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A Survey on Packet Size Optimization for Terrestrial, Underwater, Underground, and Body Area Sensor Networks

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SUMMARY

Packet size optimization is a critical issue in Wireless Sensor Networks (WSNs) for improving many performance metrics (*e.g.*, network lifetime, delay, throughput, and reliability). In WSNs, longer packets may experience higher loss rates due to harsh channel conditions. On the other hand, shorter packets may suffer from greater overhead. Hence, the optimal packet size must be chosen to enhance various performance metrics of WSNs. To this end, many approaches have been proposed to determine the optimum packet size in WSNs. In the literature, packet size optimization studies focus on a specific application or deployment environment. However, there is no comprehensive and recent survey paper that categorizes these different approaches. To address this need, in this paper, recent studies and techniques on data packet size optimization for Terrestrial WSNs (TWSNs), Underwater WSNs (UWSNs), Wireless Underground Sensor Networks (WUSNs), and Body Area Sensor Networks (BASNs) are reviewed to motivate the research community to further investigate this promising research area. The main objective of this paper is to provide a better understanding of different packet size optimization approaches used in different types of sensor networks and applications as well as introduce open research issues and challenges in this area.

KEY WORDS: Wireless sensor networks, packet size optimization, cross-layer design, energy efficiency, network reliability.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are utilized in many application areas, such as military, commercial, space, visual surveillance, precision agriculture, and logistic applications [1, 2, 3]. WSNs consist of numerous sensor nodes deployed over a sensing field [4]. These sensor nodes are responsible from acquiring measurements on physical phenomena and conveying the data towards the sink node which collects, filters, aggregates, and transports the refined information to other entities for further processing. Since sensor nodes have limited battery energy, every aspect

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of WSNs should be designed with utmost care to dissipate the limited energy to maximize the network lifetime [5, 6]. In general, WSNs can be categorized into four broad classes according to the deployment environments: Terrestrial WSNs (TWSNs), Underwater WSNs (UWSNs), Wireless Underground Sensor Networks (WUSNs), and Body Area Sensor Networks (BASNs). Each of these categories has its own unique characteristics due to the type of environment that is used for data transmission and have additional challenges because of their unreliable and variable channel characteristics in different propagation environments. In the literature, packet size optimization studies focus on a specific application or deployment environment.

The main characteristics of WSNs are scalability, energy efficiency, responsiveness, resilience, and quality of service provisioning for applications [7]. Many protocols, which provide these features, are proposed in the literature. Most of these studies are performed to reduce energy consumption and to mitigate the adverse channel conditions for meeting the requirements of WSN applications which have certain quality of service (QoS) requirements, such as energy efficiency, throughput, and delay. Requirements for WSN applications are different from each other, since some of the WSN applications need high energy efficiency, such as military surveillance systems, on the other hand, some of them, such as disaster relief operations and health care applications, need low latency. Therefore, packet size optimization approaches should meet the requirements of these WSN applications.

WSNs have considerable challenges in data processing, communication, and management. These challenges are the tight resource constraints, variable network topology, dynamically changing bandwidth, range, and computation power [8]. Among these challenges, power consumption is the most difficult resource constraint to be met for WSNs. Therefore, many power-aware protocols have been designed for providing power conservation and power management on both link layer and network layer. Although energy is consumed by the sensor nodes while sensing, processing, and communicating the data towards the sink node, communication power consumption is the dominant term in WSNs [9].

Recent studies show that packet size has a direct effect on the performance of communication between sensor nodes. It is well-known that longer packets experience higher loss rates due to harsh channel conditions, while shorter packets cause higher data overhead [10]. To balance the trade-off between network reliability and energy efficiency, many approaches are proposed to determine the optimum packet size in WSNs.

In Figure 1 we present a typical link-layer packet format in sensor networks [10]. Note that there are three main components (*i.e.*, header, trailer, and payload) of a packet. Header field contains information about current segment number, total number of segments, source and destination nodes. The trailer field includes parity bits for error control. Payload field includes information bits. Length of header, trailer, and payload are given as L_H, L_T, and L_{PL}, bits, respectively.

Packet size optimization can be done according to various wireless communication criteria [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 10, 21]. Different optimization metrics, such as the throughput efficiency and the energy efficiency, are used as the performance criteria for packet size optimization. For instance, energy efficiency is used as an optimization metric by Sankarasubramaniam *et al.* [10] to determine the fixed optimal packet length for increasing the energy efficiency. Furthermore, they explore the impact of error control on the packet size optimization for energy efficiency. On the other hand, Basagni *et al.* [22] use the throughput

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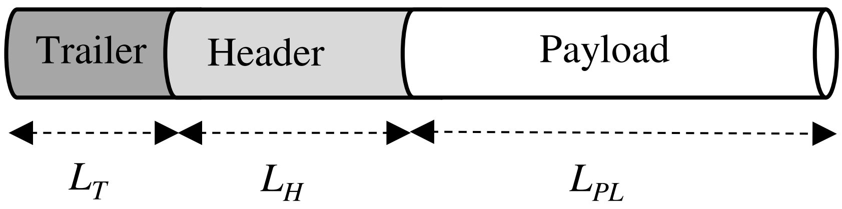

Figure 1. Typical link-layer packet format in sensor networks.

efficiency as the evaluation metric. Basagni *et al.* present their findings on choosing the optimum packet size in multi-hop Underwater WSNs (UWSNs). Their simulation results reveal that an optimum packet size exists in underwater acoustic communications, however, it is influenced by bit error rate (BER) and offered load. Leghari *et al.* [23] presents a survey on packet size optimization in Terrestrial WSNs (TWSNs) with limited coverage (*i.e.*, only a few studies on packet size optimization is surveyed). However, there is no comprehensive and recent survey paper that categorizes aforementioned approaches. To address this need, in this paper, recent studies and techniques on data packet size optimization for TWSNs, UWSNs, WUSNs, and BASNs are reviewed to motivate the research community to further investigate this promising research area. The main objective of this paper is to provide a better understanding of packet size optimization approaches used in different types of sensor networks and applications as well as introduce open research issues and challenges in this area. To the best of our knowledge, this is the first comprehensive survey paper on the current state of the art in packet size optimization techniques for different WSN environments and applications.

Packet size optimization is intertwined with numerous mechanisms in wireless communications and is affected by a large set of parameters. Therefore, a formal definition of packet size optimization in WSNs which covers all the problem types with all the associated constraints would require a very involved mathematical model. In fact, in its most general form, the problem to be solved is a stochastic non-linear multi-objective optimization problem. Furthermore, the set of constraints is very large. For example, minimization of energy dissipation and delay and maximization of network lifetime and throughput should be the constituents of the objective function. Transmission power control, modulation, coding, medium access control mechanisms among many other components of the system are all affecting packet size optimization. Therefore, efficient solution of such a model is highly challenging. Hence, all solutions proposed in the literature have been constructed by considering limited scope objective functions with limited constraint sets. In the subsequent Sections, we present these optimization approaches in a systematic fashion. Note that a significant portion of the studies on WSN packet size optimization do not propose a formal optimization model, instead, heuristic approaches constitute the majority of these studies.

The organization of the paper is as follows. Sections 2, 3, 4, and 5 explore the existing packet size approaches in TWSNs, UWSNs, WUSNs, and BASNs, respectively. In Section 6, some open issues pertaining to the packet size optimization on TWSNs, UWSNs, WUSNs, and BASNs are discussed. Conclusions are drawn in Section 7.

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2. PACKET SIZE OPTIMIZATION FOR TERRESTRIAL WSNS

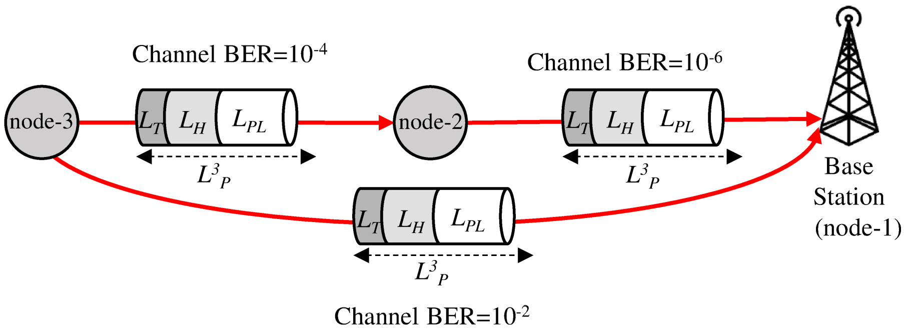

Figure 2. A fixed packet size approach in a linear TWSN.

There are many techniques proposed for the packet size optimization in TWSNs. In this section, we present a taxonomy, which categorizes packet size optimization approaches into three major groups. These groups are listed below:

- Fixed packet size approaches,
- Dynamic packet size approaches,
- Mathematical optimization frameworks.

Each of these groups has advantages and disadvantages when compared to each other. Advantages of the fixed packet size approaches are that they are easy to implement and create less overhead. Disadvantages of the fixed packet size approaches are that they are inefficient to adapt variable channel conditions and therefore, they cannot enhance overall throughput and network efficiency. On the other hand, dynamic packet size approaches enhance overall throughput and efficiency of the network since they generate packets according to channel condition. But dynamic packet size approaches cause a large amount of overhead at each node because of the extra control packet traffic and computational burden at each node. Furthermore, mathematical optimization frameworks are built to increase throughput while minimizing power consumption. However, mathematical optimization frameworks are difficult to implement for such resource constrained networks. The classification of these proposed techniques is also summarized in Tables I–III and compared in Table IV.

2.1. Fixed Packet Size Approaches in Terrestrial WSNs

Utilizing a single optimal packet size has the distinct benefit of reduced network management complexity in comparison to dynamic packet size utilization [24, 25, 26, 27, 28, 29, 10, 30, 31, 32, 33, 34]. In Figure 2 we present a possible fixed packet size approach in a linear TWSN. In this scenario, two sensor nodes are linearly spaced on a line where the base station is located at the right end of the line. Link distances have various BER values and same packet size is utilized in all links of this networks with the size L^3_P. Sharma [30] analyzes the impact of changing the packet size via the proposed multi-hop routing protocol. The main purpose of this protocol is to extend the network lifetime by decreasing the power consumption of sensor nodes. Therefore, a

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cluster head is selected by the algorithm according to remaining energy of each sensor node. A node becomes the cluster head if it has the highest energy and minimum mobility. The proposed protocol determines the clusters first. In this respect, the protocol selects an unvisited node and retrieves its reachable neighbors density according to radius of cluster (*i.e.*, Eps) and minimum number of nodes necessary inside the cluster (*i.e.*, MinPts). A cluster is formed when MinPts is equal to (or less than) the number of neighbors. After the clusters are formed, a Time Division Multiple Access (TDMA) based scheme is utilized by the cluster heads to schedule the sensor nodes in the clusters. Residual energies and mobilities of the cluster heads are continuously observed by the base station. If it is below a certain threshold, another cluster head is selected by the base station. Routing paths are controlled by the cluster heads. A routing path is changed by the base station if a node fails or remaining energy of routing path is less than the threshold. Routing paths are selected according to Received Signal Strength Indication (RSSI) values which are calculated by using two ray ground model. Collected data is aggregated by the cluster heads and sent to helper nodes which have second highest energy. Helper nodes send the aggregated data to the base station via shortest path that is calculated by the base station. Therefore, the proposed protocol increases the network lifetime. The proposed protocol is evaluated with simulations and compared with Assisted Low Energy Adaptive Clustering Hierarchy (A-LEACH) protocol [35]. The effects of varying packet size on the performance of A-LEACH and the proposed multi-hop routing protocol are analyzed. It is shown that throughput increases when the packet size increases and reaches the peak value at the packet size of 256 Bytes. Furthermore, they also show that with the increase in packet size, the energy consumption reduces until a certain point at the packet size of 256 Bytes and remains the same even if the packet size continues to increase.

Energy efficiency is chosen as an optimization metric by Sankarasubramaniam *et al.* [10]. Sankarasubramaniam *et al.* determine an optimal fixed packet size for a set of parameters to increase the energy efficiency. It is argued that although the dynamic packet size may increases the throughput performance, they are not preferred for WSNs due to costs of extra overhead and resource management. Therefore, the optimal fixed packet size according to the radio and channel parameters is used in [10]. In addition, the effect of error control on energy efficiency is also considered. It is argued that error control techniques such as Automatic Repeat Request (ARQ) consume much more energy when compared to Forward Error Correction (FEC), therefore, binary Bose-Chaudhuri-Hocquenghem (BCH) codes are preferred to be used. Simulations are performed with and without these error control mechanisms. Results show that when error control is not used, optimal packet size and energy efficiency increase with decreasing channel BER. At BER $= 10^{-4}$ (considered to be a reliable channel condition), energy efficiency reaches the maximum with the optimal packet size of 200 bits. This demonstrates that higher packet lengths can be used when channel quality is good for achieving maximum energy efficiency without error control. Furthermore, two error control techniques, which are BCH codes and convolutional codes, are used to find the maximum energy efficiency with an optimal packet size. Simulations show that binary BCH codes are 15% more energy efficient than the convolutional codes and provide the maximum attainable energy efficiency, which is 0.9485, when the packet size is 2047 bits and error correcting capability equals to 6.

