Energy Consumption Optimization in Wireless Sensor Networks

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1. Introduction

The term "wireless sensor network" (WSN) encompasses a wide range of configurations and deployment strategies. A typical sensor network consists of nodes, a large number of low cost, low power distributed devices, called nodes. These nodes are installed in the environment which is to be sensed and controlled[1]. To put it differently, this type of network is made up of a large number of small nodes that can interact with one another and may be used to monitor dangerous and inaccessible places. Each nodes consists of processor, memory, wireless antenna, battery along with the sensor itself. Temperature, sound, and light scalars can not only be sensed by nodes, but also they can also be processed and sent through radio. The network can be characterized as homogeneous or heterogeneous, which means that certain individual nodes have unique hardware or software configurations. However, even in homogeneous networks, a special node called a Base Station (BS) is required to collect, store, and analyzed data from the WSN's nodes.

Current technologies for WSNs are based on low-cost processors resulting in limited energy budget and restricted memory space. Because most of these networks are employed in distant regions, recharging and/or replacing power supply units is deemed difficult or prohibitive owing to dangerous and inaccessible situations where they are required to operate. Hence, it is envisioned that the sensor node last for a long period in many applications. Furthermore, because of the widespread availability of low cost of hardware and the variety of radio transmission frequency options, a variety of WSN topologies may be used[2] [3] [4].

As previously stated, the nodes in these networks are often cheap, hence WSNs can be made up of a large number of sensor nodes, each of which is placed inside and/or around the phenomena being monitored. In certain adoptions, the geographic location of the sensor node is not known in advance, since when the nodes are required to function in dangerous or inaccessible regions, it may be difficult to avoid their random deployment. Therefore in order to implement this sort of application, it is necessary to use protocols and methodologies that can self-organize and self-optimize energy consumption of a large number of nodes that cooperate in order to achieve a global goal[5].

WSNs differ from conventional ad-hoc wireless networks due to the qualities listed above and the ability to interact with the environment. WSNs are application driven because to limited software and hardware resources; hence, WSN applications are created with a specific problem in mind. Collaboration between nodes is required to properly utilize the WSN's resources, and this effort can also extend the WSN's lifetime[6 7].

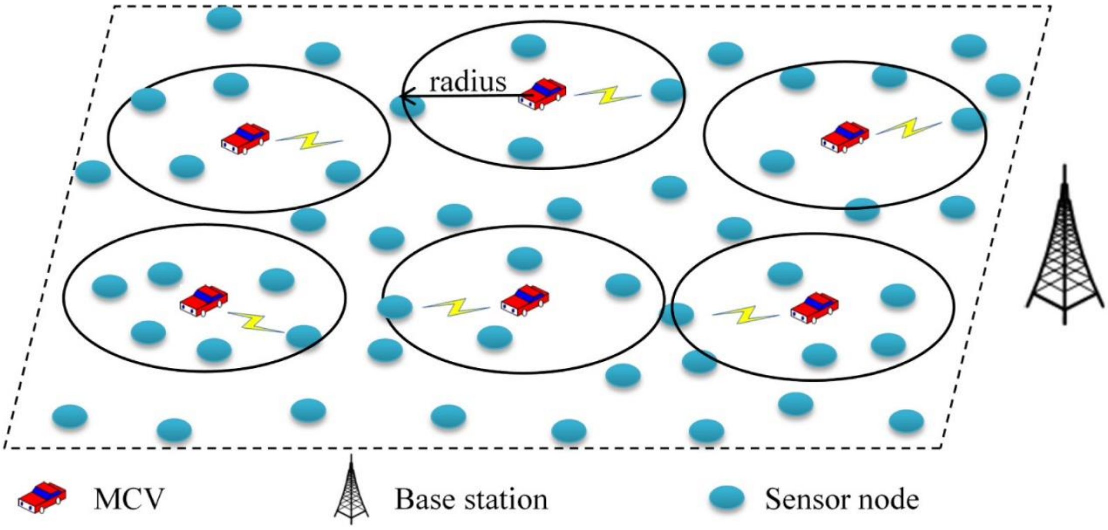

Figure 1. Sketch map of a WRSN with MCVs[8].

Figure 1 shows the sketch map of WRSN system with MCVs. WSNs have a lot of environmental interaction, and there are both implicit and explicit timing constraints depending on where the sensor nodes are installed. Data freshness is an essential issue in this context since it determines how long a sensed scalar may be deemed relevant and when it should be discarded. In the following example, data acquired by a security application based on WSN technology identifies each individual who enters a certain section of the building within a specified amount of time; any data collected after this time restriction is useless. Despite time limitations, ensuring real-time qualities becomes exceedingly challenging owing to high node density, no determinism, noise, and finite WSN resources[9]. Despite time limitations, ensuring real-time qualities becomes exceedingly challenging owing to high node density, no determinism, noise, and finite WSN resources[10 11].

- Paradigm change: WSNs are primarily used to gather scalars from the environment and provide assistance for control applications. The WSN application must perceive the surroundings and, on occasion, act on the environment in some fashion. As a result, obtaining a cooperative behaviour of thousands of sensor nodes, where the data from just one node may not be essential, is deemed vital. Because messages are often transmitted to a space or region rather than a single node, the sensor nodes do not have a permanent identifying address. As a result, obtaining a cooperative behaviour of thousands of sensor nodes, where the data from just one node may not be essential, is deemed vital. Because messages are often transmitted to a space or region rather than a single node, the sensor nodes do not have a permanent identifying address. Because WSNs require physical environment contact, they differ significantly from regular adhoc networks, and traditional distributed system approaches do not apply to them. Real-time needs, noise, a high incidence of faults, and no determinism provide a new set of limitations that must be addressed[12].

