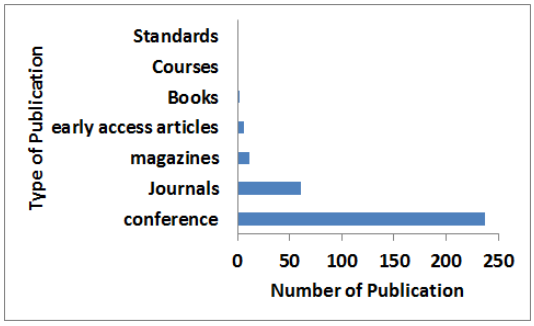
(a) Research trend for CPS



(b) Research trend for CPS with energy problems



(c) Research trend for IoT with energy problems



(d) Research trend for CPS with IoT and energy problems

Figure 3 Research Trend Visualization

The outcome shows that there are very less research towards CPS combined with IoT focusing on energy issues which are direct representation that there is more need of work considering both the constraints

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and issues with both CPS and IoT in order to evolve with better energy efficiency solution.

VI. Research Gap

After reviewing the work carried out in existing system towards energy efficiency in CPS as well as IoT, there are various forms of the inferences that can be drawn with respect to conclusive remakes of the approaches. Although, all these studies have explicitly discussed about the solution for addressing specific issues in the existing approaches; however, certain problems are yet open end. Following are the explicit points associated with problems after reviewing the existing approaches.

- *Unequal Focus on Domain*: An effective solution towards addressing problems associated with the energy efficiency of the CPS should consider all the constraints associated with the physical entities of the device as well as computational attributes included in the modeling. However, studies shows that approaches towards IoT emphasize over computational attributes and less on physical entities. Similarly, studies towards CPS based approach are again witnessed with unequal focus on energy conservation over device and very less on networks.
- *Very Less Routing-based Approach*: There is no doubt that existing routing based approaches are focused on energy efficiency but they are much inclined towards IoT domain only which emphasize more on service design and less on physical device. Existing energy-efficient routings are more emphasized on WSN considering their deployment on IoT only and not in CPS environment explicitly.
- *Less Scheduling Approach*: At present, scheduling based approaches are mainly performed over clustering approach to some extent. There is no doubt that scheduling based approach could offer energy management system in very structured way, but still there is a need of work to be carried out towards dynamic forms of devices connected in CPS applications. There is no scheduling work that has been carried out directly towards energy allocation towards the physical devices connected over error-prone wireless networks in CPS.
- *Less Extensive Test Environment*: A true case of CPS could be tested in multiple wireless environments. A closer look into the existing approaches shows that there is an inclusion of static factor in the network topology along with placement of different forms of physical devices. Unfortunately, such environment just acts as a proof of concept but still not applicable for network with uneven traffic condition as well as dynamicity of user behaviour. A better test environment of energy efficiency in CPS should include both IoT and CPS in order to consider all the near-real time constraints associated with the device and communication environment.

Therefore, all the above written points are required to be addressed in order to ensure higher degree of energy efficiency in CPS. At the same time, a robust computational modeling is required to be used in order to testify all the above mentioned open end problems more closer investigation.

VII. Conclusion

Cyber-Physical System is an upcoming technology that is going to facilitate better form of machine to machine communication. Energy is one of the essential demands for physical devices in CPS as majority of them are sensor and actuator with low resource availability. This paper has discussed about the existing approaches towards the solving the energy problems in CPS and following are the findings: i) it is explored that majority of the solutions are highly device specific which render higher narrowness in the implementation strategy, ii) heterogeneity of the device as well as network consideration with presence of artifacts is not much considered in existing system, iii) there are less attempts of work towards energy required for performing successful transmission without which the applicability of energy efficiency cannot be

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proven, iv) there are less number of attempts where a comprehensive computational modeling towards usage of the service-based and device-based routing strategy is ever formulation considering network constraints. Therefore, our future direction of research work will emphasize on constructing a novel model where scheduling based approach could be testified and implemented for energy efficient routing strategy formulation in CPS. Such modeling will also demand an effective local and global constraint modeling in order to prove its effectiveness.

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