A bi-level programming model is presented by Zhao *et al.* [34] for WSNs in order to find the optimum transmission radius and the packet size for minimizing average delay of flooding with

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increasing the energy efficiency. This model requires bi-level programming, since its goals must be achieved at two different network layers. Delay of flooding must be minimized at the network layer and the energy efficiency must be maximized at the medium access control (MAC) layer. In this respect, firstly, an estimation model is presented for calculating the contention time of the Carrier Sense Multiple Access (CSMA) and then it is combined with the settling time for finding the delay of flooding. Secondly, the energy consumption of CSMA is calculated to model energy efficiency in the MAC layer. Finally, all of them are combined in the bi-level programming model as the upper level model and as the lower layer model. The upper level model works in the network layer and provides the minimum delay flooding. On the other hand, the lower layer model works in the medium access layer and aims at achieving the maximum energy efficiency. Although these goals are conflicting with each other, they can be achieved when the optimum transmission radii R and the optimum packet size are settled. The proposed bi-level programming is implemented in MATLAB to determine optimal parameters. First analysis is performed on upper level model and shows that how receive time, contention time and settling time are affected with the increase of transmission radii (*i.e.*, R) for fixed packet size (*i.e.*, L). The results reveal that the receive time decreases and the contention time increases while R is increasing. Furthermore, minimum settling time, which is 0.12 s, are found at transmission radii $\approx$ 50 m. Second analysis, in which the R is fixed and the packet size varies between the 0 and 400 bits, is done in the lower layer model. According to the analysis, the maximum energy efficiency is obtained at the packet size of about 50 bits. Finally, the results from these analyses are used to obtain a global optimal solution. Therefore, the algorithm iterates with different initial settings. As a result of the iterations, $\approx$ 50 m and $\approx$ 39 bits are found as the optimum transmission radius and the packet size, respectively for the investigated scenario.

Abdulhadi *et al.* [24] proposes an algorithm called α-Branch-and-Bound (αBB) to improve energy efficiency in wireless cooperative ad hoc networks for determining the optimal packet size. This algorithm provides an efficient solution for the joint packet size and power allocation problem, which is a non-linear non-convex optimization problem and hard to solve, of a cooperative wireless ad hoc networks. For that, the convex relaxation of the non-convex formulation, which requires to find lower and upper bounds for all the non-convex expressions to calculate formulation, is used by the proposed algorithm. As a result, all the non-convex terms are replaced with the improved convex lower bounding functions and a convex relaxation of the problem is constructed. The purpose of this solution is to increase the energy efficiency by obtaining the optimal packet size and power allocation for source and relay nodes. Analyzes are done to show the impact of relay node locations on the packet size and the power allocation. Numerical results show that BER at destination is minimum and the data transmission efficiency is maximum when the packet size is $\approx$ 570 bits and when the relay node is located in the middle of source and destination.

Reliability of low power wireless links is analyzed by Kilic and Gungor [28] for different smart grid environments which are 500 kV outdoor substation environment, indoor main power control room, and underground network transformer vaults. This issue is important for wireless links because radio signals, which are propagated through these links, are affected from various factors such as reflection, diffraction and scattering. Furthermore, effects of them increase due to low antenna heights of sensor nodes and obstructions. Log-normal shadowing path loss model is used by this study to model the wireless channel with considering these effects. The impact of sensor radio parameters, such as modulation scheme (Frequency Shift Keying – FSK, Amplitude Shift Keying

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– ASK, and Offset Quadrature Shift Keying – O-QPSK), encoding scheme (Non-Return-to-Zero – NRZ and Single Error Correction and Double Error Detection – SECDED) and packet size (frame size=30, 60, 90, 128 Bytes and preamble length=2 Bytes) on the performance of sensor network in smart grid communication environment is investigated. In this respect, performance evaluations are done in different smart grid environments to show the changes of received power when the distance between the receiver and sender increases, the variation of transitional region according to smart grid propagation characteristics and the impact of modulation scheme on the transitional region. Furthermore, the impact of packet size is observed in 500 kV outdoor substation environment on the transitional region and different frame sizes, which are 30, 60, 90, and 128 Bytes, are evaluated with simulations. Results show that received signal strength decreases when the distance increases and O-QPSK is the most efficient modulation scheme which increases the packet reception rate values more than FSK and ASK. In addition, results also show that small frame size must be used to decrease the packet losses in harsh smart grid environments and the high output power must be used to increase the size of the transitional region.

Holland *et al.* [25] proposes an approach to reduce energy loss at physical layer. In this respect, optimum relay distance and transmit power are found depending on the modulation scheme and the channel model to increase the network lifetime. Additive White Gaussian Noise (AWGN) and a block Rayleigh fading are employed as the channel models and the relationships between the physical layer parameters such as modulation scheme, transmit power, hop distance are investigated while the channel parameters are changed. The main goal is to increase the network lifetime by minimizing the energy consumption with using optimum physical layer parameters. In this respect, energy per successfully received bit (ESB) metric, which is a function of hop distance, transmit energy, modulation scheme and distance between the receiver and sender, is defined. A wide range of numerical analysis are done to minimize the ESB by finding the optimal transmission energy and optimum hop distance according to different modulation schemes. The results of the analysis reveal that when the hop distance is fixed, which is 15 m, transmission energy and the optimal ESB increase as the noise level increases with respect to modulation schemes which are Binary Phase Shift Keying (BPSK), QPSK, 8-PSK, 16-PSK, 4-Quadrature Amplitude Modulation (4-QAM) and 16-QAM. Results also show that optimum hop distance decreases and energy per successfully received bit per meter (ESBM) increases as the channel noise increases when the transmit energy is 5 nJ. The impact of packet overhead on energy efficiency in WSNs is also investigated by Holland *et al.* [25]. Holland *et al.* propose that the energy efficiency increases when small packets are used without considering the per packet overhead. In this respect, the ESB is measured while the packet size is varied from 200 bits to 1600 bits for different sizes of per-packet overhead. As a result of their measurements, Holland *et al.* show that when the packet has zero overhead, the energy efficiency becomes maximum. Furthermore, it is also demonstrated that the optimal packet size also increases when the packet overhead increases.

Wang *et al.* [32] propose an energy-balanced routing algorithm on a heterogeneous WSN deployment. The goal of the proposed algorithm is to improve the lifespan of WSN by avoiding the energy hole problem and by providing the energy-balanced routing. In the proposed algorithm, two kinds of nodes, which are ordinary sensor nodes and energy heterogenous sensor nodes, are used. Ordinary sensor nodes are distributed to the area and both collect and route the data. On the other hand, heterogenous sensor nodes are deployed close to the sink node and only route the data.

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Two different types of packets including the update packet and the data packet are defined and used in their proposed energy-balanced routing algorithm. The update packet includes 6 fields, which are packet type, node type, source address, depth, residual energy, and energy density. Several number of bits are defined for each of these fields. They are used to control the working state of the neighbor nodes, which update these packets with their own state information. As such, a more robust and energy efficient communication regime is achieved by reducing the number of retransmission. The data packet has 5 fields which are packet type, data, source address, route line, and hops. Data packet size is larger than the update packet and used for event-driven and data-driven applications. The algorithm starts with the broadcasting of update packets to all nodes by the sink node. A node receiving the update packet, creates the routing table after it calculates its depth. Then, next hop node is defined to send the data packets through the sink node by considering the remaining energy of next hop node. Before the transmission to the next hop, the algorithm updates the route line and hops value in the data packet. According to these values, routing table is updated again. Simulations are done to find the optimal number of heterogenous sensor nodes (a), optimal coverage of heterogenous sensor nodes (b), and optimal initial energy of heterogenous sensor nodes (c). The optimal parameter values for a, b, and c are found to be 0.1, 0.3, and 2, respectively. The performance of proposed algorithm is also evaluated based on the network lifespan, network delay, and energy imbalance factor. Results show that the proposed algorithm extends the network lifespan by up to 90.5% on heterogenous deployment and reduces the network delay while achieving energy balance when compared with Mini-Hops and Energy-Balanced Routing Protocol (EBRP).

Variance-based distributed contention control (DCC-V) and packet size optimization are proposed by Yaakob *et al.* [36] to solve the congestion problem in WSNs. The proposed technique is operated on MAC layer and uses contention window (CW) in DCC-V to minimize the packet collisions by solving resource-sharing problem in WSN. In this technique, CSMA/CA protocol is used with considering slot utilization and average collision values while determining CW. Furthermore, DCC-V is enhanced by integrating it with packet size optimization. DCC-V firstly guarantees the successful allocation of the channel according to probability of successful carrier sense and the probability of collision occurred in the channel. These probabilities are predicted based on the previous packet transmissions. Simulations are performed to evaluate the performance of the proposed technique. Results show that the proposed technique can alleviate the congestion and outperform the IEEE 802.15.4 protocol. Because more than 20% packet loss occurs for IEEE 802.15.4 when the BER is 10^{-3} and contention window and number of nodes are high. However, in the same situation, the proposed method reduces the packet loss rate to approximately 15% when the optimum packet size is 60 Bytes and to 12% when the optimum packet size is 30 Bytes. This shows that small packet size is useful in decreasing the packet loss rate. On the other hand, results also show that the number of collisions increases if the small packet size is used. This is because more packets are transmitted through the network when the smaller packet size is used and this yields to contention among the packets. Furthermore, throughput and delay evaluations of the proposed method show that the proposed method is more efficient when the BER is 10^{-6} with small number of nodes and with the optimum packet size of 30 Bytes. Finally, as a result of the experiments, when the BER is low and the congestion is high, higher packet size should be used with the DCC-V. In contrast to this, when the BER and number of nodes are high, smaller packet size should be used with the proposed protocol since larger packets are more error prone. According to these results,

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Table I. Literature overview of fixed packet size optimization techniques in TWSNs

Taxonomy	Techniques	Purpose	Performance Metrics
Fixed packet size	αBB algorithm [24]	Improving the energy efficiency in wireless cooperative ad hoc networks.	Energy efficiency
	Optimizing physical layer parameters [25]	Providing energy-efficient transmission over a noisy channel by setting up optimal physical layer parameters	ESB
	Measuring the impact of packet size on the performance of WSNs [26]	Determining the optimum packet size to increase performance of WSNs	Energy consumption, latency, packet delivery ratio
	Evaluating the performance of IEEE 802.15.4 standard-based WSN on star topology for large scale applications [27]	Obtaining the optimum packet size, number of nodes, and PIT to increase throughput and to decrease end-to-end delay	throughput, latency
	Analysis the reliability of low power wireless link in different smart grid environments [28]	Investigating the impact of different radio parameters on the performance of sensor network.	PRR
	Analysis the performance of IEEE 802.15.4 standard-based WSN on mesh topology [29]	Maximizing the throughput for mesh topology.	Throughput
	Energy efficiency based packet size optimization [10]	Finding the most energy efficient packet size for WSNs.	Energy efficiency
	Multihop LEACH protocol [30]	Analyzing the impact of the changing packet size on the proposed routing protocol.	Throughput, average energy consumption
	An energy-efficient transmission recovery algorithm with the optimum packet size [31]	Reducing the transmission errors in the channel and extending WSN lifetime.	Energy efficiency
	An energy-balanced routing algorithm [32]	Improving lifespan of WSN by balancing energy consumption of sensor nodes	Network lifespan, delay, energy imbalance factor
	DCC-V with packet size optimization [36]	Minimizing packet collisions in WSNs.	Packet loss rate, delay, throughput
	SPSA theory based packet size optimization algorithm [33]	Increasing the ECE in real-time of WSN applications	ECE
	Bi-level programming model [34]	Minimizing average delay of flooding with increasing the energy efficiency.	Delay, energy efficiency

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DCC-V can provide delay and throughput requirements of WSN applications if it is used based on network conditions with the optimum packet size.