- Resource Constraints: WSNs, as previously stated, face significant resource restrictions. The following are the key resource constraints: limited energy budget, limited CPU frequency, limited memory, and limited network bandwidth. These qualities need the use of novel solutions. The fact that WSN topologies include a large number of nodes is a new issue that hasn't been addressed in traditional ad hoc networks. For example, tradeoff strategies aimed at ensuring an energetic economy and real-time features have become important[13].
- Unpredictability: There are several unknowns that might have an impact on a WSN. For starters, WSN are used in situations where there are a lot of uncontrolled events. Finally, nodes are not trustworthy on their own. Furthermore, it is not always feasible to fully calibrate the nodes prior to their use; routing components such as pathways and connections might be dynamically added or removed throughout the WSN's operational period. Permanent defects or battery depletion may necessitate the installation or removal of nodes. Furthermore, even during the first deployment, the energy level in some nodes might change dramatically. Finally, nodes may be physically removed owing to environmental factors or purposeful control, necessitating network redesign.
- Self: Developing the WSN's vision at the network application layer is one of the most difficult tasks. Because WSNs are designed to function with little to no human interaction, self-features like self-organization, self-optimization, and self-healing become essential[14] [15]. Although they are very tough to obtain, these qualities are easily mentioned as challenges.
- High scale/density: There are numerous WSN systems that take into account a high number of nodes in order to overcome hardware or software failures; nonetheless, there is a minimum number of nodes required to ensure the WSN's function. The key issues include processing such a vast amount of produced data, ensuring that the WSN requires the minimal desired density, and developing solutions that require the least density and energy consumption in order to optimize the WSN's lifetime. A large-scale system is defined as a WSN with a large number of nodes spread over a vast region. These systems are vulnerable to malfunctions, noise (which can sometimes be created by the WSN itself), and other uncertainties as a result of their properties[16].
- Real-time: WSNs operate in the actual world, which necessitates the use of real-time characteristics to ensure proper operation. Implicit real-time limitations exist in these systems. Its tasks' reaction times are also crucial, therefore system activities must be completed as quickly as feasible. A number of WSNs have explicit real-time limitations.

A structural monitoring application, for example, sets specific data sensing deadlines[17]. However, due to the enormous number of nodes, no determinism, and noise, ensuring real-time qualities may be exceedingly difficult.

- Security: Because WSNs might be employed in safety-critical applications, their security is an important consideration. Denial of Service attacks are simple to carry out via a WSN. Furthermore, approaches to coordination and real-time communication do not take security into account. As a result, an attacker can readily take advantage of these WSN security flaws. The big question is how to apply security procedures that need a lot of computing power in a system that has a lot of hardware limits.

Power conservation is one of the most essential challenges of these networks in this situation, as nodes are likely to function on restricted resources, and different tactics and protocols must be devised to cope with it[18]. More specifically, network lifespan may be increased if the system's software, which includes many layers and protocols, is built in a way that reduces energy usage[19]. In order to reduce the power consumption of WSNs, several strategies have been presented in the literature. These strategies apply to a variety of features of sensor networks, including hardware platforms, MAC protocol, routing, and topology management.

WSN applications and hardware characteristics

WSNs are regarded as an application-oriented technology. They are developed with specific applications in mind; hence they cannot be used for different uses. To ensure that a node is suitable for a given application, it is crucial to take important hardware-related factors into account. When defining the nodes for a given application, considerations on the kind of processing unit, as well as communication, power supply, and sensing devices, must be made exhaustively.

Generally, a microcontroller or a microprocessor is used as the processing unit. The designer must take the intended performance level into account when selecting the best microprocessor for the system since high performance microcontrollers consume more power. Another significant factor is related to the fact that microcontrollers often support many operating modes, like active, idle, and sleep mode, which directly impact the node's power consumption. Another intriguing design alternative recommends dividing the burden between two low power microcontrollers, with one microcontroller handling the sensing control and the other handling networking-related activities such as managing the Radio Frequency link and executing the algorithms[20]. Lastly, it is possible to use techniques like Dynamic Volta Scaling (DVS)[21]. DVS trades off performance and power supply for energy savings by dynamically adjusting the microcontroller's power supply voltage and operating frequency to fit the processing need.

To communicate data between nodes, a variety of communication devices employing media like radio frequency or optical communications, for example, can be used. The sensor nodes need both a transmitter and a receiver to communicate. The primary function of these gadgets is to transform a microcontroller bit stream into radio waves and vice versa. More specifically, the transceiver is typically seen to be the biggest power consumer. Optimizing its power consumption can have a substantial positive impact on the whole system[22]. The kind of modulation scheme, data rate, transmission power, and operating duty cycle of a transceiver are some of the elements that influence its power consumption characteristics[23]. The user may usually be able to adjust the power level on many transceivers. Transceivers typically have four different operating modes: transmit, receive, idle, and sleep. By switching between these modes, energy can be saved. Be aware that managing the transition between operational modes is necessary since rousing up a transceiver from sleep mode and forcing it into transmit mode involves some start-up time and energy. Thus, putting a node into sleep mode only makes sense when the energy saved during sleep mode outweighs the energy required to put the node back into active mode, which means that the time until the next event should be long enough.

Most often, a battery is utilized as the power supply device, which significantly affects the lifespan of the sensor node. The rate capacity impact, which is associated with the discharge rate, or the amount of current drawn from the battery, is therefore one of the most crucial elements that a designer must take into account. Drawing more current than the recommended value significantly reduces battery life. Because the diffusion of electrolyte lags behind the rate at which they are used at the electrodes. It is crucial to note that the majority of WSN applications require placing sensor nodes in challenging and distant environments, making it challenging to employ conventional battery charging methods. Utilizing external energy sources like sunshine or wind is a viable alternative in some situations.

