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DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING

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ACKNOWLEDGEMENT

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ABSTRACT

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Note: This chapter can be split into multiple sections as needed

Chapter 3: This chapter Proposes the technology/application/concept in detail. This chapter presents the detailed realtime application/case study of the concept

Note: This chapter can be split into multiple sections as needed

Chapter 4: Conclusion and Future work

Chapter 5: References

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Note : Refer link above for more information

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CHAPTER 1

Introduction

Background

Over the last few years, wireless sensor networks (WSNs) have been drawing attention from the research community with increasing popularity. The merging of advanced computing and wireless communication technologies made WSNs a possible realization, with unique applications requirements leading to diversity in hardware and software designs. Implementation and deployment of WSN applications present various design challenges, many of which are inherent to time-varying characteristics associated with wireless transmission media and scarcity of resources imposed by the decreasing size of sensor nodes [1]. However, the distributed and decentralized nature of WSNs, together with operation without infrastructure support and administration evoked a considerable research work and effort to improve their operation. WSNs are therefore both appealing and technically challenging, as they can be rapidly deployed without established infrastructure, particularly to serve and meet specific application requirements [2]. Being distributed in nature, WSNs can be highly robust with large node redundancy for communication, eliminating single points-of-failure and performance bottle-necks in network deployments. It follows therefore that protocols for WSNs should be designed to be self-organizing and self-configuring. Moreover, the protocols should be highly adaptive to address the dynamic and non-uniform nature of the highly unreliable wireless channel link conditions in WSN communications; as such channels degrade the quality of transmissions, leading to poor network performance [1]. Most importantly, understanding the trade-offs between power consumption, signal processing and wireless communication is a nontrivial and unavoidable design issue as the sensor nodes have scarcity of resources such as battery-power, available memory and processing capabilities [1]-[2].

Power associated with packet transmissions may often be assumed to dominate energy consumption in WSN designs [2]-[3]. Available energy from the hard to replace and non-rechargeable batteries of the sensor nodes in a WSN is the most crucial resource, as it determines the lifetime of individual nodes; hence network operation and partitioning [4]. Energy trade-offs across hardware and software platforms are normally part of design techniques aiming to reduce energy consumption in WSN communications. In addition to idle listening, there are various sources of energy waste in WSN communications, which include control packets overhead, erroneous packet retransmissions and overhearing packets destined for other nodes. Moreover, energy consumption associated with exchange of routing control packets alone is significant and non negligible in WSN communications, as much as packet transmission is one of the most energy-expensive operations for sensor nodes [3]. Consequently, the research in design of protocols for WSNs mostly focuses on development of energy-aware algorithms to minimize energy consumption and prolong network lifetime. Dynamic power management strategies can also be employed to ensure economic power consumption by the nodes in a WSN, whereby energy consumption of individual nodes and the overall network is minimized [2]. Energy consumption associated with routing control packets has not received much attention in literature, and still remains an open problem [2], [4]. Despite the small size of the routing control packets, their effects on energy consumption in WSN communications is significant. The diverse and unique applications in WSNs lead to various requirements with different performance constraints in which a good solution for a specific type of WSN application might not be equally good for another. Maintaining a balance between WSN implementation constraints and applications requirements may therefore lead to a design dilemma [5]. For instance, if a WSN is designed to achieve maximum flexibility in support for a variety of applications, the design may possibly result in poor performance against the applications requirements. Inversely, designing a WSN to efficiently support a few applications requirements leads to inflexible solutions, in which a variety of solutions would have to be re-implemented for different applications. However, a good design in WSNs should sufficiently and flexibly support a variety of applications without compromising performance.

Brief History of WSNs

Sensor networks technology was first initiated by the Defense Advanced Research Projects Agency (DARPA) through Distributed Sensor Nets Workshop (DAR 1978), which focused on research challenges encompassing networking technologies, signal processing techniques, and distributed algorithms [2]. In 1980, DARPA also carried out the Distributed Sensor Networks (DSN) program, which was then followed by the Sensor Information Technology (SensIT) program [6], which provided sensor networks with new capabilities such as ad hoc networking, reprogramming, dynamic querying and multi-tasking. On noticing the low expense and high capabilities offered by sensor networks, the Institute of Electrical and Electronics Engineers (IEEE) defined the widely adopted IEEE 802.15.4 standard for low data rates in wireless communication networks; from which ZigBee Alliance published the ZigBee standard which specifies a suit of high level protocols that can be used in WSN communications. A communication-oriented operating system (OS) called Accent was developed at the Carnegie Mellon University (CMU), which allowed flexible and transparent access to distributed resources required for fault-tolerance in DSN [7]. The Accent OS later evolved into Mach OS, which commercially found a considerable acceptance. The research efforts at CMU also included communication protocols to support interface specification language for building distributed system software, dynamic load balancing and fault-reconfiguration in DSN.

As a demonstrative application of DSN, a helicopter tracking system was developed at the Massachusetts Institute of Technology (MIT) using a distributed array of acoustic microphones by means of signal abstractions and matching techniques [8]. Extensive acoustic sensor networks were also developed in the United States of America (USA) for submarine surveillance during the cold war. Some of those sensors are still used by the National Oceanographic and Atmospheric Administration (NOAA) to monitor seismic activity in the ocean [9]. Rockwell Science Center, together with the University of California at Los Angeles proposed the concept of Wireless Integrated Network Sensors (WINS), which resulted in Low Power Wireless Integrated Microsensor (LWIM) in 1996 [10]. In 1999, the University of California at Berkeley started Smart Dust project which focused mainly on development of extremely small sensor nodes. Moreover, the Berkeley Wireless Research Center (BWRC) carried a PicoRadio project in 2000 which aimed at developing low-power sensor devices [11], with the capability of harvesting energy from the environment in which they are deployed (*e.g.* solar energy). Most of the aforementioned research accomplishments were academically driven. Nonetheless, recent works include commercial companies such as SensorWare Systems [12], Sensoria [13], Crossbow [14], Sensicast Systems [15] and Dust Networks [16] to mention but a few.

WSNs Architecture and Characteristics

The number of nodes in a WSN can range from a few tens to thousands of nodes. The sensor nodes can be scattered without predetermined configuration depending on the application requirements over a deployment area to achieve a common goal, as illustrated in Figure 1-1. Traffic in a WSN is usually directed towards a single base station or sink node to report the measured phenomenon from the physical environment, in which the reporting can be periodic, event-driven, or query-based [2], [17]. In periodic reporting, measurements are sent by the sensor nodes to the sink node at predetermined time intervals, whereas in event-driven, the report sending is triggered by specific events of interest from the monitored physical environment. In query-based reporting, a query is initiated from a base station node to the sensor nodes in a WSN, in request for sensed information or measurements from specific nodes or from all the nodes in the entire network. Fundamentally, WSNs vary in characteristics and constraints from traditional wireless networks such as mobile ad hoc networks (MANETs) and cellular networks for example. The following are the unique constraints and characteristics of WSNs, which dictate their associated network capabilities and performance [2]:

(a) WSNs comprise sensor nodes which are small scale devices with severely limited resources in terms of memory, available energy, processing and communication capabilities [1], [2], [4], [6].

(b) Sensor nodes are sometimes deployed to operate in potentially unfavorable and extreme environmental conditions where it is difficult to employ energy harvesting or recharge the nodes' batteries [1], [2] [17].

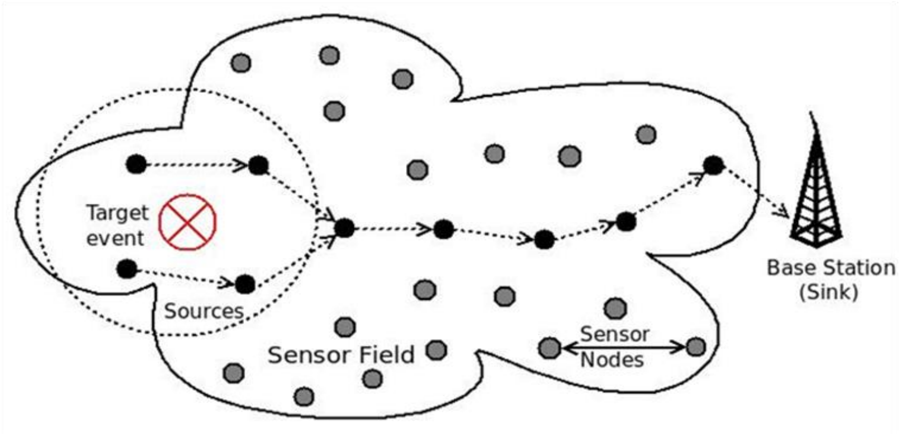

Figure 1-1: WSN architecture.