Kohvakka *et al.* [29] analyze the performance of IEEE 802.15.4 standard-based WSN on mesh topology for large scale applications, such as industrial automation and intelligent households, by considering number of nodes, packet size, and packet interval time. The main objective of this study is to maximize the throughput by determining the optimum number of nodes, packet size, and packet interval time. Simulations are performed with OPNET simulator. According to the simulation results, the maximum throughput for the mesh topology is obtained when the optimum packet size, which is 1408 bits, is used with 3 s packet interval time for the 50-node topology. These parameters can be used in intelligent household applications and industrial automation for increasing the throughput performance.

Impact of packet size on the performance parameters of WSNs, including energy consumption, latency, and packet delivery ratio, is studied by Karthi *et al.* [26]. It is aimed to determine the optimum packet size for increasing the performance of WSN applications, such as habitat monitoring, structural monitoring, and data logging, which use IEEE 802.11 MAC for achieving higher transmission rates. Simulations are done with ns2 simulator by deploying 25 nodes and one sink node on a flat grid topology. Different packet sizes (*e.g.*, 128, 256, 512, and 1024 Bytes), and inter-arrival times (from 5 s to 55 s) are used in the simulations. Average end-to-end delay, packet delivery ratio, and residue energy of a node parameters are varied. Simulation results show that as the packet delivery ratio increases, average end-to-end delay and residue energy of a node decreases when considering highly inter-arrival times for small sized packets. The reason behind for such a behaviour is the increment in number of packets generated (*i.e.*, growth in network traffic) when inter-arrival times are shortened. Therefore, when the network traffic grows, longer packets yield more packet drops which results in more retransmissions.

Another packet size optimization study is reported by Singh *et al.* [31] for WSN applications, such as environmental monitoring, battlefield monitoring, industrial process control, and security. In this study, an energy-efficient transmission recovery algorithm with the optimum packet size for WSNs is proposed. This algorithm can be computed by using 4 different methods. Method 1 is that if the packet is corrupted, the entire packet is sent again. Method 2 is that if the packet is corrupted, send the corrupted portion of the packet again. Method 3 is that dividing packets into small sub-packets and retransmitting only the corrupted sub-packet. Method 4 is that dividing the packets into small sub-packets and retransmitting only the corrupted portion of the sub-packet. The proposed algorithm is designed to reduce the transmission errors, which occur due to radio frequency (RF) interference, fading, and mechanisms related to time-frequency coherence in the channel. Simulations are performed to compare 4 methods for three cases. In the first case, fixed data packet and sub-packet size are used with varying error occurrence percentage. In the second case, data packet size and error occurrence percentage are kept fixed with varying sub-packet size. In the third case, fixed data packet size is used with varying sub-packet size and error occurrence percentage. For the case 1, method 4 achieves the minimum energy consumption when compared to other methods. For the case 2, method 4 provides minimum energy usage with the optimum packet size of 50 bits. For the case 3, method 4 performs better in terms of energy usage although it has the bigger percentage of error than the other methods. As a result, simulation results for these three

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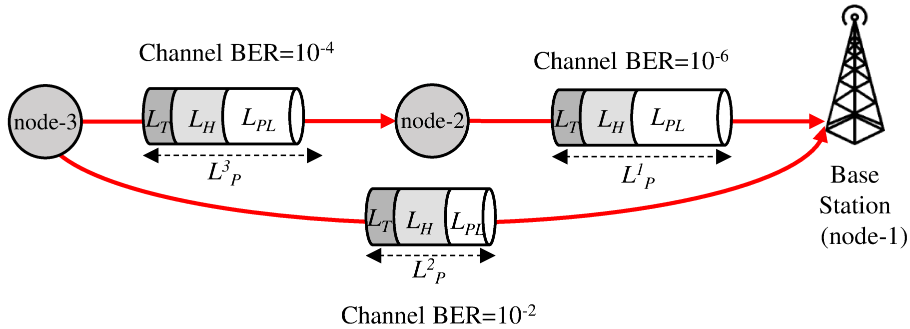

Figure 3. A dynamic packet size approach in a linear TWSN.

conditions show that the best sub-packet size is 50 bits which provides more than 30% of battery power savings.

A Simultaneous Perturbation Stochastic Approximation (SPSA) theory based packet size optimization algorithm is proposed by Xia *et al.* [33] for increasing the energy consumption efficiency (ECE) in real-time of WSN applications, such as military, industry, and environment protection applications. In this study, simulations are performed with and without using the BCH scheme for the channel encoding and decoding. The main purpose of using the BCH codes is to measure the ECE during the encoding and decoding phase. Comparative analysis of the numerical evaluations of the SPSA-based optimization model and the simulations results confirms the validity of the SPSA-based optimization model. Results also show that the ECE reaches the maximum with packet sizes of 1888 bits and 456 bits with and without using the BCH codes, respectively.

Performance evaluations are done for large scale applications of IEEE 802.15.4 standard-based WSN on star topology by Khalaf and Abdul-Hameed [27]. OPNET simulator is used to evaluate the performance of network with different number of nodes, packet size, and Packet Interval Time (PIT). The main purpose of this study is to obtain the optimum packet size, number of nodes, and PIT to increase throughput and to decrease end-to-end delay by preventing packet drops for IEEE 802.15.4 standard-based WSN applications, including building automation systems, logistics, environment, disaster monitoring, and pervasive database systems. Simulation results are performed for different cases. In the first case, optimum number of nodes, which maximizes the throughput, is found by changing the number of nodes from 30 to 260 nodes with the packet size of 1408 bits and the PIT of 1 s. The optimum number of nodes is shown to be 230 nodes for the first case. In the second case, different packet sizes (*e.g.*, 1024, 1408, 2048, and 3072 bits) are used to obtain the optimum packet size with 230 nodes. The results of the simulations reveal that the maximum throughput is achieved with the packet size of 2048 bits. In the third case, the optimum PIT is found to be 2 s.

2.2. *Dynamic Packet Size Approaches in Terrestrial WSNs*

The use of dynamic packet sizes for increasing performance of WSNs is an approach pursued by many studies [37, 38, 14, 15, 39, 40, 41, 42, 43]. In Figure 3 we present a dynamic packet size approach in the same linear TWSN as in Figure 2. In this case, packet sizes are adjusted according to link BER values. For lower link BER values, higher packet sizes are utilized, and smaller packet sizes are used when link BER is high. (*e.g.*, packet sizes of links (3,2) and (2,1) are higher than

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the packet size used in link (3,1) since the BER values of links (3,2) and (2,1) are much lower than the BER value of link (3,1)). Jelenkovic and Tan [40] design an algorithm that divides the frame into fragments to fit them into available channels by dynamically matching channel failure characteristics. This algorithm models the wireless environment as $(A_i, U_i)_i \geq 1$ which is an on-off process. A_i means that channel is available and transmission can be done. On the other hand, U_i means that channel is unavailable, transmission is pending for the available channels. When the packet of size L comes, the packet is fragmented into several small packets L_f and these fragmented small packets are sent. Fragmented packet L_f is successfully transmitted if $L_f \leq A_i$. Otherwise, the next available period $A_{(i+1)}$ is waited to retransmit the packet. This process is repeated until all the data units are transmitted to the receiver. The proposed algorithm dynamically fragments the packets whose size is k_{th} largest value according to previously measured k+m available channel periods. When the data unit L is received by the receiver, packet fragment L_m, which has the maximum length, is set as the maximum of k^{th} value. If the data unit $L \leq L_m$, the data unit is not fragmented by the algorithm. Otherwise, the data unit is fragmented into $\lceil L/L_m \rceil$ packets. Simulations are also performed to evaluate the performance of proposed protocol. Results show that the proposed dynamic fragmentation algorithm reduces the number of retransmissions and decreases the packet loss probability when compared to static fragmentation. However, in this algorithm it is necessary that the determination of channel availability period be made by the sender and this is influenced adversely by the hidden terminal problem.

Dynamic Packet Length Control (DLPC) scheme is proposed by Dong *et al.* [14, 15]. This algorithm dynamically creates the packet based on the channel condition for maximizing throughput and efficiency. If congestion level is high, small packets are created by the algorithm to reduce the packet losses. On the other hand, if congestion level is low, the algorithm generates large packets for reducing the overhead. To achieve these, DPLC uses a dynamic packet length adaptation scheme, an accurate link estimation method and two easy-to-use services. The work flow of DPLC with these methods and services is as follows. Message comes from the application for transmission. Sender has the DPLC module and firstly it decides to aggregate or fragment the arrived message by using two easy-to-use services. DPLC module aggregates the message if the message size is smaller than the maximum packet length supported by the radio; otherwise, fragments the message. Optimal packet length is estimated by the link estimator, which is inside the DPLC module, according to channel conditions. According to the estimation outcome, the number of messages are found to be aggregated or to be fragmented. After these operations, frame is transmitted through the MAC layer. When the DPLC module of the receiver receives the frame, it aggregates or fragments the frame again to obtain the original message. Experiments are done to evaluate the performance of DPLC. Results show that DPLC reduces the transmission overhead and energy consumption by 13% and by 41.8% respectively when compared to original protocol which does not use link estimation algorithm. Furthermore, DPLC is also compared with simple aggregation scheme and comparison results show that it achieves 21% less transmission overhead and 15.1% less energy consumption than the simple aggregation scheme.

The solutions proposed by Dong *et al.* [14] and Jelenkovic and Tan [40] work at link layer. In contrast to these approaches, a solution that works at network layer is proposed by Deng *et al.* [38]. Fixed-size packets are used by the traditional transmission in IPv6 networks over networks of resource-constrained nodes (6lo) . Using the fixed packet size decreases the network performance

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when bulk data transmission is required by the applications. Deng *et al.* [38] propose an adaptive mechanism, which works at IP layer, for dynamically adjusting packet size according to network conditions. Their proposed method uses 6lo fragmentation for creating and sending large packets. The proposed adaptive mechanism has two modules to adjust the packet size. One of these modules is a Unit Discovery Module which finds the unit value by increasing or decreasing the packet size in the mechanism. This module inside the sender sends the Internet Control Message Protocol (ICMP) Echo Request message, which has the size of the current unit value, to receiver before bulk data transmission begins. After the message is received by the receiver, it decides whether the message should be fragmented or not. If the fragmentation is needed, message is not received by the receiver and receiver sends an ICMP message, which contains the Packet Too Big message and the new proper unit value, to the sender. After sender receives this ICMP message, sender retransmits a new ICMP Echo Request message, which has the size of the updated unit value, to the receiver. This is continued until sender sends an ICMP Echo Reply message. In this way, the unit value is found and the process of the second module, which is the Packet Adjustment Module, starts. Packet Adjustment Module adjusts the packet size based on the network conditions by using this discovered unit value. Simulations are performed to evaluate the performance of this proposed mechanism. Results show that transmission time and total transmitted octets decrease until the packet size reaches a specific value. End-to-end transmission time and total transmitted octets are improved from 65 s to 40 s and from 200 KB to 160 KB, respectively.

The optimal transmit power and optimal packet length for WSNs in log-normal shadowed channel is investigated by Nandi and Kundu [43]. Both the optimal transmission power and the optimal packet size are important objectives for maintaining network connectivity with minimum BER and for achieving the energy efficiency during transmission. In this respect, simulation studies are performed to determine the optimal transmit power under different network conditions, including node density, data rate, and different levels of shadow fading. Infinite ARQ model is considered to successfully transmit the data from sender to receiver in presence of shadowing. Furthermore, a variable packet size scheme is also performed in order to use the packet size, which maximizes the energy efficiency. The impact of shadowing is also analyzed on the optimal transmission power and packet size. Considered performance metrics are the route BER (*i.e.*, BER_{route}) as a function of node spatial density, optimal common transmit power as a function of bit rate, energy efficiency as a function of packet length, and the comparison of energy requirement of a file in two cases (fixed packet length and an optimal packet size). These results are evaluated and it is observed that the performance of BER_{route} increases when the node spatial density increases until a certain node density. This is because the Signal-to-Noise Ratio (SNR) cannot be improved after a certain node density while the interference between the nodes increases with the increase of node density. It is also seen that the performance of BER_{route} decreases in log-normal shadowed channel. The optimal transmit power as a function of bit rate is evaluated with and without considering the shadowing. It is observed that optimal transmit power and the data rate are directly proportional to each other since they increase together. This is because thermal noise increases when high bit rate exists in the network. It is also seen that the optimal transmit power increases when severity of shadowing increases. It is observed that energy efficiency reaches the maximum value at a given packet size. Packet sizes, which provides the maximum efficiency, differ according to shadowing and the optimum packet size decreases with the increase of shadowing. This shows that the optimal

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Table II. Literature overview of dynamic packet size optimization techniques in TWSNs

Taxonomy	Techniques	Purpose	Performance Metrics
Dynamic packet size	Adaptive frame size predictor [37]	Increasing energy efficiency by adjusting frame size according to channel quality	energy consumption, throughput, delay
	An adaptive mechanism at IP layer [38]	Improving 6lo performance for bulk data transmission	Reliability, Goodput
	DPLC [14]	Dynamically creating packets according to channel conditions	Energy efficiency, transmission efficiency, reliability
	DyPSOCS for CRSNs [39]	Adapting packet size according to the selected channel.	Energy efficiency, latency, BER, throughput
	Dynamic packet fragmentation algorithm [40]	Dividing packet into smaller fragments dynamically by utilizing the channel statistics	Number of retransmission
	Optimized dynamic packet size formulation [41]	Finding the optimal amount of smart metering records to be aggregated into one packet to maximize energy efficiency.	Energy efficiency
	Optimized dynamic packet size with FEC method [42]	Finding the optimal amount of metering records to be aggregated into a single packet using FEC schemes.	Energy efficiency
	Packet size adaptation for CRSNs [44]	Improving the energy efficiency by transmitting the optimum sized packets according to the state-varying channel conditions	Energy-per-bit
	Optimal transmit power and packet size in WSNs [43]	Maximizing the energy efficiency in the shadowed channel.	Low BER, Energy efficiency

packet size changes according to network conditions. Furthermore, it is also observed that the energy efficiency decreases suddenly when the packet size is smaller than the optimum packet size. This is because smaller packets cause higher overhead and consume more start-up energy. In addition, performance results show that using the optimum dynamic packet size instead of a fixed packet size reduces the energy consumption.