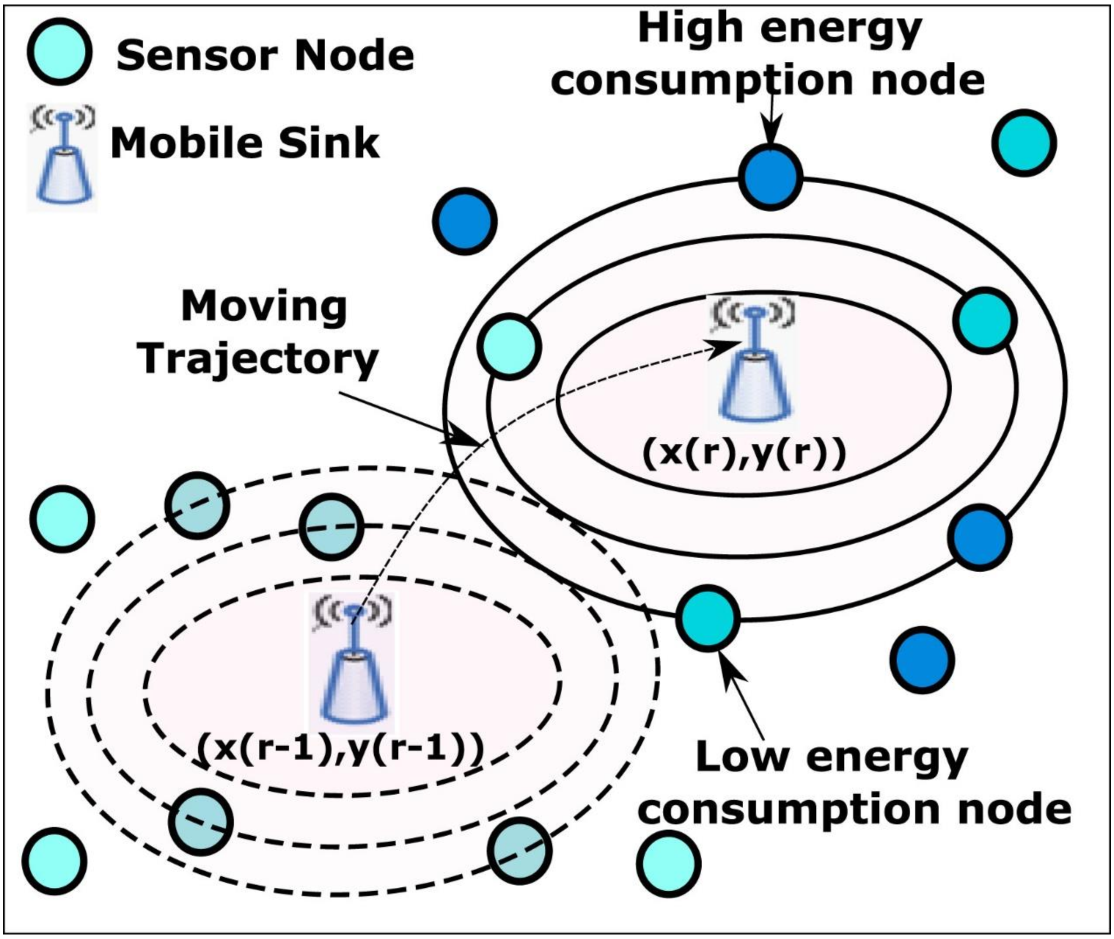

Figure 2. Distribution of energy intensity[24].

Figure 2 shows the distribution of energy intensity. Finally, depending on the type of output they provide, sensors in WSNs can be categorized as analogue or digital devices. Sensors convert physical events into electrical signals. In a nutshell, there are a number of causes of power consumption in a sensor, including signal sampling, signal conditioning, and analogue to digital conversion[25]. When compared to active sensors, like sonar, which require energy to send out a signal to probe the item being viewed, passive sensors, like temperature sensors, use less electricity. Indeed, the sample rate is crucial because greater frequency sampling demands more energy. In this situation, sensors should only obtain a measurement sample if, when, where, and at the appropriate degree of fidelity[26]. This tactic lowers the subsystem's energy requirements and, in some cases, the processing and communication burden as well. Therefore, using mechanisms that can alter the bit resolution and sampling rate of measurement samples, as well as adaptive spatiotemporal sampling, utilizing correlation, and redundancy models to predict a measurement rather than actually taking one, and lastly, hierarchical sensing, can result in a reduction in power consumption.

Several WSN applications will be briefly introduced in the paragraphs that follow. The applicable algorithmic solutions may change significantly depending on the time requirements of the applications. In contrast to a military application, which has considerably shorter temporal validity, an environment monitoring application may have minute-long deadlines. While some applications require event-driven approaches, others require regular sensing and transmission.

Environment monitoring, military, demotic, and industrial monitoring and control are some potential uses for WSNs. For instance, a habitat monitoring application of WSNs has been installed on Great Duck Island[27]. Its major objective is to establish a correlation between various environmental data (temperature, light, and humidity) observations and the activity of bird nests on the island. The major objective of the Great Duck Island application is to extend the network's lifetime because this application has slack real-time requirements and because it is anticipated that the WSN's infrastructure would remain operational for months or even years without human intervention. As a result, there may be a considerable reduction in the time between delivering signals and between each subsequent sensing.

Another use for a WSN is structural monitoring. In this case, a linear WSN topology was employed to monitor the Golden Gate Bridge's structure, necessitating the employment of a routing approach to guarantee the delivery of messages to the BS at one end of the construction. This application is based on accelerometer sensors that look for changes to the bridge's physical structure[28].