(c) Sensor nodes are usually densely deployed, with each node performing data gathering as well as cooperatively relaying data for other nodes, *i.e.* each node acts both as a sensor and a router [2], [17].

(d) WSNs are subject to frequent topology changes resulting from node-mobility, node-failures and a high degree of network dynamics caused by time-scale variations of the wireless channel conditions [1], [2].

(e) Sensor nodes are usually self-organizing and self-configuring without human intervention; administration would otherwise become difficult when the number of nodes in a network becomes too large, especially when deployed in remote and possibly inaccessible locations [1], [2], [6], [17].

(f) WSN implementations are application specific: the design requirements for WSN implementations change with various sets of applications, in which case a specific WSN implementation is usually designed and deployed for a specific set of applications [1], [2], [17].

In addition to the aforesaid characteristics, the cost of each node is important as it determines the overall cost and practical feasibility of a WSN [2], [6]. Reducing the size of each node is part of design goals to reduce production cost and energy consumption. However, reducing node size also results in short communication range and scarce availability of energy from the small nodes' batteries [17]. The highly limited capacity of the nodes' batteries therefore requires energy-efficient operation in WSN communications [1], [2], [5], [6].

Applications of WSNs

The future WSNs will experience the merging of computing and communication in the true spirit of information processing and communication technology era, with a wide variety of commercial, industrial, civilian and military applications [6]. The following are some of the example applications of WSNs [1], [2]:

(a) Military applications, where target tracking sensor nodes can be deployed in a battle-field to monitor and track geographic positions and movement of enemies [17].
(b) Safety applications, where sensor nodes are deployed to assist in rescue and recovery operations such as detecting the source of fire and direction in which it expands [2], [17].
(c) Environmental monitoring applications which periodically gather information such as temperature, humidity and light intensity for analysis of favorable environmental conditions [1], [2], [6].
(d) Industrial applications, whereby sensor nodes can be used to improve asset management by continuous monitoring of critical equipment and identify inefficient operation of the equipment [1], [2], [17].
(e) Automotive applications in which sensors can help in streamlining data collection for improved assembly line, workflow and inventory management systems [2], [6].
(f) Traffic systems where sensor nodes can be deployed to monitor flow of traffic in busy roads and automate the traffic lights systems to operate in accordance with the traffic flow [2], [6], [17], *i.e.* turning a green light longer in a direction where traffic flow is high in order to avoid traffic congestion.

Research Motivation

The motivation behind the research topic in this report dissertation is based on the fact that WSNs present unique design constraints and challenges which are different from those that are presented by conventional wireless communication systems. Among the aforementioned constraints associated with WSN communications, energy-efficiency constitutes a critical design and implementation consideration. The key issue for prioritizing energy-efficiency in design of communication protocols in WSNs is mainly motivated by the fact that sensor nodes are normally powered by small, non-rechargeable and usually hard to replace batteries which affect the lifetime and functional operation of WSNs [2], [6]. Furthermore, packet transmissions dominate energy consumption in WSN communications. Hence, the exchange of routing control packets also has a significant overhead on energy consumption, which may lead to faster depletion of energy from nodes batteries if not controlled properly with minimal exchange [4], [5], [10], [11].

Moreover, this work is motivated by the fact that wireless ad hoc and sensor networks are implemented and run based on the standard Open Systems Interconnection (OSI) protocol stack borrowed from the wired network model, where separate layers of the protocol stack are designed to operate independently, with static interfaces that are independent of the individual network constraints and applications characteristics [5]. Nevertheless, the applicability of strictly layered techniques based on the OSI protocol architecture is hardly sufficient and greatly questioned in the case of WSNs. Furthermore, WSNs operate in highly unreliable wireless channel links that are subject to fading and interference with high bit-error rates and limited bandwidth, which degrade the quality of transmissions across communication links; thereby reducing network performance [6], [18]. Therefore the design and implementation of communication protocols which address the unique constraints and characteristics of WSNs becomes a nontrivial and crucial consideration.

Research Objectives

Primary Objectives

The primary objectives of the undertaken research study presented in this dissertation are:

(a) To study and analyze the main advantages and drawbacks of the existing various routing protocols and algorithms proposed in literature for WSN communications.

(b) To modify the existing DSR protocol by developing a new routing cost function which incorporates link error rates and end-to-end packet delays for assessment of routes in WSN communications.

(c) To develop and implement a cross-layer framework that aims to guarantee energy-efficient routing in WSN communications by integrating the DSR protocol with the distributed and route aware medium access control protocol for sensor networks (DRMACSN) protocol [25].

(d) To develop an analytical approach to derive energy consumption model for nodes in a WSN, including energy consumption associated with routes establishment for the proposed protocols in this dissertation.

Organization of the report

The following provides the roadmap for remainder of the report:

Chapter 2: Presents a brief overview/working of the proposed area of interest that you have undertaken. Highlight the application of the technology/concept used, advantage and disadvantage of the technology/concept choosen,

Chapter 3: This chapter Proposes the tehcnology/application/concept in detail. This chapter highlights the detailed realtime application/case study of the concept

Chapter 4: Conclusion and Future work

CHAPTER 2

Related Work

Introduction

The purpose of this chapter is to investigate and highlight some significant research accomplishments in WSN communications, with more emphasis on the existing routing protocols and algorithms for ad-hoc and WSNs, together with CLD design techniques aiming to provide efficient communication and improved network performance. The routing algorithms mainly deal with the problem of finding the most effective and efficient routes between a source node and a destination node in a multi-hop communication, most importantly in the existence of multiple alternative routes for packet transmissions [2], [4], [6], [17].

The rest of this chapter is organized as follows: Section 2.2 provides a brief background on routing protocols for WSN communications. Section 2.3 highlights design issues and challenges associated specifically with routing protocols in WSNs, followed by classification of the existing routing protocols in literature, and routing techniques in Section 2.4. Section 2.5 highlights recent research contributions employing CLD methodologies which aim to improve performance and provide energy-efficient communication in WSNs. Section 2.6 provides the critical review for the choice of routing algorithm on which the presented work is based. Finally, Section 2.7 summarizes the main points to conclude the work presented in this chapter.

Overview of Routing Protocols in WSN Communications

Whenever a source node has data packets to send to a destination node in a WSN, but the destination node cannot be reached through a single-hop transmission, intermediate nodes are used to relay packets to the destination node on behalf of the source node; thereby routing packets from the source node to the destination node. The design and implementation of routing protocols suitable for these extremely resource constrained and special purpose types of networks is a challenging task [4]. The key responsibility of routing protocols at the NET layer is to determine routes for delivery of packets from any source node to a sink node. A good routing protocol must be able to perform effectively well (*i.e*. selecting appropriate routes) with minimum delay and energy consumption while achieving high throughput, adapting quickly to topological changes, and be light weight in order to minimize communication overhead associated with the exchange of routing control packets [5], [6], [17]. As mentioned in the previous chapter, most of the conventional routing algorithms aim to discover best routes by considering the number of intermediate nodes between a source node and a destination node, in which case minimum-hop routes are given higher preference [18]. However, minimizing the number of hops alone does not guarantee energy efficient routing in WSNs, because the routes with small number of intermediate nodes may lead to increased energy requirements to cover long distance ranges [2]. In minimum-hop routing, a route with few hops but possibly long inter-hop distances may result in low signal strength at the receiver, hence low signal-to-noise ratio (SNR) and data rates [26]-[27]. A route with a large number of short-distance hops may offer more energy efficiency per node as transmission power requirements to relay packets to a nearby next-hop node along the link decrease with reduction in inter-hop distance between the nodes [2], [28]. Instead of using hop-count as the only metric, information about energy requirements for any two adjacent nodes can help in making judicious routing decisions, together with wireless channel conditions between the nodes [29]. There are many routing protocols which have been proposed in literature for ad hoc wireless networks, most of which use hop-count as a routing metric. As a result, they do not meet the unique requirements and challenges associated with WSN communications.

WSNs Routing Protocols Design Issues and Challenges

WSNs are characterized by unique design challenges which govern their applicability, implementation and operation. The following are some key characteristics to consider in designing and implementing communication protocols for WSNs, which lead to various design parameters and constraints as guidelines for insightful and judicious trade-offs to satisfy the unique applications requirements [1]-[2], [6]:

Energy constrained operation: Sensor nodes rely on small batteries which are normally hard to replace or recharge as means of energy; this makes energy-efficiency and energy-conservation schemes a crucial design criteria in development of protocols for WSN communications, as the available energy directly affects the operation and lifetime of individual nodes in a network, as well as network lifetime.