An adaptive MAC scheme is proposed by Ci *et al.* [37] which includes the link adaptation mechanism, to increase the energy efficiency in WSNs. A variable frame size is used by the proposed MAC instead of using a fixed frame size. The proposed MAC algorithm adjusts the frame size according to the channel quality and in this way, it reduces the number of retransmissions by decreasing frame errors and increases the energy efficiency. Furthermore, using the adaptive

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frame size also increases the throughput performance of WSNs since large information packets are transmitted when channel quality is good. In this study, Extended Kalman filtering (EKF) approach is used to estimate the channel quality and find the optimal packet size. EKF is based on the Kalman filtering, which estimates the past, present, and future states of the system, and incorporates the latest observations about the system into the filtering. The proposed scheme uses EKF filtering to predict frame size according to history of the system before transmission. Simulations are performed by considering scenarios in which one, two, and three sensor nodes transmit the data at regular intervals. At the first step, simulations are performed for small clusters. Results of simulations for small clusters are as follows. Energy efficiency is measured and compared for two schemes which are the adaptive scheme and fixed scheme. Results show that the energy efficiency is improved up to 15% for three nodes with this method. Furthermore, delay and goodput performance of the proposed method is also compared with the fixed scheme. According to results obtained from this comparison, the proposed method decreases delay up to 20% and doubles the goodput when compared the fixed scheme. At the second step, simulations are performed by using large clusters and the performance of the proposed method is evaluated with these clusters. Four network scenarios, which include 2, 5, 10, 20, and 50 nodes, are analyzed in these simulations and the proposed scheme is compared with the fixed scheme. Results show that the proposed adaptive scheme improves the energy efficiency of the system more than the fixed scheme. Moreover, the delay and goodput performance of the proposed scheme are also analyzed. Results show that the proposed adaptive scheme provides more goodput and less delay than the fixed scheme. This is because adaptive scheme reduces the optimal frame size when the channel quality is bad and in this way, it reduces the number of retransmissions which occurs due to packet losses. The proposed scheme can be enhanced by including priority-based queuing and data aggregation techniques to provide real-time and reliable communication in WSNs.

An improvement in energy efficiency and network lifetime is made by Li *et al.* [44] for the cluster-based multi-channel cognitive radio sensor network (CRSN). The purpose of this approach is to increase the energy efficiency by transmitting the optimum sized packets based on the channel conditions. Proposed approach includes two techniques which are packet size adaptation technique and channel assignment with awareness of the residual energy of sensors. A set of cluster members (CMs) and an energy-rich sensor with high capabilities named as cluster head (CH) exist in each cluster in the cluster-based multi-channel CRSN. CH senses spectrum and allocates spectrum for the CMs according to idle/busy state of the primary users (PUs) and received signal power. Before allocating the channel, CH senses the channel for a certain time and forms a sample sequence by keeping states of the channel. According to this sequence, behavior model of PU is estimated and then CH decides the packet size and channel assignment. M different data channels in the same bandwidth and one common control channel in each cluster exist in the proposed model. Control channel is used to exchange the control information and at a time a data channel is assigned to one sensor node for transmission. Before transmission CMs sense the channel and send the sensed data to CH. CH collects the data from all the CMs and sends them to the base station through the cluster head backbone. Inter-cluster communication is not considered by this study and therefore, performance of proposed model is only evaluated within a single-cluster. Energy-per-bit (EPB), which is the ratio of the consumed total energy to the amount of transmitted data bits, is used as a performance metric and the performance of the proposed packet size adaptation scheme is

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measured and compared with the fixed packet size through simulations. Results show that the proposed packet size adaptation scheme provides the lowest EPB and in this way, it provides the best energy efficiency when compared to fixed scheme. Number of transmitted information is 122 Mb with 0.246 mJ/bit EPB as the packet size is increasing when the adaptive scheme is used. On the other hand, when the fixed scheme is used with its optimum packet size (60 Bytes), the number of transmitted information is 119 Mb with 0.253 mJ/bit EPB. This shows that performance of the fixed scheme is still worse than the adaptive scheme. As a result, proposed packet size adaptation scheme provides a better energy efficiency than the fixed packet-size scheme since it adjusts the packet size adaptively according to the channel behavior.

A formulation is proposed by Lendvai *et al.* [41], which finds the optimal amount of smart metering records, to aggregate records into one packet in delay tolerant WSNs by considering the SNR for increasing the energy efficiency of the system. The aim of this study is to transmit the useful information with the minimum energy consumption by considering arrival time of information. The structure of the data packets is divided into three parts: the header, the trailer, which are considered as fixed length, and the useful data, which is composed of fix length of elements and structures. The proposed formula is used to calculate the amount of records that can be incorporated in the useful data for maximizing the energy efficiency by considering the channel quality. As a result of this study, number of records, which can be aggregated into one packet, for specific SNR values are determined to maximize the energy efficiency. Furthermore, Lendvai *et al.* extend their study by creating a method, which calculates the optimal number of records to be aggregated into one packet by employing different FEC schemes while considering SNR to maximize the energy efficiency in [42]. In this respect, different FEC schemes, which are Repetition code, Hamming codes, Reed-Solomon codes, BCH codes, LDPC codes, and Raptor codes, are compared according to their energy efficiency through simulations. Simulation results show that the energy efficiency of FEC algorithms increases as long as the packet size increases. Furthermore, the study also argues that FEC schemes should not be used due to complexity when the channel quality is good because complex error control algorithms cause more energy consumption in good channels.

A dynamic packet size optimization and channel selection scheme (DyPSOCS) for cognitive radio sensor networks (CRSNs) is proposed by Jamal *et al.* [39]. DyPSOCS adjusts the packet size according to the selected channel. When PU does not use frequently the selected channel that is selected by the secondary user (SU), longer packets can be transmitted efficiently. On the other hand, if the selected channel is used by the PUs more frequently, smaller packets can be transmitted to prevent collisions between the PUs and SUs. In this respect, the best available channel and the optimal packet size are selected by the DyPSOCS to maximize energy efficiency while reducing interference level and latency. Furthermore, Markov decision process (CDMP) is used to model the optimization problem to satisfy the QoS constraints such as BER, delay and interference. The proposed method is evaluated with simulations and also compared with a baseline approach and DPLC. Simulation results show that DyPSOCS improves the QoS performance and increases the energy efficiency when compared to other schemes.

2.3. Mathematical Optimization Frameworks in Terrestrial WSNs

There are many studies [11, 12, 45, 21] that propose some frameworks for finding the optimal packet size for increasing the performance of WSNs by reducing energy consumption and by increasing

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network throughput. Chudasama and Trapasiya [45] proposed a packet size optimization framework for increasing the throughput and reducing the energy dissipation. A cross-layer analysis is done to find optimum packet length and energy consumption per bit by considering effects of channel-aware routing, broadcast channel, and medium access control. The proposed framework firstly determines the hop distance and routes through the sink. Routes are constructed between the source and the sink according to three criteria. These criteria are that the node can be chosen if its SNR value is bigger and its remaining energy is bigger than the SNR threshold and energy threshold, respectively. Moreover, the distance between the next hope and the sink is also considered while determining routes. It must be less than distance *D*, which is the distance between source and sink, and must be bigger than γ_{min}. Packet error rate is also considered for mica-z nodes, which use O-QPSK with direct sequence spread spectrum (DSSS), and for ARQ and FEC schemes. Optimization results of the proposed solution are also evaluated by analyzing the results in terms of energy consumption, packet error rate of FEC and ARQ, and packet size. Energy consumption performance is firstly measured for ARQ scheme with various payload lengths for three SNR thresholds. This result shows that packet size optimization for decreasing the energy consumption depends on the route decision and thereby on the SNR threshold. Energy consumption per useful bit performance of BCH(128,150,3) is also measured with different SNR thresholds for three power levels (*i.e.*, 0 dBm, -5 dBm, and -15 dBm) and compared with ARQ with 0 dBm. It is shown that end-to-end energy consumption decreases when the SNR threshold is between the 5 dBm and 10 dBm. Moreover, it is also observed that BCH outperforms the ARQ in terms of energy consumption when the transmit power is low. Furthermore, the energy consumption per useful bit comparison between the fixed packet length, which is 250 Bytes, and the optimal packet length is also performed with the various error correcting capability (t) of the BCH codes and ARQ at $t = 0$. It is observed from the result that the energy efficiency increases up to 20% when the longer packet size is used and has the highest value at $t = 7$. They conclude that longer packets increase the performance of MAC in WSNs when the channel condition is good. On the other hand, if the channel condition is bad, short packets are chosen because BER probability increases which leads to increase in number of retransmissions and error correcting bits. Chudasama and Trapasiya also obtain the optimal packet lengths with respect to different SNR values. As a result of their findings, the lowest energy consumption can be achieved when the packet length ranges between 200 Bytes and 270 Bytes when SNR is 10 dB.

A WSN lifetime optimization framework is proposed by Akbas *et al.* [11, 12]. Akbas *et al.* used Mixed Integer Programming (MIP) for investigating the effect of data packet size on WSN lifetime. In this study, whole link-layer handshaking cycle is modeled by selecting optimum transmission power levels for data and acknowledgment (ACK) packets and the effects of path losses are considered by employing log-normal shadowing model. A TDMA based MAC protocol is used in the proposed framework to mitigate the interference. Each time slot is set to 115 ms. Duration of a round is determined as 60 s. Each node generates the s_i number of packets at each round. According to their link layer model, each node can transmit packets at its own slot; otherwise, enters the sleep mode. Energy dissipation of sensor nodes are modeled according to the energy dissipation characteristics of Mica2 motes. Energy dissipation for ACK packets, for transmitting and receiving the data packets are all considered. MIP framework is used to maximize the WSN lifetime which is defined as the *number of rounds* $\times$ *the round duration*. Many constraints such as flow balancing constraint, base station flow constraint, total busy time of the node constraint,

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Table III. Literature overview of packet size optimization frameworks in TWSNs