Finally, other kinds of WSNs' utilization are stated below:

- Automotive industry: Cars come with sensor and actor networks that can communicate with street or highway WSN infrastructures to improve traffic flow or automate toll collection.
- Monitoring and automation of factory systems: Thousands of wired sensors may be added to industrial robots. A central computer must be connected to these sensors. The use of WSNs in these types of robots is encouraged by the high financial cost and mobility limitations of wired sensors.
- Intelligent housing: Other examples of WSN application in building automation include pressure sensors in chairs and microphones for voice activation. WSNs enable homes to be outfitted with temperature, light, and movement sensors. As a result, the air temperature, natural and artificial lighting, and other elements may be adjusted to meet the demands of each individual user;
- Precision agriculture: WSN use in farmlands makes it feasible to regulate irrigation and apply pesticides precisely
- Harsh areas monitoring: Through the usage of WSNs, difficult locations might potentially be explored and monitored.
- Freshwater quality monitoring: WSNs can be utilised for freshwater monitoring since they are compact and non-intrusive.

- Military application: Examples of prospective WSN uses for military purposes include target identification, non-human combat area monitoring, troop and vehicle position and movement management, landmine clearance, and building investigation.

To sum up, WSNs may be used for a variety of purposes, and the choice of hardware for those purposes relies on the systems' needs, the resources that are available, and the setting in which the network will be used.

2. MAC layer approaches

As mentioned earlier, one of the most crucial issues when discussing the usage of WSNs is, lifespan maximizing of WSNs. This is mostly because sensor nodes are regarded as inaccessible when the battery level is low. It is crucial to remember that in WSNs, node communication is the main energy-consuming operation. The node uses a large amount of its energy for radio broadcasts and for listening to the medium in anticipation of packet receipt[29]. In other words, exchanging messaging consumes a lot more energy than processing the data or acquiring the data by the sensors. Furthermore, the nodes share a single communication channel, and the efficiency and fairness with which they distribute it greatly affects the performance of the network. The MAC protocol manages the communication nodes in WSNs and limits access to the shared wireless medium so that the underlying applications' performance needs are met[30]. Thus, one of the most crucial concerns in WSNs is the thorough creation of protocols and algorithms for effective communication in order to increase their lifetime. In general, the MAC protocol must be energy-efficient and must work to minimize the following energy consumption-related issues[31]:

- Packet collision: A packet collision occurs when one node receives several packets simultaneously. As a result, every packet needs to be deleted and sent again.
- Overhearing: Overhearing occurs when a node gets packets that are intended for another sensor node.
- Control packet overhead: It is necessary to reduce the use of control packets while coordinating the WSN.
- Idle listening: When a node is in the listening mode on a channel that is not in use, this is known as idle listening.
- Over emitting: When a message cannot be sent because the target node is inactive, over emitting occurs.

It is crucial to stress that message collisions are regarded as the most essential factor since they compel the network to retransmit, using more energy, and necessitate the discarding of all associated messages. As a result, an energy-efficient MAC protocol must prevent collisions and minimize energy dissipation associated with overhead, overhearing, and idle channel sensing[32].

We can identify four unique types of communication patterns[33]. They are:

- Broadcast: To send specific information to every node under its control, BSs often employ the broadcast communication pattern (sink). A control packet, software updates, or consultations must be included in the broadcast information. Only when all destination nodes are within the transmitter node's radio coverage can the broadcast pattern be employed.
- Local gossip: This pattern occurs when nodes detect an event and transmit it to other nodes in the vicinity (same cluster). Within the same service area, this type of communication takes place when one node delivers messages to its neighbours.
- Converge cast: When a number of sensors deliver their packets to a single node, this pattern is known as Converge cast. The final node might be a BS, fusion centre, or cluster head.
- Multicast: According to some situations, messages must be transmitted to a specific set of sensor nodes, and only the sensors in this group will receive the message.

The IEEE 802.15.4 Standard, ZigBee technology, and the primary MAC strategies that can lower power consumption are all summarized in the following sections. A subsequent paragraph will describe other MAC strategies aimed towards MSN optimization.

2.1 IEEE 802.15.4 standard and the ZigBee technology

The major objective of ZigBee technology is to enable WSNs made up of several nodes to operate with less energy usage. To increase the lifetime of their WSN applications, the majority of WSN technologies, including Mica Motes, utilize ZigBee.

The Open Systems Interconnection (OSI) is the foundation of the ZigBee network design, however only the more crucial layers have been implemented. The physical layer and the MAC layer are the only levels of the IEEE 802.15.4 standard that ZigBee adopts[34].

The physical layer may function at either 2.4GHz or 868/915MHz, with a maximum transmission rate of 250Kbps over 16 channels. The Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism is the foundation of the IEEE 802.15.4 MAC layer. ZigBee technology is distinct from other wireless technologies for a number of reasons, it has lower data transmission rate, lower energy consumption, cheaper cost, higher level of self-organization, and more adaptable network topologies[35].

A de facto standard for transmission networks with minimal energy consumption and slow data rates is IEEE 802.15.4, which was first suggested in 2003. A central node known as the Personal Area Network (PAN) coordinator can choose between two different operating modes that are supported by the IEEE 802.15.4 MAC protocol. They are as follows:

- Beaconless mode: where the MAC protocol functions rely on a CSMA/CA packet without a beacon.
- Beacon mode: where the PAN coordinator regularly broadcasts beacons in order to synchronise related nodes and define a super frame. All node transmission must take place throughout the super frame time. Furthermore, the slotted CSMA/CA controls the MAC protocol throughout this frame's contention phase. Using synchronisation and the contention-free period based on a guaranteed slot time, IEEE 802.15.4 with beacon mode may be used for communication.