Communication range: Sensor nodes in a WSN are characterized by short transmission ranges. As a result, node-to-node communication is often of short distance range. Sensed data is therefore generally routed through multiple nodes, with each node usually acting as both a sensor and a router.

Memory and processing power constraints: Resulting from miniaturization of the sensor nodes, each node in WSN is equipped with a small processor unit and memory modules with severely limited processing power and available memory respectively.

Bandwidth constrained links: Time varying characteristics of wireless channel link conditions lead to transmissions which are subject to signal fading and interference, as much as increasing transmission power levels for high SNR also leads to fast energy depletion from nodes' batteries.

Dynamic network topologies: Sensor nodes may randomly and rapidly change their locations at unpredictable times in a WSN. Moreover, new nodes may join the network while the existing nodes die or leave the network; resulting in dynamic network topologies with which communication protocols must be able to quickly adapt, in order to maintain a satisfactory network performance and fault tolerance. The fault tolerance may be provided by multiple levels of node redundancy [17].

Network traffic patterns: In densely deployed WSNs, multiple sensor nodes in close vicinity detect and respond to the same event almost all at the same time. The nodes detecting the event therefore compete for transmission medium access simultaneously, possibly leading to congestion which may result in performance bottle-necks with failure to meet quality of service (QoS) requirements.

Classification of Routing Protocols in WSNs

In this section, several routing protocols and algorithms available in WSNs are presented; selecting a few for discussion in this dissertation as there are many routing protocols for WSNs that have been proposed in literature. Substantial research efforts in WSNs resulted in plethora of routing protocols with different criteria on which the protocols can be classified. Since WSNs are application specific, one routing protocol can only support and satisfy a specific class of WSN applications requirements, leading to development of various routing protocols which are suitable for a particular class of applications. As shown in Figure 2-1, the most common criteria is based on the operation of routing mechanisms employed, which results in: **proactive**, **reactive** and **hybrid** routing categories; while the topology-based criteria results in three major categories: **flat**, **hierarchical** and **location-based** routing categories [2], [4], [6]. Routing protocols in each category have associated advantages and disadvantages. However, classification for most routing algorithms is not an easy task as a result of some overlapping features between different categories.

Classification Based on Routing Criteria

The classification in this category is based on the procedural mechanisms employed by routing algorithms for the exchange of routing information and updates, with the following classes:

Proactive Routing Protocols

Proactive routing protocols maintain consistent and up-to-date network view by periodic distribution of routing information throughout the network [6], [17]. Hence routes are proactively maintained regardless of whether they are used or not. As a result, the advantage of routing protocols in this category is that routes are

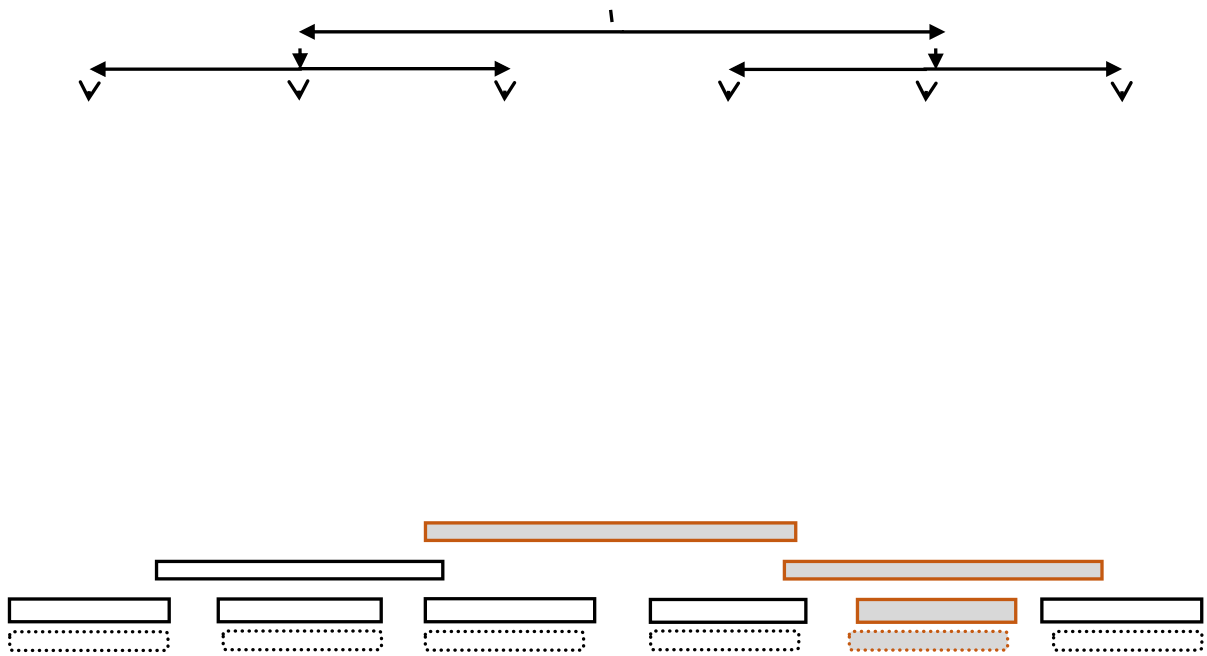

Figure 2.1: Classification of routing protocols for WSNs [2], [6]

always available prior to use. However, proactive maintenance of routing information is not appealing in WSNs as the consequent overhead is relatively high. Although the up-to-date network view is maintained at the expense of energy consumption, the main advantage of protocols in this group is that routes are readily available prior to use, minimizing latency which would otherwise be encountered during route discovery. The following are examples of the proactive routing schemes for ad hoc wireless networks and WSNs:

(a) **Destination-sequence distance-vector (DSDV)**: The DSDV is a table-driven routing scheme based on the Distributed Bellman-Ford (DBF) algorithm which was originally proposed in [30] for MANETS. This scheme uses hop-count as a routing metric for selection of best available routes to a destination node. For individual nodes, each entry in the route cache has an associated sequence number, usually with an even number to represent existence of a link between the nodes. When a node receives routing information with the latest new sequence number compared to the existing sequence number from its route cache, the corresponding route is used. If the sequence numbers are the same, the route with a better metric (minimum hops) is used. The advantage of this scheme is the readily available routes to destination nodes prior to use as each node locally maintains information about network topology, and the protocol operations also guarantee loop-free routes. Like other proactive routing schemes, the DSDV algorithm wastes the scarce energy from sensor nodes' batteries and leads to injudicious use of the highly limited bandwidth even when the updates are unnecessary, with the control messages possibly consuming the entire bandwidth even worse as the number of nodes in a network increases.

(b) **Optimized link state routing (OLSR)**: The OLSR is a link-state and table-driven routing protocol originally proposed for MANETS [31]. All nodes in a network exchange topology information at periodic intervals, using hop-by-hop routing to relay packets between a source node and a destination node, *i.e.* each node makes independent routing decisions based on its local information. Individual nodes perform a distributed election of multi-point relay (MPR) nodes which are responsible for dissemination of routing control messages in a network. The MPR nodes provide an efficient mechanism to reduce the overhead of flooding the control messages by eliminating redundant transmissions of routing control packets. The use of the MPR nodes makes OLSR suitable for large and dense network deployments. Routing information for OLSR protocol includes quality of the links along the routes in a network, which can be used to improve routing decisions rather than using hop-count alone. Being proactive, OLSR wastes energy by maintaining possibly unused routes, which also increases bandwidth usage and central processing unit (CPU) power, making it unsuitable for routing in WSNs.

(c) **Wireless routing protocol (WRP)**: The WRP described in [32] is a table-based routing protocol that aims to maintain routing information proactively. Each node using WRP maintains the following four tables: *distance-table*, *routing-table*, *link-cost table* and *message-retransmission-list* (MRL) *table*. The MRL entries in the table contain the sequence number of the update message, retransmission counter, acknowledgement-required vector, and the list of updates sent in the update message. The nodes notify each other about the link changes through the use of the update messages. The update messages are sent only between the neighboring nodes, specifying a list of updates for the destination node, destination node distance, and the predecessor of the destination; also including the list that specifies the mobile node which must acknowledge the update. On encountering link breakage between any two nodes, the update messages are sent to their neighboring nodes, which in response update their distance table entries and check for new possible routes. Any two routes are relayed back to the original nodes to update their table entries accordingly. Link connectivity is maintained by the exchange of periodic *hello* messages, in which the lack of *hello* messages along a link indicates the link failure. Just like other table-driven routing protocol, the WRP is subject to injudicious use of energy resources resulting from the exchange of the *hello* packets in an effort to maintain link connectivity in the network.