Taxonomy	Techniques	Purpose	Performance Metrics
Packet Size Optimization Framework	MIP framework [11, 12]	Maximizing the WSN lifetime.	Network lifetime, energy consumption
	Packet size optimization using a cross-layer design approach [45]	Optimizing the packet size for decreasing energy consumption and increasing the network lifetime.	Packet throughput, energy consumption
	Analytical framework in CDMA-based WSN [46]	Optimizing the packet length for maximizing energy efficiency for different channel conditions.	BER, energy efficiency, delay
	Analytical framework with nearest neighbors based routing in CDMA-based WSN [47]	Increasing resource utilization by finding optimal packet size in CDMA-based WSN.	Energy consumption, delay, BER, resource utilization
	Packet size optimization framework for resource utilization [48]	Increasing resource utilization with channel aware routing protocol by finding optimal packet size in CDMA-based WSN.	Resource utilization, delay, energy consumption, BER
	A joint optimization framework for CRSNs [49]	Supporting more users	Energy efficiency, packet reliability
	A cross-layer solution for packet size optimization [21]	Determining the optimal packet size in underwater and underground sensor networks	Packet throughput, energy consumption, resource utilization

energy balance constraint, bandwidth constraint, and the interference are all considered while designing MIP framework. According to these constraints, optimal packet size is determined by the MIP framework. Numerical evaluations are used to analyze the proposed framework. In this respect, packets, which consist of 1024 Bytes information bits and 20 Bytes overhead, are used for evaluations. ACK packet size is set to 20 Bytes. In order to show the effects of packet size on the network lifetime, data packet is divided into several packets and its effects are investigated for different number of nodes such as 15, 20, 25 and area per node values such as 1 m^2, 4 m^2, 16 m^2, and 32 m^2. Results show that normalized lifetime difference becomes lager as the number of nodes and areas per node get higher. Further it is observed that as the packet size increases the network lifetime decreases. This shows that the energy consumption for overhead is the main issue in data packet length optimization. Moreover, effects of energy dissipation of the ACK packets on the energy dissipation are also investigated. In this respect, ACK packets with different sizes such as 1 Byte and 20 Bytes are chosen to evaluate the results. As a result, it is found that the number of overhead bits directly affects the energy dissipation and the normalized network lifetime with the 1 Byte ACK packet is higher than the normalized network lifetime with the 20 Bytes ACK packet. This is because ACK packet is sent for each successful transmission and if the number of packets

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Table IV. Comparison of packet size optimization techniques based on their taxonomy

Taxonomy	Study	Energy efficiency	Reliability	Network lifespan	Latency
Fixed packet size	Sharma [30]	Yes	Yes	No	No
	Sankarasubramaniam *et al.* [10]	Yes	No	No	No
	Zhao *et al.* [34]	Yes	No	No	Yes
	Abdulhadi *et al.* [24]	Yes	No	No	No
	Kilic and Gungor [28]	Yes	Yes	Yes	Yes
	Holland *et al.* [25]	Yes	No	No	No
	Wang *et al.* [32]	Yes	No	Yes	Yes
	Kohvakka *et al.* [29]	Yes	Yes	Yes	No
	Karthi *et al.* [26]	Yes	Yes	Yes	Yes
	Singh *et al.* [31]	Yes	Yes	Yes	No
	Xia *et al.* [33]	Yes	No	Yes	No
	Khalaf and Abdul-Hameed [27]	No	Yes	No	Yes
	Yaakob *et al.* [36]	No	Yes	No	Yes
Dynamic packet size	Jelenkovic and Tan [40]	No	No	No	Yes
	Dong *et al.* [14]	Yes	Yes	Yes	No
	Deng *et al.* [38]	No	Yes	No	Yes
	Nandi and Kundu [43]	Yes	Yes	Yes	No
	Ci *et al.* [37]	Yes	Yes	Yes	Yes
	Li *et al.* [44]	Yes	No	Yes	No
	Lendvai *et al.* [41]	Yes	No	Yes	No
	Lendvai *et al.* [42]	Yes	No	Yes	No
	Jamal *et al.* [39]	Yes	Yes	No	Yes
Packet Size Optimization Framework	Vuran and Akyildiz [21]	Yes	Yes	Yes	No
	Chudasama and Trapasiya [45]	Yes	Yes	Yes	No
	Akbas *et al.* [11, 12]	Yes	No	Yes	No
	Datta and Kundu [46]	Yes	Yes	No	Yes
	Datta and Kundu [47]	Yes	Yes	Yes	Yes
	Datta *et al.* [48]	Yes	Yes	Yes	Yes
	Majumdar *et al.* [49]	Yes	Yes	Yes	No

increases, the energy dissipation of the ACK packets with higher size consume more energy. Finally, a key result of this study is that the maximum possible network lifetime can be achieved when the maximum allowable packet size is utilized.

An analytical framework is presented to evaluate the optimal packet size in code division multiple access (CDMA)-based WSNs with layered architecture by Datta and Kundu [46]. Many channel conditions, which are node density, power control error (PCE), and correlation, are considered while determining the optimum packet size and the energy efficiency is used as an optimization metric. Simulations are performed to analyze the impact of node density, PCE, and correlation on

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the optimal packet size. Results show that optimum packet size increases as node density and PCE increase. The proposed framework chooses optimal packet size based on the channel parameters to increase the energy efficiency. Furthermore, delay of file transmission is also investigated in this study. Performance evaluations show that when the optimum packet size is chosen under different network conditions, energy efficiency of a WSN is maximized. This study is extended by developing and employing nearest neighbors based routing by Datta and Kundu in [47]. To assess the resource utilization performance of the multi-hop data delivery scheme in CDMA based WSNs, several network parameters are investigated such as node density, delay, packet size on the energy efficiency and search angle. Different optimal packet sizes are found under various network conditions. Paths between the sink and source nodes are constructed among the relay nodes which are selected according to the nearest node within a sector angle. The performance of proposed framework is measured by investigating the impact of packet size under different search angles on resource utilization. Results of performance evaluations show that the best resource utilization performance is achieved with optimized packet size at low search angle. This finding is important since resource utilization is critical for providing the energy efficiency in CDMA-based WSNs.

Datta *et al.* [48] present a framework for packet size optimization to reduce the energy consumption and delay in WSNs. In this respect, a new routing protocol for a multi-hop CDMA-based WSN is proposed. The proposed protocol selects the intermediate nodes for multi hop transmission according to the probability of detection and maximum advanced distance by considering the wireless channel conditions such as, path loss and shadowing. Furthermore, the performance of this routing protocol is compared with nearest neighbor based routing scheme, which is proposed by Tsai [50], and optimal packet size for optimizing the resource utilization is found under these routing schemes. Two forwarding protocols are used to model the WSN in the proposed framework. These are a routing protocol which is based on search angle and a forwarding protocol which is based on probability of detection with maximum forwarding distance. Network architecture of the routing protocol based on search angle is modeled similar to nearest neighbor based forwarding protocol in which the N number of nodes are randomly deployed over a predetermined area (A). However, finite A causes the edge effects in this protocol. Therefore, while designing the routing protocol based on search angle, network surface is assumed to be the surface of a torus. The proposed framework uses a CDMA-based MAC protocol. Optimal packet size is estimated in order to optimize resource utilization which is a metric and consists of the combination of energy consumptions and delay of packet transmissions. Simulations are performed to evaluate the performance of forwarding protocol and routing protocol. Different optimum packet sizes are found according to routing protocols with the search angle and probability of detection. For instance, 69.59 bits/packet and 141.69 bits/packet are respectively found as optimized packet lengths for the search angles of 40° and 60° in routing protocol based on search angle. Further 164.09 bits/packet and 127.8 bits/packet are defined as the optimized packet lengths for the probabilities of detections of ≥ 0.99 and ≥ 0.8 in routing protocol based on probability detection. Results of all performance evaluations also show that channel-aware protocol with high probability of detection achieves the best resource utilization, when optimum packet size is used.

A joint optimization framework is proposed to find optimal packet size by Majumdar *et al.* [49] by using variable rate *m-QAM* based modulation scheme for the CRSN. The proposed framework is also extended to a Multiple Input Multiple Output (MIMO) CRSN to find the optimal packet

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size under bad channel conditions. Sensor node, which has the channel sensing capacity, is called as a secondary user (SU); otherwise it is called as primary user (PU) in CRSN. The proposed framework determines the optimal packet size with formulating and numerically analyzing the joint optimization problem by considering end-to-end delay. As a result, the optimization problem is formulated to determine the optimal packet size with variable rate *m-QAM* for point to point link for M cognitive secondary users in the system. In this formulation, constraints are determined as the total transmission time, transmit power, and total average BER. Performance evaluations are done with simulations for finding the optimal packet size for different users under various operating scenarios. Furthermore, simulations are also performed to show the performance of point to point scheme with variable rate *m-QAM* modulation. Firstly, it is shown that the optimal packet size increases as the number of secondary cognitive users and as the number of Industrial Scientific Medical (ISM) channels such as 10, 20, and 30 increases with the fixed rate FSK. Furthermore, FSK cannot provide the goal in the proposed CRSN design settings since it only supports 3 users and 8 users when the signal bandwidths are 20 KHz and 5 KHz, respectively. Moreover, the performance of *m-QAM* is also evaluated with the number of ISM channels 10 while the other parameters are kept same and the optimal packet size is determined by using the proposed joint optimization problem. Results show that the performance of variable *m-QAM* is better than the fixed rate FSK system. Optimal packet size increases as the signal bandwidth increases because the optimal transmission time decreases as the signal bandwidth increases. Therefore, the energy efficiency throughput reaches the maximum value as the signal bandwidth and optimal packet size increases. Furthermore, it is also shown that cost function value decreases and the optimal packet size increases as the signal bandwidth increases. For instance, optimal packet size is 125 at 5 KHz for 2 users with the maximum cost function value which is 0.75, however, it is 230 at 20 KHz with the cost function of 0.57. As a result of these evaluations, it is found that optimal packet size value increases by 20% since the optimal packet size for 3 users is 230 when the proposed framework is used; otherwise, its value is 190 when the fixed rate FSK is used. Further optimal packet size values are found when the proposed variable data rate point to point CRSN framework is extended to MIMO+CRSN architecture. It is observed that optimal packet size value is 150 at 20 KHz for 7 users with MIMO+CRSN, however, it is 100 when point to point scheme is used. This shows that 50% increase in the optimal packet size value can be achieved with the MIMO+CRSN scheme with the minimum cost function value.

3. PACKET SIZE OPTIMIZATION FOR UNDERWATER SENSOR NETWORKS

UWSNs consist of autonomous sensor nodes which are spatially deployed underwater to measure quality, temperature and pressure of the water. These autonomous sensor nodes are connected wireless to transmit various data. Communication is performed by using acoustic transceivers in UWSNs. Acoustic waves, which are transmitted by these transceivers, provide small bandwidth and long wavelengths. UWSNs are used by many applications such as monitoring marine environments for coastline protection, underwater pollution monitoring, *etc.* [51]. Although UWSNs facilitate an encouraging solution to these applications, they also present certain challenges for communication

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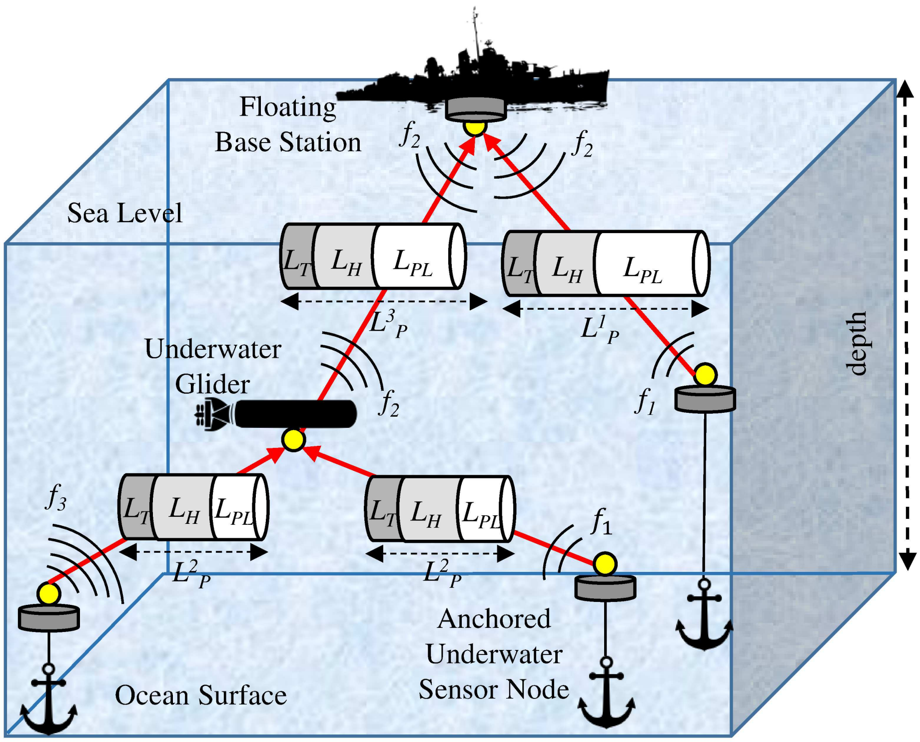

Figure 4. Packet size optimization model for a typical UWSN.

due to unique characteristics of UWSNs such as unpredictable nature of water environment, multi-path propagation, fading, shadow zones, low bandwidth, and low signal propagation speed. Many studies are performed to improve the capabilities of UWSNs. In Figure 4 we show a packet size optimization model for a typical UWSN. In this scenario, several underwater nodes (with various depths) are anchored to the bottom of an ocean and there is a floating base station on the sea surface. There is also an underwater glider acting as a relay node to reduce the propagation delays. Each node in this network operates at various frequencies (*i.e.*, f_1, f_2, and f_3). Since the nodes near to the bottom of the ocean experience higher losses, smaller packets are preferred. On the other hand, nodes close to the sea level (and thus to the floating base station) utilize longer packet sizes since the path loss in these acoustic links are much lower when compared to the previous case.