As a result, the ZigBee Alliance is in charge of standardizing the ZigBee technology. More specifically, the application and network layers are established by the ZigBee Alliance, the physical and MAC levels are based on the IEEE 802.15.4 standard. ZigBee has an address system that may support up to 65.000 nodes, and it may additionally take time synchronization into account using an optional super frame structure. Additionally, the three topologies of star, mesh, and cluster tree are supported. Since all nodes are covered by the PAN coordinator antenna and may relay messages in only one hop, the Star topology is regarded as the simplest topology. It is based on a many-to-one communication topology.

However, in order to get the messages to the PAN coordinator, the mesh and cluster tree topologies depend on a routing protocol. Cluster heads and nodes cannot interact with one another due to mesh topology. The cluster tree topology, which is still another distinction, is founded on the grouping of nodes into clusters. Basically, because no routing protocol is required, the star topology is thought to be simpler than the mesh and cluster tree ones[36].

The IEEE 802.15.4 standard is based on the CSMA/CA MAC algorithm, and its beaconless mode does not need the PAN coordinator to emit a periodic beacon[37].

The beaconless mode takes into account two parameters: the first, abbreviated NB, is the number of times CSMA/CA is required to backoff, and the second, abbreviated BE, refers to the number of back off periods a device must wait before it may access the communication channel.

The initialization of NB and BE is the first phase of the CSMA/CA algorithm. The MAC layer must wait a random time interval between 0 and (2^{BE} - 1) following activation before asking the physical layer for the Clear Channel Assessment (CCA). The MAC layer must ensure that BE never rises over macMaxBE while incrementing the NB and BE by 1 when the channel is thought to be occupied by another device. Additionally, the CSMA/CA algorithm must terminate and provide the access channel failure status when NB's value is greater than macMaxCSMABackoffs.

The three parameters macMaxBe (standard value 5), macMaxCSMABackoffs (standard value 4) and macMinBE are important for the Beaconless CSMA/CA algorithm (standard value 3).

Since devices only attempt to communicate five times before aborting the transmission, these typical values for the parameters may assist to reduce energy usage. However, raising these numbers tends to improve the network's communication efficiency. Due to the fact that dense network topologies consist of networks with a lot of nodes, the IEEE 802.15.4 protocol cannot handle them.

2.2. Other MAC approaches

Other MAC strategies have been put out in the literature in an effort to lower WSN power usage. The key solutions that investigate the optimization of MAC protocols are outlined in the following paragraphs.

Time Division Multiple Access (TDMA) and Duty Cycles are two common methods utilised in the MAC layer of WSNs (DC).

The primary concept of the TDMA approach is to split the time that devices spend on channel accesses into so-called time slots, each of which is used by just one device. As a result, any device using this method must reserve such a time slot in advance before sending any messages. A TDMA MAC[38] protocol is based on cross-layer optimization incorporating the MAC and physical layers serves as the foundation for this method. The major objective of the method that is being discussed is to lower total energy usage by using TDMA scheduling for clustered WSNs and the smallest frame length possible.

To reduce the energy consumed by the TDMA MAC protocol[39], the major goal is to schedule the sensor nodes with successive time slots in different radio states, such as: transmitting, receiving, listening, sleeping, and idle, in order to decrease energy usage. The best scheduling of these stages might result in a reduction in energy usage since sensor nodes use varying amounts of energy at each state.

FlexiTP is a TDMA MAC protocol that uses sleep scheduling approach to schedule node messages[40]. The sensor nodes must solely transmit and receive packets within their designated time slots under the sleeping scheduling scheme before going to sleep until their designated time slot is available again. Additionally, FlexiTP offers routing, time synchronization tasks, and sensor node capabilities for both sensing and routing data.

Another TDMA MAC protocol designed for multichip WSNs is PEDAMACS[41]. When compared to other MAC protocols like random access protocols, which may only extend the network's lifetime by a few days or a few months, it can increase network lifetime by many years. However, because dynamic topologies are typical in hostile settings, this TDMA protocol does not function well when used with WSNs.

Complementarily, the DC techniques separates the running time of the device into two sections: In addition, the DC approach separates a device's running time into two sections: an active section and an inactive section, commonly known as sleeping time. The gadgets remain idle for longer and, as a result, use less energy. This is true when the activity period is less than the inactivity period. The network's maximum transmission rate will therefore decrease, which is a drawback. The DC technique is able to avoid situations where a node becomes simultaneously active with other nodes that had been inactive before, preventing a node from waiting for messages that will never arrive, and ultimately preventing the waste of energy. On the one hand, TDMA enables devices to become more organized in order to avoid collisions.

These methods often help protocols handle collision, idle listening, and over emitting issues, but they come with extra costs for sending and handling control messages. In applications with low network density and few simultaneous transmissions, these extra expenditures may not be essential. Contention-based protocols like Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) appear more appropriate in this situation. Keep in mind that big networks cannot benefit from the CSMA/CA MAC protocol found in the IEEE 802.15.4 standard[42].

The foundation of a Rotational Listening Strategy (RLS) for a Wireless Body Network (WBN) is the split of channel access into mini-slots that are assigned to nodes[43]. WBNs, a specific type of WSN that are deployed over the human body region, o sense and transmit scalars as for example the body’s temperature.

Another kind of WBN application[44] describes a MAC protocol that is implemented in hardware using a 0.13-m CMOS technology. A common listen-before-transmit strategy is being employed in a wireless body network to prevent collisions with neighboring transmitters. Based on a wakeup-fallback strategy, the management of time slot overlaps was scaled back.

Another Wireless Body Networks (WBN) MAC protocol was proposed with the major objective to extend each body sensor's battery life to the maximum possible extent while keeping the same degree of transmission reliability and message delay. This MAC protocol does this by utilizing an energy-aware radio activation strategy for practical medical applications, as well as a cross-layer fuzzy rule scheduling method.