(d) **Topology broadcast reverse path forwarding (TBRPF)**: The TBRPF presented in [33] is link state routing algorithm that performs routing decisions on a hop-by-hop basis. It uses reverse path forwarding (RPF) concept to disseminate routing update information in a reverse direction along a spanning tree, which comprises minimum-hop routes originating from the source of routing update information. Hence, each node using the TBRPF algorithm calculates a source tree to establish routes to all the reachable destinations. This is achieved by using a modified version of Dijkstra's algorithm on partial network topology information from the topology tables maintained by the nodes. In order to minimize routing overhead, each node reports only part of its source tree to its neighboring nodes; by the exchange of periodic and differential *hello* messages. Instead of reporting the link status information for all the nodes, the differential *hello* messages report only the link status changes of the neighboring nodes. As a result, the overhead associated with the exchange of the *hello* packets is less in the TBRPF algorithm than other protocols which report the complete link state information.

(e) **Fisheye state routing (FSR)**: The FSR is a unicast protocol proposed in [34] based on link-state routing algorithm, which maintains network topology information with effectively reduced routing overhead. The operation of the FSR protocol is also similar to the function of a fish eye, as implied by the name. For the eyes of a fish, the pixels near the focal point are caught with a high detail, and the detail decreases with the increasing distance from the focal point. Similarly, The FSR protocol maintains more accurate route quality and distance information about immediate neighboring nodes, and the accuracy decreases with increasing distance. Link state routing algorithms usually flood link state updates through the entire network whenever topology changes are detected. However, the link state information is periodically exchanged only with the neighboring nodes to maintain updated topology information in the FSR algorithm, with each node keeping the full topology map of the entire network. This routing algorithm also uses different update periods for different routing table entries in order to reduce the size of link state update messages. In comparison to other link state routing protocols, FSR algorithm offers improved scalability as a result of not striving to keep all the network nodes on the same knowledge level about link states [34]. Rather, the topology information accuracy is proportional to distance. The link state update information is exchanged more frequently with the nearby nodes than the nodes far away, which results in reduced traffic overhead by the FSR algorithm.

In general, the main drawback with proactive routing protocols in WSNs is that they make excessive use of bandwidth and energy resources as a result of maintaining availability of routes even when they are not necessarily required, resulting in high routing overhead; while the key advantage is the readily available routes whenever they are required (*i.e.* prior to use), which reduces the latency related to route establishment.

Reactive Routing Protocols

Contrary to proactive routing protocols, reactive routing protocols discover and maintain routes to destination nodes only when the routes are required for packet transmissions, hence on-demand routing [2], [6], [17]. The on-demand routing protocols are more suitable for WSNs due to their ability and efficiency in adaptation to routing with low processing overhead and low bandwidth requirements. However, discovering routes just when they are needed may introduce more delays as the source node waits for route replies. The following are examples of reactive routing protocols and algorithms adopted in WSN communications:

(a) Ad hoc on-demand distance vector (AODV): The AODV uses route discovery mechanism, issued by a source node only when the route is needed [35]. Each node keeps a routing table from which the next hop node is locally determined. Like DSDV, AODV uses sequence numbers for routing information updates. On receiving a new route to a destination node, the sequence number of the new route is compared to the sequence number of the current route. If the sequence numbers are not equal, the route with highest sequence number is selected for use. Otherwise the new route is selected only if it has smaller number of intermediate nodes to the destination node. AODV uses *hello* packets for link validity and connectivity management, but with reduced number of routing control packets relative to proactive routing because the *hello* packets have a time-to-live

(TTL) value of 1. Because of its reactive nature, AODV can handle highly dynamic ad-hoc and sensor networks. However, the use of sequence numbers may result in routing updates instability as a result of sequence numbers inconsistencies [6], [17]. Since AODV initiates route discovery only when the routes are needed, the route discovery latency can be high relative to proactive routing protocols, more especially in large scale ad-hoc and wireless networks.

(b) Ant colony-based routing algorithm (ARA): The ARA is an on-demand routing scheme based on swarm intelligence, specifically ant-colony-based meta-heuristics [36]. The principal design objective of ARA was reduction of routing control packets overhead. The behavior of ants on food searching is used to find shortest routes in a network, especially in dynamic environments where network topology changes due to nodes' mobility. Unlike other routing protocols, ARA employs ant-colony optimization meta-heuristic based entirely on local information, without exchange of any routing table information with neighbor nodes. Analogous to ant-colony meta-heuristics, ARA uses pheromone concentration concept for each available link at individual nodes as a decision rule for selection of the next-hop node. Route discovery phase requires the use forward ant (FANT) which is an agent that establishes pheromone track to source node, and a backward ant (BANT) which establishes a pheromone route back to the source node. The FANT and BANT agents are small routing packets with unique sequence numbers. The FANT is broadcasted from a source node and relayed by the intermediate nodes till reaching the destination node. On receiving the FANT, the destination node sends a BANT back to the source node. After processing the BANT, the source node can send the data packets to the destination node as the route has been established. ARA does not use any routing control packets to maintain the established routes, but maintains the routes through transmission of subsequent data packets during communication. The pheromone values of the routes are increased as they are used and decreased at regular intervals to simulate evaporation process of real pheromone. High pheromone concentration therefore indicates a high availability of a route. Route failure is simply signified by a missing acknowledgment for a specific link along the route. As a result of the employed meta-heuristics, ARA is an adaptive, efficient and scalable on-demand routing algorithm which also supports multi-path routing.

(c) Dynamic source routing (DSR): The DSR protocol was originally proposed for MANETs [19], [24]; with route discovery and route maintenance procedures similar to AODV. Each node maintains a *route cache* for the discovered routes. Any node with packets to send examines its *route cache* to find out if a route to a destination node exists. If no valid route exists, a route discovery procedure is initiated to establish the route for delivery of packets. The route discovery procedure is initiated only when there are packets to send but no valid route exists in the *route cache* maintained by the source node. During packet transmissions, the entire route specifying all the nodes through which the packets must be transmitted is included in the packet header by the source node, hence source-based routing mechanism. The intermediate nodes only relay the packets irrespective of whether they already have a valid route to the destination node. Being source-based, DSR inherently eliminates routing loops. However, including the entire route in the packet header increases routing overhead, more especially in large scale network deployments with long routes (*i.e.* a large number of intermediate nodes through which packets are relayed).

(d) Ad-hoc on-demand multipath distance vector (AOMDV): The AOMDV presented in [37] is a reactive routing protocol based on AODV, with the key objective to compute multiple routes during route discovery; designed mainly for highly dynamic ad hoc networks with frequent link failures and route breakages. Unlike single-route on-demand routing algorithms such as the AODV algorithm where a new route discovery procedure is initiated in response to every link breakage, the availability of multiple redundant routes in AOMDV algorithm provides efficiency by reducing overhead and latency associated with route establishment. The AOMDV algorithm operates in two main components: a route update rule for establishment and maintenance of multiple loop-free routes for each node, and a distributed protocol for finding disjoint routes (*i.e.* route discovery). Route discovery is re-initiated only when all the existing routes to a destination node break. The route discovery comprises two main phases: route request phase for broadcasting RREQ packets and route reply phase by any node which has a route to the destination node. The AOMDV protocol was also based on the IEEE 802.11 standard to provide link layer feedback about detected link failures. Hence, the noteworthy feature of the AOMDV protocol is using the already available routing information based on the AODV protocol as its predecessor [35], with little additional routing overhead associated with the computation of multiple disjoint routes.

(e) Associability based routing (ABR): The ABR algorithm is a loop free and deadlock free protocol which was originally proposed in [38] for MANETS, with a new routing metric known as the *degree of association stability* on which route selection is based. The key objective of the ABR algorithm is to establish routes with high connectivity even in mobile network deployments. The nodes exchange periodic beacons to signify their existence in a network; which triggers the neighboring nodes to update their associativity tables on reception of the beacons. The association stability of a link is defined by connection stability of the link connecting the nodes over time and space; whereby a high degree of association stability indicates a high connection stability and vice-versa. The ABR algorithm operates through the following three phases: **route discovery**, **route re-construction (RRC)** and **route deletion**. The route discovery phase is initiated by issuing a broadcast query and await-reply (BQ-REPLY) cycle. A node that requires a route broadcasts a query for any other node which has a route to the destination node to send a reply back. All the nodes which receive the query but do not have a route to the destination node append their addresses together with neighbor associativities and QoS information to the query packet. On receiving the query packet, the destination node sends back a reply packet to the source node. If multiple routes exist, route selection is based on the associativity degree along each of the routes; whereby minimum-hop routing is used if the routes have the same degree of associativity. Depending on which links along a route are broken, the RRC phase may be accomplished by partial route discovery, invalid route erasure and new route discovery. A node broadcasts a route delete packet for other nodes along the discovered route to update their routing tables when the route is no longer required.

