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Adaptation in Wireless Sensor Networks

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***Abstract*— Adaptation in wireless sensor networks is an important topic that has been studied by researchers. There are various approaches to software adaptation in wireless sensor networks, including design concepts, programming constructs, and automatic verification techniques. The goal is to improve the performance and efficiency of wireless sensor networks by adapting them to changing conditions [62]. This can involve optimizing energy consumption over a link while meeting certain quality-of-service requirements. Wireless sensor network adaptation has enormous potential in various applications, including industries.**

Keywords*— Quality of Service (QoS), Wireless Sensor Networks (WSNs), Base Station (BS), Internet of Things (IoT).

I. Introduction

Wireless Sensor Networks (WSNs) are networks of tiny, energy-efficient devices that are useful for environmental data collection and monitoring [63]. WSNs are employed in many different fields, including medicine[63], industrial automation[62], and traffic monitoring[3].

Wireless Sensor Networks (WSNs) are used to monitor physical or environmental conditions and forward the collected data to a central location[4]. WSNs can measure environmental conditions such as temperature, sound, pollution levels, and more[4]. They consist of base stations and numbers of nodes (wireless sensors)[5]. WSNs can be applied in various fields such as smart homes, military applications, Internet of Things (IoT), surveillance and monitoring for security, threat detection, multimedia tracking and monitoring of events[1][3][5].

In smart homes, machine-to-machine communications take place using WSNs. Two typical examples are indoor localization and motion monitoring and the monitoring of indoor air quality[1]. In military applications, the required physical dimensions and weight of nodes are application-dependent. For instance, in some surveillance applications the sensor nodes have to be extremely small in order to be undercover[1].

WSNs can also be used for processing, analysis, storage, and mining of data. The Base Station acts as a processing unit in the WSN system which is connected through the internet to share data[3]. Area monitoring is a common application of WSNs where they are deployed over a region where some phenomenon is to be monitored[4].

Wireless Sensor Networks have numerous applications ranging from smart homes to military applications. They can measure environmental conditions such as temperature or sound levels. They can also process data for further analysis or storage.

Wireless Sensor Networks (WSN) play a vital role in the Internet of Things (IoT)[6][7][8]. WSN is an infrastructure-less wireless network that deploys a large number of wireless sensors to monitor physical and environmental conditions[6]. The data collected from these sensors can be sent to the cloud using cellular networks such as NBIoT, LTE-M, or Wi-Fi[9]. WSN protocols in IoT provide a connectivity medium between IoT sensor nodes and a central gateway[10].

IoT is a branch of engineering that primarily deals with connecting devices to the internet[11]. IoT and WSN both play vital roles in modernization[11]. A large collection of sensors, as in a mesh network, can be used to gather data individually and send it through a router to the internet in an IoT system[12]. In other words, WSN is often used within an IoT system[13].

Wireless sensor networks associated with IoT are useful networks for monitoring, tracking, and sensing physical phenomena[14]. They represent useful networks for assisting in monitoring physical phenomena such as temperature, humidity, pressure, light intensity, sound level, vibration level, etc..

II. Challenges in Wireless Sensor Networks

First Wireless Sensor Networks (WSNs) face several challenges that affect their design and performance. One of the most significant challenges is energy efficiency, as sensor nodes have limited power resources[15][16]. Power consumption can be allocated to three functional domains: sensing, communication, and data processing, each of which requires optimization[17]. The lifetime of a sensor node depends on its battery life, which is affected by the power consumed in these domains[15]. Another challenge is the inadequate power resources available for WSNs[16].

WSNs also face challenges related to their deployment. Nodes are randomly thrown for optimization during deployment, making it difficult to create an efficient network[18]. Sensor nodes interact over wireless, lossy spots without substructure, which presents another challenge[19]. Additionally, synchronization protocols for sensor networks must address peculiar limitations of these networks and resulting technical issues[18].

Other challenges affecting WSNs include high bandwidth demand, quality of service provisioning, data processing and compressing techniques, hardware and operating system for WSNs wireless radio communication characteristics, scalability and independency[20][21]. Security is also a significant challenge as sensor networks interact closely with their physical environment and people[22].

To overcome these challenges in WSNs, researchers are working on developing new technologies such as low-power microprocessors and energy harvesting techniques. They are also exploring new algorithms that optimize energy consumption in different functional domains of a sensor node. Additionally, researchers are developing new protocols that address peculiar limitations of WSNs such as synchronization protocols for sensor networks. Maintaining the Integrity of the Specifications

III. Adaptation in Wireless Sensor Networks

To ensure reliable operation, WSNs must be able to adapt to changes in their environment. This includes adapting to changes in the network architecture, such as the addition or removal of nodes[23], as well as changes in the workload and resource availability[24]. Additionally, WSNs must also be able to adapt their security measures to protect against malicious attacks[23][24][25].