In asynchronous MAC-based WSNs, an Energy-Aware Hybrid Data Aggregation (EDHDAM)[45] approach seeks to reduce the energy issue. Due to the fact that they send and receive more data to the WSN's sink than nodes farther away, the nodes nearest to the sink use more energy than other nodes. In order to eliminate the disadvantage previously mentioned, the EDHDAM technology is built to adaptively manage the quantity of data transfers.

The MAC of nodes in the game-theoretic MAC method for WSNs[46] is based on an insufficiently cooperative game mode. This method, known as GMAC, divides time into super frames, each of which has two segments: an active segment and a sleeping segment. All nodes switch down their radios to conserve energy during the sleeping portion, and during the active portion, if any nodes have packets to send, these will pass on the channel based on the partially cooperative game.

Several cross-layer protocols that merge the network layers of the MAC and WSN[47]. Regarding residual energy, connection conditions, and queue status, all of these MAC protocols are cost aware. Based on the data from the MAC protocol, the routing layer selects the most suitable relay candidates. As a result, there are fewer in-range devices competing for a single channel and there is less interference.

SMAC is a method for medium access control that is based on synchronized adaptive sleep scheduling[48]. By using low-duty cycle procedures in a multi-hop WSN, SMAC attempts to solve the overhearing issue. In order to decrease control overhead and allow traffic-adaptive wake-ups, the SMAC technique groups the sensor nodes into virtual clusters based on shared sleep scheduling.

Last but not least, MRMAC is a MAC protocol that lowers WSNs' end-to-end latency and energy usage. [49]Based on two measures, Next Packet Arrival Time (NPAT) and Medium Reservation Information, this method decreases the end-to-end latency (MRI). The NPAT and MRI measurements are packed in a packet when it is transmitted in order to enable its intended receiver to reserve the medium. By dramatically reducing both end-to-end latency and energy usage, the simulations reported by demonstrate the effectiveness of the MRMAC technique.

3. Routing approaches:

WSNs may be used for a broad range of applications, but the basic duty of the nodes in all of them is to detect and collect data, process it, and send it to a location where the monitored parameters can be analyzed. To do this duty effectively, an energy-efficient routing protocol must be developed to establish pathways between the nodes and the data sink[50]. Since sensor nodes are energy bound, a large portion of the WSN's protocols try to reduce the amount of energy required for communications. Essentially, the routing problem is made more difficult by the environment's features, which are combined with limited resources and energy. As a result, path selection must be made in such a way that the network's lifetime is maximized. Different techniques can be used in this situation to deal with the problem. One easy solution is to avoid low-quality routes, as wireless networks' instability has a negative impact on their performance. Many retransmissions are required as a result of link failures and packet losses, which result in greater power consumption.

REACA is a clustering protocol[51]. The first cycle of REACA's operation is dedicated to network setting, while the second cycle is responsible for message transmission. The cluster head to be selected is determined by the battery level of all nodes in the cluster. As a result, the cluster head is picked from among the nodes with the highest battery energy level. Furthermore, a routing method is provided, and REACA is mathematically verified.

EARQ is a routing protocol that is based on the energy level of a WSN[52]. EARQ is capable of ensuring reliability, time limitations, and energy efficiency. EARQ's major purpose is to utilize the path with the highest energy level inside a WSN. Simulations show that EARQ can be integrated into a WSN for industrial use. EARQ, on the other hand, has not been verified for any WSN prototype[53].

MMSPEED is a routing technology that can ensure probabilistic Quality of Service (QoS) metrics in wireless sensor networks. It takes into account several possibilities for rapid delivery in the temporal domain and ensures package arrival[54]. Several dependability requirements are presented, each of which is based on a different approach. End-to-end needs are delivered in a geographically distributed manner, which is advantageous in terms of scalability and adaptability in dynamic and dense WSNs. Geographic routing, on the other hand, demands that nodes be aware of their geographical location. As a result, the authors of the concept assumed that each node would have GPS devices or distributed localization techniques. This causes significant issues since GPS devices do not perform correctly in indoor situations, and distributed localization techniques add extra complexity owing to the additional package exchange required by the nodes to broadcast their geographical location in a regular basis.

The witch is a routing mechanism that supports the non-uniform node distribution approach used to address the energy hole problem in wireless sensor networks[55]. Unbalanced energy usage is also proven to be unavoidable in a circular multi-hop WSN with non-uniform node distribution and continual data transmission.

Energy Efficient Broadcast Problem (EEBP) is a technique used in ad hoc wireless networks[56]. The EEBP's concept may be summarized as follows:

In an ad hoc wireless network, we locate a broadcast tree with the lowest energy cost. It is assumed that all nodes in the network have the same transmission power. Three routing algorithms aimed at minimizing network usage are given as a solution.

Green Wave Sleep Scheduling (GWSS), which was inspired by synchronized traffic lights, is a sleep scheduling system[57]. The major purpose of this strategy is to help the WSN with its routing responsibility rotation. A green wave is a moving series of active states (green lights), and some packets may travel in a series of active nodes. As a result, nodes in sleep mode are like red lights, and packages may not be routed via them. When large WSNs are placed in structured topologies, it is demonstrated that GWSS achieves almost the same end-to-end latency as non-sleep-scheduling WSNs.

4. Transmission power control approaches

Considering nodes often operate on limited batteries, power saving is critical. MAC protocols can regulate energy usage during WSN communication, which is the most energy-intensive event in WSNs, as previously indicated. However, altering the transmission power of WSN nodes is an intriguing method for extending its lifetime. On one hand, maintaining the lowest transmission power feasible is an appealing strategy for reducing energy consumption and, as a result, extending the network's lifetime. On the other hand, using the smallest transmission power available might make the WSN more vulnerable to interference variations induced by a low Signal-to-Interference-plus-Noise-Ratio (SINR).The quality of radio communication between low-power sensor devices varies greatly with time and environment, according to extensive empirical investigations. This fact suggests that current topology management methods, which rely on static transmission power, transmission range, and connection quality, may be ineffective in the real world[58]. To overcome this issue, online transmission power regulation strategies that take into account environmental changes have become critical.