The inherent drawback with on-demand routing protocols is the induced delays when data packets are buffered as routes are established only when they are required. However on-demand routing protocols have small route discovery overhead, and the resulting use of energy and bandwidth resources is relatively low with respect to proactive routing algorithms, which is the key advantage in WSN communications.

Hybrid Routing Protocols

Hybrid routing protocols are both proactive and reactive in nature [17]. The design goal for protocols in this category is to improve scalability by partitioning a network into different zones in which nodes in the same vicinity are grouped together. The grouping can also be in a form of a tree structure or clusters. Routes are maintained proactively within one zone and discovered reactively across different zones to reduce routing overheads. The following are examples of hybrid routing protocols:

(a) **Zone routing protocol (ZRP)**: The ZRP is based on zone concept, where a zone is defined for each node in a network; with overlapping of zones on peripheral nodes [39]. The zones are defined in terms of the number of hops instead of physical distance between the nodes. Proactive routing protocols have excessive bandwidth usage for maintenance of routing information, while reactive routing protocols increase packet delays and flood a network with routing control packets on route discovery [17]. The ZRP uses a concept of **bordercasting** during route discovery. The bordercasting is a query control mechanism that uses topology information to direct queries to the border of a zone, which is more efficient than flooding the queries in the entire network. It addresses the disadvantages from both categories by merging the best properties from each. The number of member nodes in a zone can be regulated by adjusting transmission power. In order to control local congestion and excessive routing information updates within each zone, the zone radius can be reduced so that each zone has a few member nodes. The ZRP therefore reduces routing control packets overhead as well as improving network scalability in comparison to either reactive or proactive routing. Albeit the increased operational complexity for the ZRP, it provides improved performance than any single reactive or proactive protocol according to the conducted performance evaluation by the authors in [39].

(b) **Scalable source routing (SSR)**: The SSR protocol proposed in [40] is a self-organizing algorithm specifically suited for large unstructured and distributed networks such as hybrid mobile ad hoc networks, sensor-actuator networks or mesh networks. It is based on source routing and virtual-ring concepts, whereby each node does not need to know the network topology for the underlying network. Instead, each node simply has to know its predecessor and successor in a virtual ring. The SSR protocol provides efficient packet delivery and memory usage by avoiding storage of a complete network topology at each node by using source routes and avoiding flooding the network with requests in order to acquire the source routes. On network bootstrapping, each node broadcasts periodic *hello* packets to notify the neighbor nodes about its existence in a network to establish a list of direct physical neighbor nodes. The broadcasted *hello* packets include a list of physical neighbor nodes for the sender node. If a node receiving the *hello* packet finds itself listed in the neighbor list, the receiving node assumes a bidirectional link connection and adds the sender to its neighbor list as well. Being based on source routing, SSR is subject to performance degradation as the routes become long. The long routes lead to space deprivation for packet payload as the entire route is included in the packet header.

(c) **Hybrid wireless mesh protocol (HWMP)**: The HWMP in [41] is defined as a mandatory route discovery mechanism specified in the IEEE 802.11s profile for mesh networks. Being hybrid, this routing algorithm aims at merging both reactive and proactive routing mechanisms, with two modes of operation: on-demand reactive mode which is appropriate for route establishment in a peer-to-peer basis, and tree-based proactive mode which is calculated once a network node announces itself as a root for a tree based topology. The tree based approach provides route selection efficiency when significant portion of network traffic is forwarded only to a specific set of nodes in a network. Both reactive and tree-based approaches can be used concurrently, making the HWMP a truly hybrid routing algorithm [41]. This is mainly advantageous in some circumstances when for example, the tree-based route is not optimal, and the on-demand route discovery may be employed to establish a more appropriate route. The mandatory routing metric defined by the 802.11 standard is the airtime link metric (ALM), which can be calculated as shown in [41]. The ALM takes into account, the duration of time consumed to transmit a test frame with the bit-rate at which the frame can be transmitted, the overhead resulting from the PHY layer implementation in use, and the probability of retransmissions for reliable communication. The HWMP is much more scalable and considered the default routing protocol for wireless mesh networks [41].

(d) **Temporally-ordered routing algorithm (TORA)**: TORA is a loop-free and highly adaptive distributed routing algorithm based on link reversal concept [42]. This protocol was proposed for highly dynamic and mobile network environments, providing multiple source-initiated routes between any source and destination pair for packet delivery in a network. The main design goal of TORA is to keep routing control messages within a small group of nodes located in the area close to the occurrence of topological changes; which is achieved by restricting the nodes to maintain routing information about one-hop nodes. The protocol operates with the following three main mechanisms: route creation, route maintenance and route erasure. A *height* metric is used to establish a directed acyclic graph (DAG) originating from the destination node during route creation and maintenance phases, after which the routes are assigned a direction (either downstream or upstream) based on the relative *height* metric with respect to the neighboring nodes. Timing is a crucial factor when using TORA, which assumes that the time for all the nodes is synchronized; the time synchronization can be achieved by using external time source, like a GPS for example. TORA is subject to temporary oscillations when multiple coordinating nodes detect partitions, erase routes and build new routes based on each other. As a result of using inter-nodal coordination, TORA is also subject to count-to-infinity instability problem associated with distance vector routing protocols; although route convergence eventually occurs.

(e) **Hazy sighted link state (HSLS)**: The HSLS protocol is discussed in [43] as one of the most efficient routing protocols for wireless mesh networks. This protocol was originally proposed by researchers at BBN Technologies and developed by the Champaign-Urbana Community Wireless Network (CUWiN) Foundation. There are two approaches adopted in HSLS algorithm: near sighted link state routing which is used to determine the number of nodes through which data can be routed and the discretized link state routing which is used to determine the time limit for use of the routing information for data transmissions. This protocol limits the routing updates in space and time by assuming that network routing updates for link-connectivity changes are important to the nodes in close vicinity to the link than far away. Instead of sending the routing updates only to the neighbors of a node, the HSLS protocol uses time-to-live (TTL) metric to limit the spreading of routing information. The timing and TTL optimal parameters can be determined by nodes mobility rate, network size and traffic pattern. As a result, each node has precise routing information about the nodes nearby with minimal routing updates overhead. This mechanism therefore facilitates the exchange of routing information to appropriate nodes relatively faster for the HSLS routing protocol without flooding the entire network, hence making it more scalable.

The discussed hybrid routing protocols exploit proper approaches from both proactive and reactive routing techniques by combining the merits of each technique in order to eliminate their corresponding setbacks. As discussed in previous sections, proactive routing mechanism results in bandwidth wastage by continuous exchange of routing information among network nodes while reactive routing mechanism has high latency related to route establishment and excessive flooding of routing control packets during route discovery. The hybrid routing mechanism can achieve routing efficiency by limiting proactive routing information exchange locally within a zone, and reactive routing information exchange between different zones.

Classification Based on Topology

The operation of routing protocols in WSNs can be affected by the underlying network structure in which the protocols function. This section presents classification of routing protocols based on the network structure under which protocols are deployed, with the following categories:

Flat Routing Protocols

Sensor nodes in flat networks have the same roles in sensing tasks and collaborate in dissemination of sensed data to a sink node. The large number of sensor nodes makes it infeasible to assign a unique global identifier for each node in the network [17]. As a result, data-centric routing emerged; whereby a sink node sends requests for the sensed data through queries by specifying the properties of the data of interest from the sensor nodes located in a specified location [1], [2], [6]. In response to the queries, the sensor nodes in the specified region respond by sending only the data in which the sink node has shown interest. The following are examples of flat routing protocols in WSNs:

(a) **Sensor protocol for information via negotiation (SPIN)**: Among the earliest research efforts, SPIN was proposed in pursuit for a data-centric routing algorithm in WSNs [44]. High-level descriptors are used to name and specify data. The sensor nodes advertize their meta-data prior to data transmissions. On receiving new data, sensor nodes advertize the data to their neighbors for interested nodes to receive the data. There are three messages used in SPIN: ADV for advertisements, REQ for data requests and DATA for carrying the actual data. This protocol is based on controlled flooding with the use of meta-data advertisements which reduce the problems associated with traditional flooding in WSNs. The two main protocols in the SPIN family are SPIN-1 and its energy aware extension SPIN-2. The main advantage of SPIN is localizing topological changes as a result of individual nodes having knowledge only about their single hop neighbors, resulting in node failure immunity. Information exchange is also fairly simple, with exchange of ADV messages for advertizing, DATA messages for sending actual data in response to REQ messages. Thus, the use of SPIN is associated with drawbacks as well: it is based on flooding in which sensor nodes participate in exchange of defined meta-data which should be advertized; the advertizing of meta-data does not guarantee data delivery as the nodes farthest from the source may not receive the data which was received and ignored by other nodes which are found in nearby locations to the source node.