There are several packet size optimization techniques deployed for UWSN environment. The goal of these approaches is to ensure a successful transmission based on critical performance metrics. Throughput efficiency is defined as an efficiency metric by Basagni *et al.* [52]. Basagni *et al.* present their findings obtained from simulations for choosing the optimum packet size in UWSNs. According to their simulations, there is an optimum packet size in underwater wireless acoustic (UWA) communications. However, it is highly influenced by the BER and offered load. They consider the selective ARQ and packet fragmentation for random access UWSNs. Delay-aware collision avoidance protocol (DACAP) is used as a MAC protocol. The purpose of using this protocol is to prevent the destructive effect of collision by reducing the number of retransmission, hence decreasing network traffic. In addition, fragmentation is used to increase the throughput efficiency which is especially high at low BER values. In the proposed solution, each packet is

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divided into k fragments and each node sends these fragments with ACK bits. If a fragment is delivered successfully, the receiving node sends back 1 as a success indicator otherwise sends 0 and failed fragments are re-transmitted. Simulations are performed with two BER values (*i.e.*, 10^{-6} and 10^{-4}). 10^{-6} BER value performs better than 10^{-4} BER value when fragmentation is not done and their performance are close to each other when the number of fragmentations increases. As a result of the simulations, optimal fragmentation for both BER values is range of between 20 and 50. Simulation results show that there exist an optimal packet size in UWSNs for increasing throughput efficiency. However, simulations do not demonstrate the power efficiency of the finding packet size since no power control mechanism exists in their proposed approach.

The impact of packet size selection on CSMA and DACAP are investigated by Basagni *et al.* [53] for UWSNs. Simulations with ns-2 are performed by considering BER and interference to make a comparative analysis. Two different BER values (*i.e.*, 10^{-6} and 10^{-4}) are chosen for their experiments. Results from these experiments are evaluated by using three performance metrics: the throughput efficiency, the end-to-end packet latency, and the energy consumption. It is observed from the obtained results that packet latency increases depending on increase of packet size for both BER values. When the selected BER value is 10^{-6}, energy consumption reaches the minimum value with the packet size of 500 Bytes. On the other hand, when the BER value is 10^{-4}, energy consumption increases. As a result of these analysis, it is shown that the suitable packet size can be selected for UWSNs based on the data rate, BER, packet arrival rate, and the chosen MAC protocol. Furthermore, their comparative analysis also shows that although performance of CSMA is better when the short packet size is used, DACAP is more efficient with longer packet size.

Another study is proposed by Jung and Abdullah [54] to increase the energy efficiency in UWSNs by finding the optimal data packet size. In this study, the relationship between the energy efficiency and the optimal packet size is investigated through UWSN simulations. The optimal packet size, providing the optimum energy efficiency, is specified with a look-up table located in a database. Jung and Abdullah choose the energy efficiency as a performance metric to meet power constraints of power-limited underwater sensor nodes. This study is only done for UWSNs at very warm shallow tropical waters (50 m to 200 m) with medium transmission range (100 m to 2 km). ns-2 miracle package, Ubuntu platform, and ns-2 network simulator are used for network setup. 100 nodes are deployed in the middle of a 2 km$\times$2km$\times$200 m area. Shallow water environment is simulated in the depth of 200 m. A sink node is deployed at the center of the cluster to collect the data packets from other nodes. Distance between the sink node and the source node is varied from 100 m to 1 km. One transmitter and one receiver are created at a time with constant bit rate (CBR) in the simulation. From transmitter to receiver the CBR packet flow is started using the ns-2 miracle layered framework. The CBR module of the transmitter generate the required packet size. BPSK modulation is used to transmit the packets through the underwater channel by the MIRACLE physical layer (MPHY). Packets have 10 bits of header and the payloads change from 10 bits to 1000 bits. ALOHA protocol is used to send the packets through the network. It retransmits the packets if a packet collision occurs; otherwise, it sends the ACK for successful transmission. Simulations are performed to measure the energy efficiency and the obtained results put into a database. Firstly, energy efficiency is measured as packet size increases under different BER values (0.0001, 0.001, and 0.01). It is shown that an optimum packet size, which maximizes the energy efficiency, can be found for each BER. For instance, the optimum packet size is 100 bits, which provides the

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maximum energy efficiency of 84%, with the 0.001 BER value. Further it is also found that energy efficiency decreases as the BER value increases because more data packets are corrupted and more retransmissions are needed when the link quality is bad. In addition, it is also observed from the simulations that energy efficiency does not sharply reduce with low BER after its peak value and optimal packet size decreases as the link quality reduces.

Data link protocols are developed and analyzed for UWA system by Stojanovic [55]. The aim of this study to develop an efficient protocol at data link layer for UWSN with formatting of data packets controlled with ARQ protocol. The ARQ is a Stop-and-Wait (S&W) protocol that is affected from low throughput efficiency in UWA channel because of the high BER and the long propagation delay. In this study, the basic S&W protocol is improved to solve this problem by transmitting data packets in groups and performing selective acknowledgement method. The throughput efficiency can be maximized with this modified S&W protocol if the optimum packet size, which is influenced from range, rate and error probability, is selected. In this respect, three types of S&W protocols are employed which are the basic S&W protocol called as S&W-1 and two S&W protocols proposed in [56] and in [57] called as S&W-2 and S&W-3, respectively. S&W-2 and S&W-3 provide group transmission by sending up to M packets. In the proposed protocol, it is assumed that each packet has a total number of $N = N_d + N_{oh}$ bits. The number of data bits is defined as the N_d, and the packet overhead is defined as the N_{oh}. $T_p = N \times T$ is determined as the packet duration. T is the bit duration and defined as $T = 1/R$, where R is defined as the bit rate. By combining this formula with the acknowledgment time (T_{ack}) and with the total waiting time (T_w) the formula of total transmission time for sending M packets is: $T_M = M(T_p + T_{ack}) + T_w$. Throughput efficiencies of protocols such as S&W-1, S&W-2, and S&W-3 are formulated by using this total transmission time formula. All these efficiency formulas are combined and an upper bound of throughput efficiency expression is obtained, which is $\lim_{M \to \infty} \eta_{2,max} \approx 1 - \sqrt{N_{oh} \times P_e}$, where P_e is the packet error rate. Performance evaluations are done to show the throughput efficiency of S&W protocols. Firstly, throughput efficiency of them are shown as the packet size increases for several values of rate-range product such as 5×10^4, 5×10^5, and 5×10^6 meter-bits/second. The N_{oh} and M are set to 8 and 16, respectively. It is shown that S&W-2 and S&W-3 outperform the S&W-1 with the optimal packet size since throughput efficiency of S&W-1 is low in all rate-range products. Further it is also observed that the performance of the S&W-2 is better than S&W-3. In addition, the optimal packet size values for S&W-1 and for S&W-2 are shown under different P_e which are 10^{-3} and 10^{-4} and various rate-range products such as 5×10^4 and 5×10^5. Further optimal packet size of the limiting case of S&W-2 with $M \to \infty$ is also shown. As a result, it is seen that the optimal packet size highly varies according to BER value. However, S&W-2 protocol can improve the throughput efficiency by reducing sensitivity of optimal packet size with respect to BER.

An algorithm is proposed by Ayaz *et al.* [58] to determine optimum packet size for increasing the transmission reliability in UWSN. The proposed algorithm uses a two-hop acknowledgement (2H-ACK) model where the same copy of a data packet is maintained by the two nodes in the UWA network. The aim of this algorithm is to increase energy efficiency and throughput with decreasing BER by reducing channel impairments such as path losses and fading in UWSNs. 2H-ACK algorithm follows the data forwarding and acknowledgment method. Each node in the network has its own HopID. A source node, which has the data packet to send, firstly asks its neighbors for their HopIDs before transmission, then its neighbors reply their HopIDs to the source node. HopIDs

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are compared and the neighbor node, which has the smallest HopID, is selected as the next hop by the source node. After this selection, source node sends the packet to the selected neighbor node, the neighbor node does not send ACK to source node, immediately. It firstly tries to find next hop node for sending the data packet through the sink node by repeating the same process as the source node. After it finds the next hop, it sends the ACK packet and the data packet to the source node and its next hop node, respectively. When the source node gets the ACK, it removes the sent packet from its buffer. This is continued until all data packet transmitted to the sink node. In this way, this algorithm provides reliability for UWSNs which are highly affected from sparseness and continuous node movements. Simulations are performed to evaluate the performance of the proposed algorithm. In the first analysis, impact of packet size on the BER is analyzed with various header sizes (*i.e.*, 30, 40, 50, 60, 70, 80, 90, and 100 bits) when the proposed algorithm is used. It is observed that optimum packet size increases as the BER decreases. Further it is also shown that header size does not effect the optimal packet size when the BER is high, however, optimal packet size with the higher header size increases as the BER decreases. Furthermore, energy efficiency of the proposed algorithm is also shown under different BERs such as 0.01, 0.001, 0.0001, 1e-005, and 1e-006. Results show that high energy efficiency is achieved when the BER is low, however, energy efficiency sharply decreases for high BER if the packet size is continued to increase after the maximum energy efficiency value. According to these results, it is found that an optimum packet size, which maximize the energy efficiency, can be defined for each BER value. For instance, 100 bits is found as the optimum packet size, which provides the maximum energy efficiency about 84%, for 0.001 BER. Moreover, the simulations are also performed to compare the proposed 2H-ACK scheme with the hop-by-hop ACK method (HbH-ACK) which uses one ACK during hop-by-hop transmission. Performance of these methods are shown with number of delivered data packets as the number of nodes increases. Results show that the proposed 2H-ACK scheme outperforms the HbH-ACK method. Further it is observed that the number of delivered packets increased as the number of nodes increases.

4. PACKET SIZE OPTIMIZATION FOR UNDERGROUND SENSOR NETWORKS

WUSNs are used in a wide range of applications, such as agricultural applications for monitoring soil properties and environmental monitoring applications for surveillance of toxic substances [63]. Existing underground monitoring applications use many sensors, which are connected to the surface via wires. On the other hand, WUSNs have sensors which are completely deployed under the ground and do not require wired connections. Wireless communication under the ground is much more challenging than the communication through the air because of the nature of the underground environment. Therefore, this factor plays a crucial role to determine the optimum packet size for WUSNs together with redesigning the communication protocols to increase the performance of monitoring applications. There are only a few studies are done on WUSNs [64, 65, 66]. Similarly there are a few studies on the packet size optimization for WUSNs [67, 68, 21].