Adaptive software is necessary for WSNs to be able to respond quickly and reliably to changing conditions. Design concepts, programming constructs, and automatic verification techniques have been developed to support the development of adaptive WSN software[23]. Additionally, adaptive SWL provides a web application with a reliable mechanism for automatically tracking and displaying changes in sensor network architecture[26]. Finally, security-aware concepts have been proposed which give WSNs the ability to adapt the level of security according to workload and resource availability[27].

IV. Cross-Layer Design in Wireless Networks

Cross-layer design is a technique used in wireless sensor networks (WSNs) to share information among layers for efficient use of network resources and achieving high adaptivity[28]. In cross-layer design, each layer is characterized by a few key parameters and control knobs[28]. Cross-layer optimization is an escape from the pure waterfall-like concept of the OSI communications model with virtually strict boundaries between layers[29].

Cross-layer design ensures that the route that best meets both performance and energy requirements can be determined[30]. The communication protocols devised for WSNs that focus on cross-layer design techniques are reviewed and classified based on the network layers they aim at replacing in the classical open system interconnection (OSI) network stack[31]. Furthermore, systematic methodologies for the design of cross-layer solution for sensor networks as resource allocation problems in the framework of non-linear optimization are discussed[32].

The design of a cross-layer optimization algorithm for WSNs that consider both performance and energy factors requires efficient communication between protocol layers[33]. Cross-Layer Designs with the ability of inter-layer communication plays a crucial role while dealing with different issues and challenges in WSNs[34].

The main advantage of cross-layer design is that it enables interoperability and improved design of protocols, which results in modularity[33]. Cross-layer design ensures that the route that best meets both performance and energy requirements can be determined, which is not possible in a layered architecture using Transmission Control Protocol (TCP)[35]. In next-generation WSNs, various protocols may be used, such as upward information flow to provide the application layer with information about network status[35].

Cross-layer design overcomes limitations posed by wireless nature of transmission links by allowing coordination, interaction, and joint optimization of protocols crossing different layers[36]. Lack of coordination between layers limits the performance of such architectures due to specific challenges posed by wireless nature of transmission links. Cross-layer design maintains functionalities associated with original layers but allows coordination, interaction, and joint optimization of protocols crossing different layers[36].

Cross-layer design in WSNs has several benefits including improved performance and reliability, efficient use of network resources, interoperability, modularity in protocol design, joint optimization of protocols crossing different layers, and determination of routes that meet both performance and energy requirements. Some specific examples of cross-layer design techniques used in wireless sensor networks include:

- Smart routing: A network architecture is designed to analyze the impact of smart routing on resource allocation for WSN applications with varying requirements[36].
- Unified cross-layer protocol: A unified cross-layer protocol is developed, which replaces the entire traditional layered protocol architecture that has been used so far in WSNs. The proposed cross-layer protocol significantly improves communication efficiency and outperforms the traditional layered protocol architectures[37].
- Vertical calibration between layers: In next-generation wireless sensor networks (WSNs), a number of protocols may be used. For example, upward information flow may be used to provide the application layer with feedback on network conditions, while downward information flow may be used to provide lower layers with information about application requirements[35].
- Interference-aware routing: A cross-layer interference-aware routing algorithm is proposed that jointly optimizes routing and transmission power control decisions to minimize interference and energy consumption in WSNs[38].

Cross-layer design techniques are crucial while dealing with different issues and challenges in wireless sensor networks such as resource allocation, congestion control, and event communication[33][34][35].

V. Adaptation and Cross-Layer Design

Adaptation and cross-layer design are important concepts in modern wireless communication systems, including wireless sensor networks. Cross-layer design refers to the optimization of communication protocols across different layers of the protocol stack, such as the physical layer, data link layer, network layer, and application layer[39][40][41][42]. This approach can improve network performance by allowing different layers to share information and coordinate their actions.

Adaptive techniques are also crucial for wireless sensor networks. These techniques can help optimize resource usage, such as power and bandwidth, in response to changing network conditions[39]. For example, a cross-layer sleep and rate adaptation mechanism was proposed for a slotted ALOHA WSN[42]. This mechanism used sensors' sleep periods to adjust transmission rates and reduce energy consumption.

Overall, adaptation and cross-layer design are important considerations for optimizing wireless sensor networks. By using these techniques, it is possible to improve network performance while minimizing resource usage.

VI. AI Based Adaptation in Wireless Sensor Networks

Wireless Sensor Networks (WSN) are an emerging technology that can be improved by introducing computational intelligence capability for the wireless sensor networks to become adaptive to changes within a variety of operational contexts and to exhibit intelligent behavior[43]. Artificial Intelligence (AI) techniques have been proposed to optimize the issues of WSN, such as resource allocation, routing, and data optimization[43][44][45]. AI-based resource allocation methods have been developed using deep learning architectures for wireless sensor IoT networks with energy efficiency as well as data optimization[43].