(b) COUGAR: The cougar protocol in [45] uses a data-centric routing concept in which a WSN is viewed as a large distributed database system, where each node corresponds to a database side holding part of the network data. The authors employ the existing techniques borrowed from heterogeneous and distributed database systems to model a WSN. The main idea is utilization of declarative queries for abstraction of query processing from the network layer. The use of declarative queries shields the users from physical characteristics of a network. A query optimizer is used to generate an efficient query plan that facilitates in-network query processing based on user queries, reducing the burden on network resource usage and possibly extending the lifetime of the network nodes [45]. In support for abstraction, additional query layer exists between the NET layer and the APP layer. Sensor nodes select one node as a leader for data aggregation and transmissions to the sink node. A query plan is generated from the sink node and sent to relevant nodes in the network, which specifies the required information by the sink node, including information about selection of a leader as well. The advantage of cougar protocol results from in-network processing which provides efficiency, most importantly when a large amount of data is generated in a WSN. The key disadvantage of this protocol is the expensive memory utilization and increased energy consumption as a result of extra overhead associated with the additional query layer [2], [45].

(c) Energy aware routing (EAR): The EAR protocol proposed in [46] is a flat routing scheme which aims to improve lifetime in WSNs. For each node, EAR protocol maintains a set of routes to a destination node for redundancy and fault-tolerance. The design goal of this protocol is motivated by the fact that using the low energy routes for all data packet transmissions does not necessarily provide the best solution with regard to network lifetime. A probabilistic forwarding mechanism is employed to send traffic through different routes without introducing additional complexity. Thus, sub-optimal routes are occasionally used rather than using only the routes with low energy consumption as they are given higher preference for data transmissions to increase network survivability and to avoid network partitioning. Data transmission is therefore performed using different routes at different times in order to avoid depletion of energy from the nodes along a single used route, which would also result in energy utilization imbalance among the sensor nodes in a WSN. The EAR protocol therefore improves lifetime in WSNs since energy utilization is uniformly distributed among several nodes along various routes between a source node and a destination node, which also ensures that the entire network degrades gracefully as a whole. Nevertheless, routes setup in EAR increases routing control information overhead as the nodes attempt to maintain and use routes with lower energy consumption continuously.

(d) **Directed diffusion**: Directed-diffusion is a popular data aggregation and dissemination algorithm proposed in [47] for routing in WSNs. This is a data-centric and application aware concept in which data originating from different sensor nodes in a WSN is combined to eliminate redundancy and minimize the number of data transmissions. For data requests, a sink node broadcasts interest messages for data in a network. An interest message is simply an interrogation or a query which specifies the type of data required by a user. In directed-diffusion, the data is named using a list of *attribute-value* pairs that describe a task. Thus, transmission of the interests from the sink node is not reliable throughout the network. As a result, the sink node refreshes and resends the interests periodically as it begins to receive data from the source nodes. Although each node needs to distinguish its neighbors, there is no need for globally unique identifiers. Being application-aware, the sensor nodes in a directed-diffusion based network minimize energy utilization through caching and in-network processing of data. Unlike in SPIN algorithm where sensor nodes advertize data availability for interested nodes, the sink node floods queries to the sensor nodes through the network using directed-diffusion [6], [17]. Furthermore, data aggregation and caching is performed on a neighbor to neighbor basis in directed-diffusion. As a result, directed-diffusion minimizes energy consumption and improves lifetime of sensor nodes in WSNs.

(e) **Rumor routing**: Rumor routing algorithm is an alternative to directed-diffusion which is mainly targeted for WSN applications where geographic routing cannot be employed [48]. In directed-diffusion, flooding is generally used to propagate queries throughout the entire network in the absence of geographic criterion to distribute tasks. Thus, the use of flooding becomes unnecessary when the amount of data requested from the sensor nodes is little. Alternatively, events are flooded throughout the network when there is a large number of queries but small number of events; in which case the rumor routing algorithm uses packets referred to as *agents* to flood events through the network. On event detection, a node adds such event into its local event-table and generates an agent for the detected event. The generated agent is then propagated through the network to disseminate information about the local event to other nodes in the network. In contrast to directed-diffusion where data can be sent through multiple routes, rumor routing algorithm maintains a single route between a source node and a destination node for data transmissions. Nonetheless, rumor routing performs fairly well when there are only few events generated in a network as the maintenance cost for agents and event tables for individual nodes becomes highly infeasible with increasing number of generated events.

(f) **Active query forwarding in sensor networks (ACQUIRE)**: The ACQUIRE protocol [49] is used for querying named data in a WSN, with the key aim to deal with one-short, complex queries for data from multiple nodes. Similar to the COUGAR protocol, the ACQUIRE protocol views a WSN as a distributed database in which complex queries can further be divided into several sub-queries. A query is initiated by the sink node and used by each node upon reception to update pre-cached information before being forwarded further. The queried information is either sent back through the reverse route or along the shortest route back to the original querier. The ACQUIRE protocol handles complex queries by allowing several simple responses from multiple relevant nodes, which provides superior query optimization for specific types of interest for the named data (queries). Each sub-query is replied based on the currently available data at relevant nodes. The next node to forward a query is selected randomly or based on a specified trajectory until the query is replied by the relevant sensors along the route using a localized update mechanism. The ACQUIRE protocol provides efficient querying by adjusting the look-ahead parameter d-hops, for d representing the nodes through which a query can be propagated in a WSN.

(g) **Constrained anisotropic diffusion routing (CADR)**: The CADR protocol proposed in [50] is a general form of directed diffusion. The main aim is to query sensors and route data through a network in a manner that the acquired information is maximized, while minimizing latency and bandwidth usage. Queries are diffused by using a set of information criteria to select the sensors from which data can be obtained, which can simply be achieved by activating only the sensors which are located close to the event of interest and dynamically adjusting data routes. In addition to communication cost, considering the information gain by the CADR algorithm provides the key difference from the previously discussed directed-diffusion algorithm. Each node using the CADR algorithm evaluates cost objective and routes data based on its local information and user requirements. Routing is directly addressed to the sensor node that is closest to the optimal position, with the aid of global knowledge of nodes' positions.

(h) **Minimum cost forward algorithm (MCFA)**: The MCFA algorithm proposed in [51] is based on the fact that the direction through which data must be routed to a fixed sink node is always known in a WSN. Therefore the nodes neither need to have a unique identifier (ID) nor maintain a routing table for delivery of packets. Rather, each node maintains a minimum cost route between itself and the sink node. During data transmissions, each node along a route to the sink node broadcasts data packets to its neighbors till the packets reach the sink node. Only the nodes which are listed as intermediate nodes in the minimum cost route participate in re-broadcasting the data packets to the sink node. To establish the minimum cost route, the sink node broadcasts a message with the initial cost set to zero, while the other nodes set their initial cost to infinity (∞). Upon receiving the broadcast message from the sink node, each node examines the message to check if the cost estimate together with the link cost on which the message was received is less than its current estimate. If less, both the current estimate and the message estimate are then updated and the message is re-sent; otherwise the message is just ignored. In order to avoid a situation whereby the nodes which are located further away from the sink node receive multiple updates from those that are located closer, MCFA uses a back-off algorithm which prevents the nodes from sending updates for some time period $k_c \times link(u,v)_c$ from the time at which the message was updated [51], where k_c is a constant and $link(u,v)_c$ is the link cost from which the message was received.