Lin *et al.* [67] propose a distributed cross layer optimization framework, Xlayer, that conserves energy with a gain of throughput for magneto-inductive WUSNs which satisfies a pre-defined level of QoS. Authors compare the performance of Xlayer with current layered protocols in the

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Table V. Literature overview of packet size optimization techniques in UWSNs, WUSNs, and BASNs

Environments	Techniques	Purpose	Performance Metrics
UWSNs	Optimal packet size selection [52]	Improving the throughput efficiency, latency, and energy consumption in UWSNs.	Throughput efficiency, latency, energy consumption
	Measuring impact of packet size selection on the CSMA and DACAP protocols [53]	Determining the optimum packet size according to the BER value.	Throughput efficiency, latency, energy consumption
	Finding the optimal packet size with using a lookup table [54]	Increasing the energy efficiency by finding the optimal packet size	Energy efficiency
	A cross-layer optimization framework [21]	Finding the optimal packet size in TWSNs, UWSNs, and WUSNs.	Packet throughput, energy per useful bit, resource utilization
	Developing data link protocols for UWA system [55]	Developing an efficient data link layer protocol with formatting the data packets.	Throughput efficiency
	An optimum packet size algorithm with 2H-ACK [58]	Increasing the energy efficiency and throughput by reducing channel impairments	Energy efficiency, throughput
WUSNs	A cross-layer optimization framework [21]	Finding the optimum packet size for all TWSNs, UWSNs, and WUSNs	Packet throughput, energy per useful bit, resource utilization
BASNs	Analysis of packet size optimization for BASNs and applying hop-length extension to FEC block codes [59]	Finding the most appropriate error control scheme to increase energy efficiency with the optimal payload packet size.	Energy efficiency
	Optimizing the MAC frames in IEEE 802.15.6 UWB [60]	Increasing the energy efficiency by optimizing MAC frames.	Energy efficiency
	A flexible non-layered and application-oriented role-based architecture for BASNs [61]	Increasing the energy efficiency with the error control schemes for an optimal packet size.	Energy efficiency
	A solution to prevent the congestion problem in BASNs [62]	Minimizing the retransmission attempts by determining the optimum packet size.	Packet delivery ratio, average end-to-end delay, number of retransmissions, overhead

literature. On the physical layer, authors investigate two modulation/FEC combinations (*i.e.*, BPSK or BFSK modulations / no FEC or BCH(63,57,1)) to determine the amount of energy consumed for a

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Table VI. Comparison of packet size optimization techniques based on their environments

Environment	**Study**	**Energy efficiency**	**Reliability**	**Network lifespan**	**Latency**
UWSNs	Basagni *et al.* [52]	Yes	Yes	Yes	No
	Basagni *et al.* [53]	Yes	Yes	Yes	Yes
	Jung and Abdullah [54]	Yes	Yes	No	Yes
	Vuran and Akyildiz [21]	Yes	Yes	Yes	No
	Stojanovic [55]	Yes	Yes	No	No
	Ayaz *et al.* [58]	Yes	Yes	No	No
WUSNs	Vuran and Akyildiz [21]	Yes	Yes	Yes	No
BASNs	Domingo [59]	Yes	Yes	No	No
	Mohammadi *et al.* [60]	Yes	Yes	No	No
	Domingo [61]	No	Yes	No	No
	Yaakob and Khalil [62]	No	Yes	No	Yes

successfully decoded payload bit. Authors reveal that proposed framework performs better for short transmission distances. At MAC and network layers authors examine the energy and throughput performance of Xlayer against two popular centralized cross layer protocols (*i.e.*, Geographical Routing – GEOR and Transmitted Power Level-based Greedy Routing – TPL-GR). Proposed framework performed better than GEOR and TPL-GR with a minimum energy saving of 40% and 8 dB of throughput gain. The authors expand their work in [68] and reported that energy saving can be up to 50% with a 6 dB of throughput gain. In addition, a two-phase decision game is developed to determine the best energy savings and throughput gain with a low computation complexity.

Vuran and Akyildiz [21] developed a cross-layer optimization framework to optimize the packet size for WSNs, UWSNs, and WUSNs. While designing this solution, broadcast feature of the wireless, underwater, and underground channel, the cross-layer effects of multi-hop routing, and error control techniques effects are all considered. Relationship between the packet size and routing decision and requirements of different types of applications are also considered in this study. Three different objective functions such as throughput, energy per useful bit, and resource utilization are formalized in the proposed optimization solution. Each of these functions can be used according to the application requirements. Moreover, reliability and delay effects are investigated.

For WSNs perspective, a log-normal shadowing path loss model is employed. The optimal packet size is determined by the framework based on the medium access collisions and routing decisions. Optimization results show that packet size and the SNR threshold value directly affect the energy consumption, end-to-end packet error rate, and end-to-end delay. SNR threshold is used to construct the routes because it checks minimum quality of wireless channel at each hop for transmission. If this value is small, low quality links are chosen and the average hop length decreases. This causes high energy consumption due to retransmissions. Therefore, small packet size should be chosen when the SNR threshold is low. This shows that SNR threshold value directly affects the size of the optimum packet. In this respect, the optimum packet sizes and the optimum SNR threshold values

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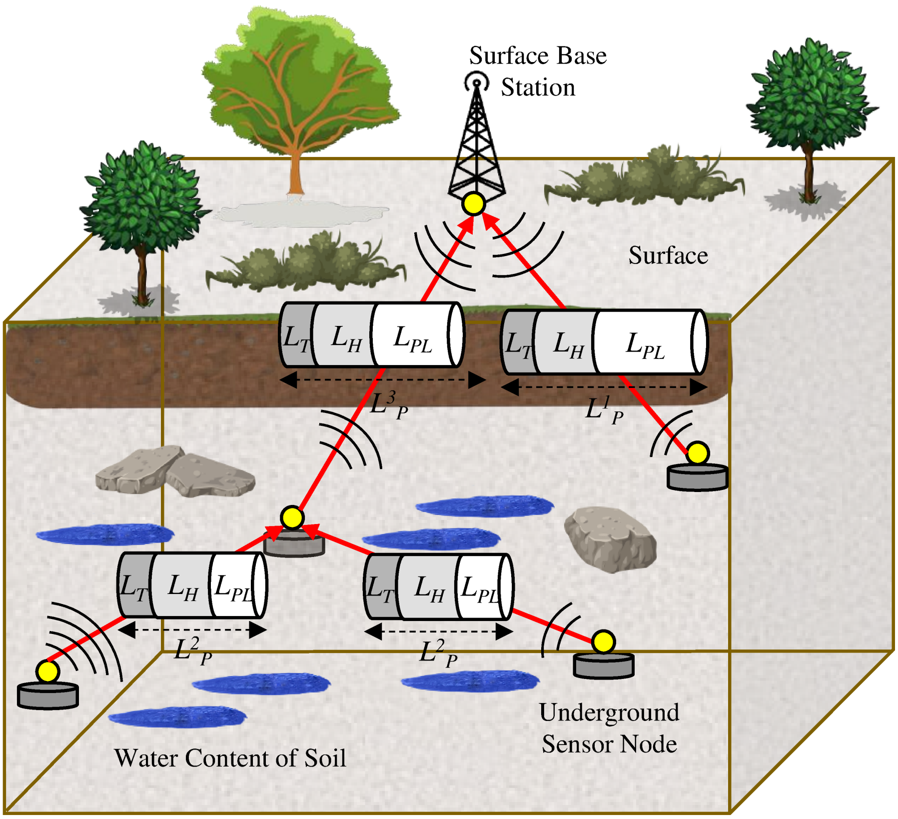

Figure 5. Packet size optimization model for a typical WUSN.

are found with the energy consumption per useful bit, end-to-end latency, throughput, and end-to-end success rate for maximizing throughput, for minimizing energy consumption and resource utilization. Two error control mechanism, ARQ and FEC, are used to prevent the packet errors. Therefore, these error control mechanisms are also considered while deciding the optimal values. For instance, it is found that when the energy per bit minimization problem is considered, ARQ scheme with a payload length of 473 Bytes achieved the minimum energy consumption. For UWSNs perspective, Urick path loss formula and Rayleigh fading channel model are used to characterize the underwater channel model. Deep water environment and shallow water environment for UWSNs are also investigated for determining the optimum packet size. Analysis is done with various optimal packet lengths (50, 100, 150, and 200 Bytes) with different forward error control capabilities in which the error correcting capabilities (t) are 2, 3, 5, 7, and 9. Results show that FEC schemes provide higher energy efficiency with longer packet length than the ARQ scheme at a certain packet length. Furthermore, latency, energy consumption, and expected BER are also analyzed through simulations. As a result, it is found that 547 Bytes is obtained as an optimum packet size for throughput maximization in deep water environment when ARQ scheme is used. On the other hand, 616 KB is found as an optimal packet size for maximizing throughput in deep water when reed-solomon (RS) (255,239,8) code is used. RS(255,239,8) increases the throughput by 9% when compared to ARQ scheme since it sends larger packet size than ARQ scheme.

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For WUSNs perspective, the underground channel is modeled based on the findings reported in the study of Li *et al.* [69] to determine the optimum packet size. They present the path loss function depending on the soil properties, the volumetric water content of the soil, the BER based on the error function, and SNR. ARQ and BCH(128,78,7) error control techniques are considered for the simulation results. Authors demonstrate that there is a significant dependence between the volumetric water content and the packet size. Further energy consumption increases by 60% and packet throughput decreases by 37% when the volumetric water content increases from 5% to 20%. Moreover, it is found that if the volumetric water content increases, the optimum packet size decreases. Therefore, communication protocols must adapt the changes in the water content of the soil and change the packet size accordingly to increase the performance of underground monitoring applications. In Figure 5 this result is visualized by using several underground nodes that are located in various depths. The sink for this network is chosen as a surface base station. Similar to the underwater case, each node operates at various frequencies. Deeper nodes are located in a soil where the volumetric content of water is higher than the soil near to the surface. It is seen that deeper nodes opt to utilize smaller packets since the water content of the soil is high and nodes closer to the surface (which is assumed to have lower water content) use larger packets.

As a result of analysis in [21], it is shown that the optimal packet sizes are varied according to wireless sensor network types (*i.e.*, TWSNs, UWSNs, and WUSNs) and should be determined according to application requirements.

5. PACKET SIZE OPTIMIZATION FOR BODY AREA SENSOR NETWORKS

BASN devices can be embedded inside the human body or mounted on the surface of the body to monitor body motions and to track physiological parameters. Most of the BASN applications are related to health-care for continuous monitoring of patients who have chronic diseases. There are also other applications where BASNs are commonly used such as emergency response, disaster victim monitoring, and performance evaluation of the athletes [70, 71, 72, 62].

Even though TWSNs and BASNs have similar architectures, BASNs have some different requirements, including smaller scales and different frequency bands for body monitoring. Furthermore, sensor nodes used in BASNs have also different operational characteristics and channel characteristics of in-body and on-body environments are very different compared to TWSNs [73]. Human movements and dynamic propagation environments make realization of reliable and energy-efficient BASNs a challenging task. In addition, the body shadowing, which occurs when the signal path between the implant wireless device and the transceiver is obstructed, is also another challenging issue for BASN communication [74]. Energy consumption is the most critical issue in BASNs [75, 76]. Existing TWSN-based packet size optimization techniques may not be directly applied to BASNs due to the aforementioned differences between BASNs and TWSNs. Packet size optimization for BASNs is analyzed for increasing the energy efficiency by Domingo [59]. Different error control mechanisms including ARQ, FEC block codes such as BCH, RS, and FEC convolutional codes are analyzed. The hop-length extension technique with FEC block codes are applied. Longer distances can be reached by the FEC block codes with the hop-length extension technique because this technique extends the transmission range for the same transmission power.

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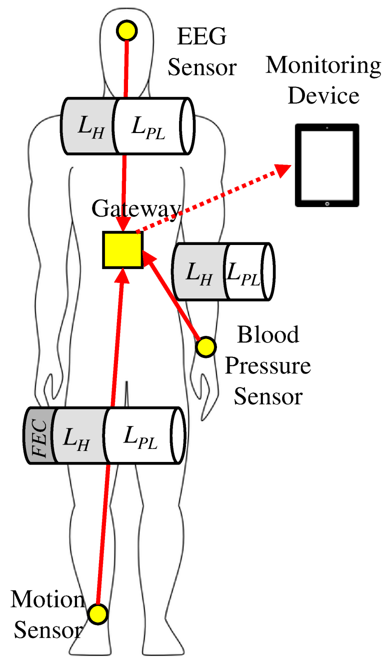

Figure 6. Packet size optimization model for a typical BASN.

This result is illustrated in Figure 6, where three sensor nodes are used to monitor EEG, motion, and blood pressure. These sensor nodes are conveying the acquired data to the central gateway node which can be monitored by a mobile monitoring device (such as a smart phone or tablet). Since the distance between motion sensor and gateway sensor is higher, by using a FEC mechanism, longer distances can be reached with less errors hence longer packets are favored in this case. On the other hand, sensor nodes do not use a FEC mechanism, thus smaller packets are used.