Several Transmission Power Control (TPC) techniques have been developed where the TPC algorithm can lower energy usage while increasing channel capacity. TPC methods, in more detail, employ a single transmission power for the whole network, ignoring the customizable transmission power given by radio hardware to save energy, or assume that each node picks a single transmission power for all of its neighbors, known as neighbor-level solutions. In fact, most present WSNs assign each node a network-level transmission power. Numerous TPC research have demonstrated that TPC lowers energy usage in low-power WSNs.

Numerous TPC studies have been done to improve the channel capacity[59, 60]. Many experimental studies have demonstrate how TPC lowers energy usage in low-power WSNs. Each node delivers packets at multiple transmission power levels to identify the best transmission power based on the Packet Reception Ratio (PRR) in the Power Control Algorithm with Backlisting (PCBL). In order to achieve the best transmission power consumption for defined connection characteristics, an Adaptive Transmission Power Control (ATPC) algorithm is presented. The Received Signal Strength (RSS) and Link Quality Indicator (LQI) for radio channels are employed with an ATPC algorithm to determine the best transmission power level, and a feedback-based ATPC algorithm is used to dynamically change the transmission power over time. As a result of implementing this technique, each node knows what transmission power level to use for each of its neighbors, and each node maintains high link quality with its neighbors by dynamically modifying transmission power via on-demand feedback packets.

When the objective is to implement WSNs in the physical world, although, the influence created by diverse inference sources must be addressed. Many WSN devices on the market operate in the 2.4GHz ISM band, making them susceptible to interference from other wireless networks like IEEE 802.11 WLANs and IEEE 802.15.1 Bluetooth. WSN devices, on average, have lesser transmission power than WLAN or Bluetooth devices. As a result, the TPC method for WSNs must take into account the interferences created by other 2.4GHz wireless devices, which might reduce performance significantly. In this regard, the Interference Aware Transmission Power Control (I-TPC) algorithm has been presented as a viable TPC solution for WSNs[61] . When interferences are identified, the I-TPC algorithm assumes that each node modifies the RSS goal to produce an acceptable SINR. The ITPC algorithm is made up of two separate functional procedures: two-tier transmission power regulation and RSS goal modification. The appropriate RSS goal, which may fulfil the necessary PRR, is first identified. Using the two-tier transmission power control process, each node tries to modify its transmission power based on the RSS target to keep the RSS value between the upper and lower RSS target values. As a result of this operation, the suggested method strives to obtain a satisfactory connection quality as rapidly as possible, though there are small scale link quality changes. The RSS target and transmission power are promptly raised via the RSS target adjustment mechanism when interference is detected, resulting in an adequate SINR.

Two separate local algorithms are used to regulate the transmission power of the nodes independently[62]. For route finding, such local techniques do not require any specific MAC protocol or specialized protocol. Each node transmits a life message on a regular basis, and all receiving nodes react with life acknowledge messages, according to the so-called Local Mean Algorithm (LMA). Before delivering fresh data, each node records the amount of acknowledge messages it has received and compares it to the thresholds it has established.

If a node receives fewer messages than the lower limit, the transmission power is raised by factor A_{inc} for each node that falls short of the lower threshold. There are no adjustments to transmission power if this value is between the upper and lower limits .With life and life acknowledge messages, the Local Mean Number of Neighbors (LMN) method operates similarly. The life acknowledgment message also includes the node's own count of neighbors, in addition to the LMA method. Every node receives information comprising of the value which represents the number of neighbors of the sending nodes, calculates an average value from all the information received, and uses this value, along with the amount of nodes that replied to its life message, to calculate the NodeResp value, which is compared to the thresholds and, if necessary, the transmission power is adjusted as given by the LMA technique. When compared to fixed and global algorithms, these two strategies beat the fixed approaches while only attaining around half the lifespan of networks using global algorithms like the Equal Transmission Power (ETP) algorithm in the specified indoor situation. When compared to ETP, local algorithms are virtually competitive in terms of network trust level, and on top of that, they are scalable and easy to implement, whereas global algorithms are not.

TPSO is given in[63], the fundamental component of the Transmission Power Self Optimization (TPSO) approach is an algorithm capable of ensuring connection and a good Quality of

Service (QoS) while focusing on the WSN's Efficiency (Eff) and optimizing the required transmission for data communication at each node. The method tries to preserve each node's connection to the WSN and overall network dependability while modifying each node to consume the least amount of transmission power feasible. In various EMI settings, the trade-off between the WSN's Eff and the data transfer energy usage is assessed. Its decentralized method utilizes an Eff value generated using the number of messages received and an estimate of the number of messages sent, and it operates on the application layer. To determine whether to alter the node's transmission power, this Eff is contrasted with the desired Eff. According to experimental findings, automated adaptation is superior to methods that rely on fixed transmission power.

The results of the studies showed that employing the self-optimization method instead of specifying the highest transmission power level was more convenient. The transmission power is established at the start of the communication and stays the same throughout the communication's lifespan when a WSN without the TPSO approach is taken into account. When used in a WSN in an actual scenario where the natural noise is not always consistent, this property might be detrimental. As a result, because the underlying environment noise is fully changeable and random, the TPSO approach will always ensure the lowest feasible transmission power during communication and, where possible, the goal Eff.

5. Autonomic approaches

In order to define computer systems that can govern themselves, IBM coined the phrase "autonomic computing" in 2001[64].

Simple definitions are given below[65] :

- self-configuring: The capability of the system to arrange itself in accordance with high level aims.
- self-optimizing: In order to improve performance or service quality, the system may decide to initiate a change as a proactive measure.
- self-healing: The system identifies and treats issues, which may be caused by defective memory chip bits or by software errors.
- self-protection: It is possible for the system to defend itself from malicious assaults or illegal changes.