Hierarchical Routing Protocols

Hierarchical routing concept is employed in WSNs to provide network scalability and maintain energy efficient communication; whereby the network nodes are divided into different groups based on tasks assigned and available resources for each node [1], [2], [6], [17]. For instance, nodes with high energy resources can be assigned for information processing and dissemination, while other nodes with low energy levels perform the actual sensing. This subsection presents the following hierarchical routing protocols:

(a) Low energy adaptive clustering hierarchy (LEACH): The LEACH protocol proposed in [52] is based on clustering to reduce global energy consumption in WSNs. This protocol uses randomized rotation of cluster members for selection of cluster heads, which attempts to uniformly distribute the energy load among the member nodes in a cluster to avoid a situation where a single node acting as a cluster head quickly runs out of energy. The cluster head is responsible for forwarding of data on behalf of the cluster member nodes. The advantages associated with the use of LEACH protocol are: improvement in energy efficiency as a result of uniform distribution of cluster heads' responsibility among the cluster members. LEACH also makes implementation of data fusion and aggregation much easier at the cluster heads for improved energy efficiency. However, the use of LEACH has the following disadvantages: clustering introduces a single point of failure as connectivity and communication for the entire network relies on the operation of cluster heads. Moreover, selection of a cluster head increases routing information overhead for severely limited energy resources associated with the sensor nodes in a WSN. The operation of LEACH protocol is based on time division multiple access (TDMA) scheduling algorithms [6]; therefore it is subject to increased delays when used in large networks with high contention for transmission media.

(b) Power-efficient gathering in sensor information systems (PEGASIS): The PEGASIS routing algorithm was proposed in [53] as an improvement to LEACH. Instead of each node transmitting directly to a cluster head when forwarding data to a sink node, the sensor nodes communicate in a multi-hop manner to reach the sink node, each node communicating only with the closest neighbor node. The nodes adjust their transmission power levels (TPLs) for the transmitted data to be received only by the closest neighbor node in a cluster. Received signal strength (RSS) is used to estimate the distance between the nodes in a neighborhood to determine the closest neighbor node. The nodes form a chain for connectivity to the sink node, with only one node referred to as the chain leader transmitting directly to the sink node. The chain leader is selected in terms of residual energy in every selection round, with the main task of collecting data from the neighbor nodes for transmission to the sink node. The advantages associated with PEGASIS algorithm are: reduced bandwidth requirements at the sink node as only one node is needed to send data to the sink node. Short transmission ranges with transmission power adaptation improves energy efficiency of the sensor nodes, even more in dense network deployments [53]; although the dense deployments may also complicate the chain-based communication with short inter-hop transmission distances [2]. The main drawback of PEGASIS is that the estimation of the neighbor distance based on RSS is subject to computation inaccuracy. RSS depends not only on distance, but also some time varying characteristics of the wireless channel link conditions [6], [17].

(c) Virtual grid architecture (VGA): The VGA is an energy-efficient routing algorithm proposed in [54] to improve lifetime of sensor nodes in WSNs through data aggregation and in-network data processing. There are two levels of data aggregation performed by local aggregators (LAs) and master aggregators (MAs) in

VGA algorithm; LAs and MAs comprise sets of cluster heads in a WSN. First aggregation is performed by all the LAs in the network, and another global aggregation is finally performed by a set of MAs. The advantages of VGA algorithm are inherent to in-network data processing and aggregation while the major drawback of this technique is the use of cluster heads: their selection and maintenance is energy expensive, especially when performed at two levels for information dissemination, and synchronization is also a major challenge which cannot be ignored for proper data aggregation.

(d) Threshold-sensitive energy efficient sensor network (TEEN): TEEN is a hierarchical routing protocol which is based on clustering technique [55], specifically for time-critical and delay sensitive applications in WSNs. A cluster head sends the following two values to cluster members: *hard threshold* and *soft threshold*. The hard threshold represents the actual sensed attribute while soft threshold represents the small change in hard threshold for triggering the sensor nodes to switch on their transmitters. The hard threshold attempts to minimize the number of transmissions by allowing the transmissions only when the sensed data attribute is within the range of interest, while the soft threshold minimizes further, the number of transmissions that might possibly occur on little or absence of changes in sensed data attribute. The nodes perform continuous sensing of events of interest from the environment. Each node records the sensed value of data attribute in an internal variable called *sensed value* (SV). The advantage of the TEEN protocol is that there are no routing control packets transmitted by the cluster members except for exchange of threshold values with the cluster members, as more energy consumption is associated with data transmissions than processing. The main disadvantage is that there is no communication in association with sensed data in the network if the nodes do not receive the threshold values. As an enhancement to the TEEN protocol, an adaptive periodic threshold-sensitive energy efficient sensor network (APTEEN) was proposed in [56], which takes into consideration, user needs and application requirements for threshold values. In APTEEN, if a node does not send data for some timeout period, the node is forced to sense the data attributes and transmit such attributes to a sink node. The APTEEN protocol provides some flexibility for users to set timeout intervals and threshold values. However, the protocol introduces more overhead associated with formation of clusters and more complexity for implementation of count timers and threshold-based functions.

(e) Hierarchical power-aware routing (HPAR): HPAR is a hierarchical power-aware routing protocol proposed in [57]. This protocol divides a network into zones, with groups of sensor nodes in the same geographic vicinity forming the zones; treating each zone as a single entity. The main objective for the protocol operation is to maximize the lifetime of sensor nodes in the network. Data messages are transmitted along a route with maximum residual battery power but minimal power consumption for data transmissions. HPAR operation aims to find a balance between minimizing energy consumption during data transmissions and using routes with maximum remaining power in a WSN. The algorithm operates as follows: firstly, routes with minimum power consumption are established using Dijkstra's algorithm. Secondly, among the established routes, a route that maximizes residual power is established. Data messages across the network are sent using a global route on a zone-by-zone basis. A node with the highest power in the network is assigned a role of being a global controller for managing communication across different zones. Nonetheless, centralizing communication control to the global controller node leads to a single point-of-failure and increased overhead on selection of the global controller.

(f) **Minimum energy communication network (MECN)**: The MECN protocol proposed in [58] aims to achieve minimum energy consumption for randomly deployed nodes in a network by dividing the network into sub-network regions that maintain minimum energy consumption for data transmissions. A relay region (sub-network) is identified for each node in a network; which consists of nodes that provide energy-efficient communication when used to relay data instead of direct transmission. The MECN is a self-configuring protocol that maintains network connectivity by computing an optimal spanning-tree rooted from a sink node in a WSN referred to as minimum energy topology, which contains only the minimum energy routes from each node to the sink node. It consists of two main phases: **enclosure graph construction** and **cost distribution**. For the enclosure graph phase, MECN algorithm constructs a sparse graph called enclosure graph based on the immediate locality of the sensor nodes. Each node does not consider the nodes which are located in its relay region as potential candidates to forward its sensed data. In the cost distribution phase, non-optimal links are eliminated from the enclosure graph, and the resulting graph is a minimum energy graph with a directed route to the sink node and consumes the least total energy among all other graphs having directed routes to the sink node.

(g) **Self organizing protocol (SOP)**: The work in [59] proposed the SOP with an application taxonomy used to build an architecture that supports stationary or mobile heterogeneous sensor nodes. There are four modes of operation for SOP: **discovery phase** for establishing neighborhood information, **organization phase** for organizing a height balanced hierarchy, **maintenance phase** for maintaining routing table information and **self-reorganization phase** for recovery from link failures. Some of the sensors in the network are assigned a task of probing the environment for monitored events and forward the sensed data to the designated nodes that act as routers, which in turn forward the data to the sink node on behalf of the sensing nodes. The router nodes are usually stationery; forming the backbone for WSN communication and each sensing node must be able to reach a router node to be considered as part of the network. Moreover, the sensing nodes are identified by the address of the router node to which they are connected, forming a hierarchical routing architecture. As a means of broadcasting, fault-tolerance is provided by a local Markov loop (LML) which employs a random walk on spanning trees of the graph formed by the network nodes. According to the work in [59], the SOP incurs small cost for routing table maintenance and maintaining a balanced routing hierarchy. The authors also found that the SOP consumes less energy for broadcasting a message in comparison to SPIN protocol. However, the organization phase of the SOP is proactive, therefore may introduce unnecessary extra overhead to maintain the routing information; with the reorganization phase which is evoked due to link breakages also becoming a more expensive operation when network connectivity is unreliable.