This study is done by considering health-care monitoring. In this respect, the physiological states of a person is monitored with in-body and on-body sensors and the collected states are transmitted through a gateway with single-hop transmission. Then, this data is transmitted through a monitoring station by the gateway. In this study, energy efficiency and optimal packet size are formulated with different error control schemes for in-body and on-body sensor networks. Simulations are performed by considering different scenarios for in-body and on-body propagation environments. Numerical evaluations are performed to show the energy efficiency performance of ARQ and FEC codes. Firstly, impacts of modulation schemes such as On-off keying (OOK) and BPSK on the BER for on-body and in-body sensor networks are analyzed as the distance between the gateway and the body surface get increased. Line-of-sight (LOS) and Non-Line-of-Sight (NLOS) channel models are used in this simulation. NLOS model has higher path loss than the LOS model and therefore, lower hop-length extensions are supported by the NLOS model. It is found that BPSK can extend the hop-length more than the OOK for a specific BER value and for all NLOS and LOS channel models in both in-body and on-body sensor networks. Further it is shown that BPSK achieves lower BER than OOK modulation for a specific distance. In addition, the impacts of packet size optimization on the energy efficiency for the error control schemes such as ARQ and convolutional

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code with R_c = 1/2 are investigated with different BER values which are 10^{-3} and 10^{-5}. The energy efficiency is higher and decays lower with the increase of packet payload for in-body sensor networks than the on-body sensor networks. This is because on-body sensor networks are affected from the variation of fading. As a result, the optimal packet payload lengths are obtained for both in-body and on-body sensor networks according to the different BER values. Results show that optimal packet size is smaller for on-body sensor networks than the in-body sensor networks because of the fading effects. Further, it is also shown that ARQ scheme provides more energy efficiency as the payload length increases than the convolutional code with R_c = 1/2 for both in-body and on-body sensor networks. Moreover, energy efficiency is analyzed as payload length increases with FEC block codes such as BCH(127,8,31), BCH(127,12,1), BCH(127,120,10), BCH(127,120,1), and BCH(127,120,5) for an in-body and on-body sensor networks. It is found that FEC block codes provide more energy efficiency than the other error control schemes. If the payload length k of the block code increases, the optimal packet size and energy efficiency increase for the same error correcting capability and same block length because packet error rate decreases. Moreover, when the error correcting capability decreases, Packet Error Rate (PER) increases, however, the energy efficiency increases because energy consumption of decoding decreases. For this reason, energy efficiency of BCH(127,120,5) is 20.3% lower than BCH(127,120,1) for 3600 bit payload length. Finally, the hop-length extension is analyzed between the gateway and the sensor nodes for providing high energy efficiency. Evaluations are done for the energy efficiency as the distance increases for payload lengths of 2000 bits and 350 bits for in-body and on-body sensor networks. 31.7% higher energy efficiency is achieved with the payload length of 2000 bits when compared with the payload length of 350 bits. Further it is observed that the energy efficiency of the ARQ scheme and the convolutional code with R_c = 1/2 are the lowest for in-body and on-body sensor networks, respectively. In addition, energy efficiency of convolutional code with R_c = 1/2 with a payload length of 2000 bits and BPSK modulation is 7.6% and 6.2% lower than RS(63,55,4) and ARQ, respectively, for on-body sensor networks. As a result of all simulations, it is observed that the maximum hop length can be extended with the FEC block codes and with BPSK modulation.

MAC frames are optimized to increase the energy efficiency in IEEE 802.15.6 ultra-wideband (UWB) BASNs by Mohammadi *et al.* [60]. In order to achieve this goal, the probability of packet detection and the successful reception of the packet are computed for the two QoS modes: the default mode and the high QoS mode, of UWB. The default mode uses BCH(63,51) code for FEC and on-off signaling for general WBAN applications. On the other hand, the high mode is used for high priority and medical applications and exploits type II hybrid automatic-repeat-request (H-ARQ) with differential signaling. In this study, energy efficiency is modeled by combining energy consumption costs of uplink and downlink channels and reception and transmission energies. In the proposed system model, IEEE 802.15.6 UWB physical layer protocol data unit (PPDU) is used. PPDU consists of three parts such as physical layer (PHY) service data unit (PSDDU), a physical layer header (PHR), and a synchronization header (SHR). Packet detection and synchronization are provided by SHR. Formulations are done in order to find the probability of successful packet detection (P_{SHR}), the probability of successful reception of PHR (P_{PHR}), and the probability of success of transmission of packets (P_{PPDU}). Theoretical results are compared with the simulated results for default mode and high QoS mode as the SNR increases. As a result, it is found that minimum SNR values must be 15.5 dB and 9.8 dB to achieve 99% packet success probability

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(P_{PPDU}) for energy detection with default mode and for autocorrelation with high QoS mode, respectively. Furthermore, energy efficiency is measured for various frame lengths and bit error probabilities such as 7.3×10^{-2}, 1.2×10^{-2}, 8.8×10^{-3}, 5.2×10^{-3}, and 3.4×10^{-3} as the frame length increases. Results show that the optimal packet size increases as the bit error probability decreases. For instance, the optimal packet size is 300 octets when the bit error probability is 5.2 $\times$ $10^{-}3$ for default mode and it is 76 octets when the bit error probability is 1.2×10^{-2}. Finally, optimal frame length to maximize energy efficiency in IEEE 802.15.6 UWB BASNs is also found according to a closed form expression for the default mode.

A flexible non-layered and application-oriented role-based architecture for BASNs is presented by Domingo [61]. Various scenarios such as health care tracking, emergency case, entertainment, sport, and military are given as potential applications for BASNs. Monitoring movements of pregnant women or people who has psychological problems can be given as examples of health care scenario. In addition to this, real time data transfer is crucial for emergency cases such as fire and natural disasters. In this scenario, BASN network can supply key information as condition, location, and injury of victims and officers. Game systems are changed by using wearable technology. Nowadays, gamers are more interacted with games, some of the games let users to control their character with their whole body by wearable technology. Gamer sends their control command to system over BASN network. In the military scenario, soldier protection is done with monitoring the soldier vital sings and send them to medical personal through the BASN network. Based on the observation that requirements of each BASN application is different from each other, the proposed architecture assigns three functional roles which are basic roles, specific roles, and particular roles. Basic roles include context-aware information role, QoS role, routing role, error-free delivery role, security and privacy role, and fragmentation role. On the other hand, applications, which are under the same scenario, share the specific roles and the particular roles, separately. Role data of application is put into the role headers and can be used by the other applications. Therefore, other roles do not need to be inserted and the network load decreases with the role selection. Furthermore, throughput efficiency of error control schemes, such as ARQ, BCH(127,20,1) and convolutional code R_c=1/2, are evaluated for the proposed role-based architecture. The optimal packet size for each of these error control schemes are also found to increase the throughput performance. For instance, optimal packet size, which maximizes the throughput efficiency, is 211 bits for ARQ scheme with 10^{-3} BER. Performance evaluations show that the proposed role-based architecture outperforms the traditional layered architecture in terms of throughput efficiency. In addition, the throughput efficiency performance of the proposed role-based scheme is also evaluated with the same error control scheme under various BER values (*i.e.*, 0.001 and 0.00001) as the payload length increases. It is shown that throughput efficiency and the optimal payload length increase as the BER value decreases. Moreover, throughput efficiency with several payload lengths such as 350 bits and 2000 bits are measured as the distance increases with the same error control schemes for in-body and on-body sensor networks with LOS channel model and on-body sensor networks with NLOS channel model. It is observed that larger payload provides higher throughput efficiency (*e.g.*, throughput is 12.8% higher with 2000 bits payload length than with 350 bits payload length). Further it is also shown that throughput efficiency of the error control schemes is good as the payload size increases. It is also observed that FEC block codes combined with the hop-length extension technique and BPSK modulation achieves the highest throughput with the optimal packet size.

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Table VII. Optimum packet sizes according to WSN applications

WSN Application	Requirement	Optimum Packet Size
Health-care & military applications	High energy efficiency & error-free transmission	640 bits [62]
Industrial automation & intelligent households & intelligent households	High throughput	1408 bits [29]
Habitat and structural monitoring & data logging	High energy efficiency, low delay & high packet delivery ratio	1024 bits [26]
Environmental and battlefield monitoring & industrial process control and security	High energy efficiency	50 bits [31]
Military, industry and environment protection applications & industrial process control and security	High energy efficiency	456 bits without BCH codes & 1888 bits with BCH codes [33]
Building automation systems, logistics, environment and disaster monitoring & pervasive database systems	High throughput	2048 bits [27]

A solution to prevent the congestion problem in BASNs is presented by specifying the optimum packet size, which minimizes the retransmission attempts when error conditions occur by Yaakob and Khalil [62]. In BASNs, sensor nodes are deployed over a human body for health-care or military applications. Vital signals from the human body are collected by these sensor nodes and are sent to the base station (or the sink node). However, high BERs occur in BASNs due to lossy links, noise, interference, and fading. Furthermore, congestion occurs during the emergency situations when the network load is high which decreases the channel quality as well as energy efficiency and causes increased transmission delays. All of these problems should be solved by handling the congestion problem for efficient data transmission in an emergency situation. As a remedy for such situations, the effects of varying packet sizes on the performance of BASNs under different BERs are investigated and evaluated with simulations by considering packet delivery ratio, end-to-end delay, number of retransmissions, overhead, total packet sent, and received over time [62]. Results show that the packet delivery ratio decreases, end-to-end delay and the number of retransmissions increases when longer packet size is used in high BER environments due to contention occurring at high traffic. On the other hand, using the smaller packets can cause large amount of overheads in low BER environments. The optimum packet size, which is 640 bits, is obtained by considering these issues. To this end, the performance of military and health-care applications using BASNs is increased by preventing congestion.

Based on these existing studies, which are summarized and compared in Tables V and VI, respectively, from the UWSNs, WUSNs, and BASNs perspective, it is observed that the optimum packet size significantly changes according to WSN application requirements and also varies between the topology and the method. Therefore, application requirements (*e.g.*, high throughput, high energy efficiency or low end-to-end delay) must be considered before specifying the optimum

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packet size. As a concise summary, optimum packet sizes based on the requirements of some specific WSN applications are listed in Table VII.

6. MAIN OPEN RESEARCH ISSUES

Most of the research to determine the optimum packet size in WSNs are conducted for the energy efficiency, high throughput, and low latency. However, such studies face many challenges due to specific application requirements and propagation characteristics of deployment environments. In this section, we highlight these open research issues and the challenges for determining the optimum packet size in WSNs.

- *Service provisioning:* QoS requirement of each WSN application varies from each other. Hence, the packet size optimization technique should meet the specific application requirements (*e.g.*, energy efficiency and low delay). While specifying the optimum packet size, wireless channel conditions must be considered to develop realistic solutions. Furthermore, the optimum packet size can be adjusted according to the traffic types, which can be real-time, non-real-time or best effort. Real-time packets need low latency and thus, small packet size can be used. On the other hand, longer packet sizes can be preferred for non-real-time and best effort packets.
- *Transmission power control:* Power consumption is an important issue due to limited-battery budget of the sensor nodes. Many studies explored the design space to determine optimum packet size to increase the energy efficiency. Most of works in the literature use the small packet size for decreasing transmission power. However, if the transmission power is controlled according to the channel conditions, the optimum packet size can be found more accurately.
- *Cross-layer design:* The design of a complete cross-layer approach from the physical layer to the application layer for the packet size optimization in WSN is not addressed in the literature for different WSN applications. For example, different antenna models (*e.g.*, omnidirectional or directional antennas) at physical layer, or different MAC protocols (*e.g.*, TDMA, CSMA, hybrid) at the link layer can be considered to determine the optimum packet size.
- *Reliable communication:* Error control is another critical issue in WSNs, since the number of retransmission decreases when the error-free transmission is achieved. In the literature, some error control mechanisms, such as ARQ, FEC, and hybrid techniques, are applied while obtaining the optimum packet size. However, the performance of these mechanisms are not fully compared with each other for different WSN applications and deployment fields to obtain the corresponding optimum packet size.
- *Cognitive spectrum access:* Recently, CRSNs have been proposed to address the spectrum scarcity issues of WSNs. However, the existing optimal packet size solutions devised for WSNs are not directly applicable to CRSNs [20]. To improve network throughput and energy-efficiency while maintaining acceptable RF interference level for licensed users, spectrum-aware optimal packet size solutions are required.
- *Energy-harvesting WSNs:* Energy harvesting may enhance the performance of WSNs with its self-charging capability. Available energy in the environment, such as solar, thermal, and

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magnetic, can be scavenged to power wireless sensor nodes. However, the existing packet size optimization studies for WSNs cannot be directly applied to energy-harvesting WSNs. This is because the available energy fluctuates with time, instead of monotonically decreasing in energy-harvesting WSNs. To this end, optimal packet size solutions are required for energy-harvesting WSNs to balance the trade-off between energy consumption and QoS.

7. CONCLUSION

Packet size is an important parameter for increasing the performance of WSNs. Different packet size optimization techniques are proposed by the researchers to improve the network performance in terms of the energy-efficiency, throughput, and delay (among other performance metrics). These approaches are classified into different taxonomies since some of them offer to utilize the fixed packet size or the dynamic packet size, while others offer to use different packet formats or optimization frameworks. Different types of WSNs (*e.g.*, underwater, underground or body area sensor networks) must also be considered while specifying the packet size due to the change in specific channel characteristics, such as the path loss and interference, according to the nature of the WSN. In this context, packet size optimization techniques with respect to different types of the WSNs are also reviewed. Each of these WSN types has various requirements, such as the energy efficiency, low delay or high throughput. We also overview the state of the art packet size optimization studies, which are done to meet the requirements of specific applications to determine the optimum packet size. Finally, we stated the main open research issues in the area of packet size optimization for fostering future research avenues.

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