A paper proposes employment of artificial neural network techniques to develop in-network "intelligent computation" and adaptation capability for wireless sensor networks to improve their functionality, utility, and survival aspects[44][45]. The goal is to introduce computational intelligence capability for the wireless sensor networks to become adaptive to changes within a variety of operational contexts and exhibit intelligent behavior. The characteristics of wireless sensor networks bring many challenges such as limited resources, dynamic topology, and harsh environments. AI implemented in Intelligent Transportation System (ITS) based on WSN has been used for monitoring homes, gathering information, and transmitting it to a central station[46].

In conclusion, AI-based adaptation in Wireless Sensor Networks is an emerging field that aims at improving the functionality, utility, and survival aspects of WSNs. AI techniques such as deep learning architectures and artificial neural network techniques have been proposed for resource allocation, routing challenges, data optimization, and intelligent computation. These techniques aim at making WSNs more adaptive to changes within a variety of operational contexts while exhibiting intelligent behavior.

Recent studies have utilized artificial intelligence (AI) techniques to solve various challenges in wireless sensor networks (WSN)[47][48][49]. One of the main challenges is routing, which can be addressed by using swarm intelligence algorithms such as Fish school [47]. Other AI techniques used in recent studies include machine learning, deep learning, and fuzzy logic[48].

Several recent studies have focused on addressing the routing challenge in WSN using AI methods[48][49][50]. These studies have identified and classified the AI techniques used and provided a comprehensive discussion of their effectiveness. The aim is to promote further research and identify promising research directions for applying AI-based solutions to various WSN challenges[48].

In addition to routing, recent studies have also utilized AI methods to address data collection, aggregation, dissemination, coverage, deployment, and localization challenges in WSN[47][51]. For example, Kulkarni et al. conducted a survey of various WSN challenges and presented recent research that uses AI techniques to solve them[51].

Overall, recent studies have shown that AI methods can effectively address various challenges in WSN. However, further research is needed to explore their full potential and identify new applications for these techniques.

VII. Challenges in Wireless Sensor Networks

Wireless Sensor Networks (WSNs) are resource-constrained devices that are connected to the internet and used for real-world services [52]. Integrating WSNs with heterogeneous data traffic has brought forward the requirements of an end-to-end Quality of Service (QoS) guarantees [52]. QoS guarantee in WSNs is difficult due to the limited resources available for sensors and the dynamic nature of wireless communication [53]. The concept of Adaptive Service Differentiation for Heterogeneous Data in WSN (ADHERE) is proposed based on varying QoS factors and requirements analysis of mixed traffic within an IoT-based WSN [53]. The objective of the QoS framework is to meet the requirements of heterogeneous data traffic in the WSN - in terms of delay, throughput, reliability, and energy consumption [52].

Several techniques have been proposed to achieve QoS in WSNs. Ref.[53] discusses the use of multiple technologies for WSNs in smart grids, highlighting their strengths and limitations. Ref.[54] proposes a path selection strategy for WSN routing based on PRR predictions using regression algorithms and other network characteristics. This method seeks to improve network QoS by selecting the path with the highest PRR value.

Improving the service quality and extending the network lifetime poses a significant challenge [55]. QoS in WSNs can be characterized by reliability, timeliness, robustness, availability, and security among others [56].

WSNs have a vast variety of applications with different levels of QoS requirements. Critical applications such as chemical, defense, and healthcare require timely and guaranteed data transfer accuracy[1][56]. However, due to resource constraints in WSNs, it is hard to maintain QoS.

Researchers are focusing on QoS issues and challenges to get maximum benefit from their applications [57].

The primary challenge in providing QoS guarantees in real-time applications is how to maintain them over an extended period [55]. Some critical challenges include limited data processing capability of sensor nodes, energy consumption limitations, network topology changes due to node mobility or failure, bandwidth limitations caused by wireless communication channels among others [57][58].

Achieving QoS guarantees in WSNs is challenging due to limited resources and dynamic wireless communication. Several techniques have been proposed such as ADHERE framework, multi-objective optimization solutions using genetic algorithms, and integrating existing QoS techniques with WSNs [59]. These techniques aim to meet the requirements of heterogeneous data traffic in terms of delay, throughput, reliability, and energy consumption.

In conclusion, providing QoS guarantee in WSNs is difficult because of the different constraints and requirements of resources available for sensors and various applications running over these networks [60]. The primary challenges include limited data processing capability of sensor nodes, energy consumption limitations, network topology changes due to node mobility or failure among others [60]. Researchers are focusing on addressing these challenges to achieve maximum benefit from their applications [60] [61].

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