Despite the fact that dense WSNs have many benefits, managing a plenty of nodes requires self-management capabilities. Autonomic computing strategies, which may well be used to handle WSNs with competing aims (energy efficiency, self-organization, time limitations, and fault tolerance), include self-management techniques.

The creation of a computing platform that doesn't require human input is the primary objective of self-management. When computer systems adhere to the global objectives set by a system administrator, they can self-organize and optimize themselves in this fashion[66].

For instance, the traditional IEEE 802.15.4 protocol does not appear to be able to handle the complexities in dense WSNs made up of numerous sensor devices in a star network topology when the network presents conflicting objectives (increase reliability and energy efficiency while meeting time constraints).

For instance, as the number of nodes in a network rises, the WPAN may get crowded in an effort to improve dependability, and fewer messages arrived, reach the base station on time. Using the True Time simulator1, tests were carried out to show how the WSNs would behave in this circumstance. Eff (efficiency) and QoF are two measures that have been embraced. Usually the number of messages the base station receives over a given period of time is represented by QoF, a statistic that gauges the ratio of transmitted to receive messages[67]. The Genetic Machine Learning Algorithm (GMLA) is aimed for applications that make trade-offs between several metrics. The primary objective of the GMLA technique is to increase communication efficiency in communication environments where the base station is unaware of the network architecture.

As a result, it is reasonable to draw the conclusion that the GMLA method is capable of balancing QoF and Eff, and that GMLA consumes less energy than IEEE 802.15.4.This method, however, is only appropriate for situations where the signal is uniform over the whole monitoring region.

A variable offset algorithm (VOA) is one that seeks to maximize communication effectiveness in heavy WSNs with star topology. The VOA is a light middleware which is used at the application layer, making it simple to integrate into IEEE 802.15.4 devices.

With the use of an experimental procedure based on actual circumstances, the VOA method was evaluated, and one of the trials involved changing the quantity of slave nodes. The objective was to assess how the number of nodes affected the Eff and QoF parameters. For just one scenario—a network with four slaves—IEEE 802.15.4 exhibits findings that are comparable to those of VOA . The disparity amongst VOA and IEEE 802.15.4 widens as the number of slaves rises.When 29 slaves are taken into account, the efficiency gap among VOA and IEEE 802.15.4 is greater than 100%. These findings demonstrate that VOA performs satisfactorily and keeps the minimal QoS level even when there are a lot of slaves.

The major objective of the Decentralized Power-Aware Wireless Sensor Network (DPAWSN) strategy is to maintain a minimal QoF while enhancing the Eff and conserving energy. Because nodes have the freedom to choose whether or not to deliver messages, this method may be viewed as concentrated. A specific QoF level is mandated by the network administrator on the one hand, and the WSN's lifespan is extended by the power consciousness choice made in each node on the other.

The primary concept underlying DPAWSN is that when the QoF level is higher or lower than the specified value, the base station will direct each node to change the transmission rate accordingly. As a result, because the nodes' transmission rate is based on each one's particular residual voltage, DPAWSN is capable of maintaining a QoF level and lengthen the WSN's lifetime. The test evaluation used an unknown number of computers interacting through IEEE 802.11 in a noisy setting. The transmission rate can also be automatically adjusted by DPAWSN based on the nodes' voltage levels. Additionally, it can fulfil a specified QoF that system administrators have set.

6. Final considerations and future directions

WSNs are among the most intriguing technologies for monitoring and sensing data in dangerous or unreachable environments. This chapter discussed a variety of ways that designers may take to create an energy-efficient WSN. Since these networks can be employed in such a wide range of situations, there are several obstacles and limits to consider when choosing an optimization strategy? Furthermore, different objectives and applications require different targets, which may or may not all be satisfied at the same time. Each of the solutions offered in this chapter aims to address at least one recognized reason of high energy use. The methods make use of the WSN's many design levels to extend the network's lifetime, improve QoS, or optimize other factors which might or might not be desirable to the designer.

Given that one of the main goals of WSN approaches is to maximize lifetime, and that WSN devices consume more energy during packet transmission and reception, even over short distances, than other tasks such as processing, sensing, and data storage, the development of improved protocols and interaction algorithms is a direction for future research.

The present trend toward solutions that entail a tradeoff between many constraints or that adapt or modify the behaviors of the WSN's nodes during operation demonstrates that researchers are cognizant of the complexities and uncertainty of the surroundings and job of such networks.

However, due to the current technological progress of these networks, several established study topics are becoming more significant. As a result, the hardware evolution pattern encourages researchers to use multi-objective optimization methodologies to build more complex and resilient approaches in an autonomous and distributed manner, with minimum power usage as a primary aim.

The progressive replacement of highly expensive centralized sensor systems with a network of wireless sensor nodes that function in a cooperative and autonomous manner (mostly with self-management and self-healing features) is also becoming popular. As a result, multi-agent methods and lightweight optimization methods are becoming more popular. This is owing to the dispersed and optimized manner in which these systems operate.

Furthermore, the employment of WSN data mules has been prompted by the increasing expansion in the motes' local storage capacity. The study focuses on the creation of architectures and methods in which nodes must store their sensed data locally until mobile nodes collect it.

Finally, it should be noted that the diversity of issues has resulted in an even larger range of techniques in dealing with the problems that WSNs encounter in today's harsh and loud surroundings. Now it's up to the designers to determine the ideal match or combination for optimizing the network based on its environment, jobs, and most critical needs and restrictions. Since there is not one solution that can solve all difficulties at once, one of the most significant aspects of today's designers' job is the accurate assessment of issues to be expected.

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