(h) **Sensor aggregates routing (SAR)**: The authors in [60] proposed the SAR algorithm for constructing and maintaining sensor aggregates for target tracking application, with the objective to collectively monitor target activities in a monitored environment. A sensor aggregate is formed by a group of nodes that satisfy a specified grouping predicate with a collaborative task processing. The work in [60] discussed the formation of appropriate sensor aggregates in terms of resource allocation for sensing and communication tasks. The sensors in a WSN are divided into different clusters, such that there is only one node acting as the cluster-head per cluster. The local nodes in a cluster exchange information in order to elect a leader. During information exchange, a node with the highest sensed signal strength declares itself as the leader among its one-hop neighbors. Three algorithms were proposed in [60] for the sensor aggregates: The first being a distributed aggregate management (DAM), which is a light-weight protocol for forming sensor aggregates. The DAM algorithm has a decision predicate P for each node to decide if it can participate in an aggregate, and a message exchange scheme M which determines how the grouping predicate is applied to the network node. The second is the energy based activity monitoring (EBAM) algorithm which estimates the energy level at each node by computing the signal impact area, combining the weighted form of the detected target energy, with the assumption that each sensor has a constant or equal target energy level. The third is the expectation-maximization like activity monitoring (EMLAM) which does not assume constant and equal target energy levels like the EBAM algorithm, but estimates the target position by using received signals; and also uses the resulting estimations for predicting how signals from the targets may be mixed at each node.

Location-Based Routing Protocols

In location-based (geographic) routing, sensor nodes are addressed by their relative positions in a WSN. Hence, the geographic routing uses location information for delivery of packets. The nodes can exchange their location information and estimate the distance between any neighboring nodes from RSS. As an alternative, a global positioning system (GPS) can be used for location information of the sensor nodes in a WSN, whereby each node is supplied with a low-power GPS receiver using satellite communications [61]. Each node makes forwarding decisions based entirely on its local information. The most common forwarding strategies for geographic routing protocols in WSNs are [1], [6]:

(i) **Greedy-forwarding:** The greedy-forwarding technique selects a neighbor node that minimizes the distance to reach the destination node, which would be node **E** in Figure 2-2. The main goal being to minimize the number of relay nodes required to reach the destination.

(ii) **Nearest with forwarding progress (NFP):** NFP technique selects the closest neighbor node that makes a positive progress towards the destination; node **A** in Figure 2-2. To save power, nodes with adaptive TPLs can transmit at the lowest required power-level to reach the destination node; reducing energy consumption and packet collisions as a result.

(iii) **Most forwarding progress within radius (MFR):** MFR strategy chooses the neighbor node that makes the greatest positive progress towards the destination. The positive progress is based on the distance between the source node and its neighbor node projected onto a line drawn between the source and the destination; node **B** in Figure 2-2 for example.

(iv) **Compass routing:** The compass routing technique selects the next neighbor node with the smallest angle between a line connecting the source node and the neighbor node, with the line drawn from the source node to the destination node; node **C** in Figure 2-2. This strategy attempts to minimize the spatial distance traversed by a packet to the destination node.

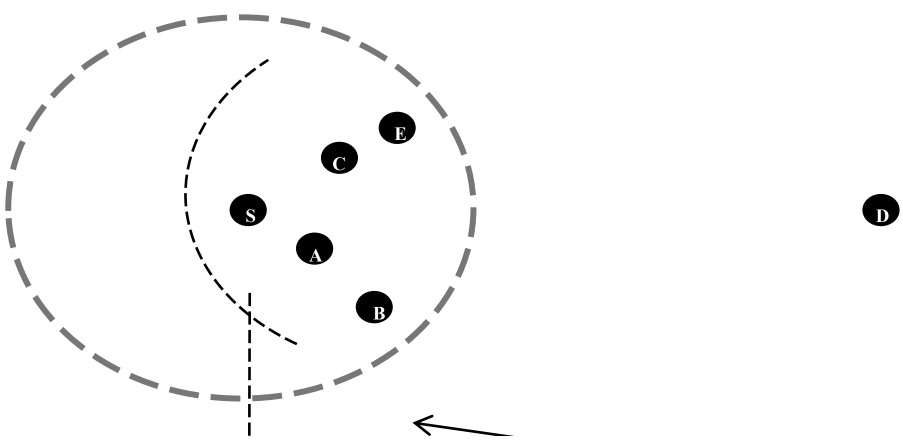

Figure 2-2: Forwarding strategies in geographic routing protocols, [1]-[2], [6].

The following are examples of location-based routing protocols for WSNs:

(a) **Greedy perimeter stateless routing (GPSR)**: The GPSR protocol proposed in [62] operates on geographic information for routing decisions, using the location of sensor nodes relative to destination node for packet forwarding. The sensor nodes are assumed to know the location of other nodes in their neighborhood. For forwarding decisions, the location of the destination node is included in the packet header. The forwarding nodes determine the next hop for the packet from a routing table with the aim to minimize the distance traversed by data packets. Therefore packet forwarding does not require any route information, but is based entirely on the location of the destination node. The advantage of GPSR protocol in WSNs where energy consumption is a crucial issue is low routing control packets as the nodes do not necessarily have to exchange any routing information, except their location information in the network. The major disadvantage of this protocol is that it is based on greedy forwarding, whereby intermediate nodes may have to modify data packet attributes for routing in a region where greedy forwarding is not supported, referred to as *void-region*; with the modification on data packets introducing some packet delays for end-to-end transmissions.

(b) **Geographic adaptive fidelity (GAF)**: GAF is a zone based geographic routing algorithm which was originally designed for MANETS [63]. In operation, GAF divides a network into fixed zones which form a virtual grid. The nodes in each zone share different roles and tasks in collaboration. For instance, the nodes in a virtual grid area collaborate in selection of a single node responsible for monitoring and dissemination of data to a sink node, while all other nodes turn-off their radio and go to sleep mode. Turning-off the radio is done in a manner that it does not degrade the routing efficiency and effectiveness. There are three modes of operation for each node using GAF protocol [6], which are: **discovery** for identifying the neighboring nodes for individual nodes in a network in order to form virtual grids, **active** when a node participates in monitoring and reporting of data to a sink node and **sleep** when a node switches its radio off for some timeout interval. As a result of collaboration in sharing of tasks between the nodes in a virtual grid, GAF reduces energy consumption and improves network lifetime by switching off the radio of other nodes not participating in communication; with improvement in energy-efficiency, more especially when the number of nodes in the network increases.

(c) **Geographic and energy aware routing (GEAR)**: GEAR is an energy aware location based routing protocol that aims to minimize energy consumption by restricting data queries in directed fusion to appropriate regions in a network instead of the entire network, with each data query including geographic attributes of data of interest [64]. To reach a destination region through neighbors, each node in a network records an estimated cost and a learned cost. The estimated cost is a function of residual energy and distance to the destination, while the learned cost is the adjustment on the estimated cost that is required for routing around *holes* in a WSN. A *hole* is encountered when a node does not have any neighbor node closer to the target region than itself. There are two phases through which GEAR protocol operates. The first being forwarding of packets towards a target area in a network, whereby a node checks if any of its neighbors is closer to a target region than itself. The nearest neighbor node is selected as the next hop for packets forwarding. If the nearest neighbor node cannot be found, a hole is encountered; in which case the node selects the next-hop node based on the learning cost function. The second phase is forwarding of packets within a target region. In this phase, a received packet is diffused by either restricted-flooding or recursive geographic forwarding. Restricted-flooding is more suitable for sparsely distributed network deployments, while recursive geographic flooding offers relatively improved energy efficiency than restricted-flooding in densely distributed network deployments [61].

(d) **Geographic distance routing** (GEDIR): GEDIR is a variant of position-based and greedy routing algorithms based on directional forwarding and distance using backward rule [65]. In backward rule, a data packet is dropped only if it has been sent back to the previous node from which it was forwarded. A node forwards a data packet to the next-hop neighbor node with the least Euclidian distance to the destination node among all the neighbors for the packet to make most progress to the destination. A major drawback with routing algorithms based on greedy forwarding is dropping of packets by nodes which have no neighbor nodes closer to the target node, a situation referred to as *local-minima*. However, GEDIR permits sending of packets in reverse direction if a node closer to destination is not available. To avoid routing loops when reaching *local-minima*, the packets are sent back via an alternative route instead of the previous node from which it was forwarded. Two variations of GEDIR algorithm were proposed to address the *local-minima* problem. These are flooding GEDIR (F-GEDIR) and 2-hop GEDIR [56]. F-GEDIR floods packets at the *local-minima*, maintaining routing effectiveness at the expense of increased routing control overhead. The 2-hop GEDIR maintains neighbor information to predict and avoid *local-minima*, but introduces rooting loops for the 2-hops neighbor information.

(e) **Face routing:** Early research work in geographic routing led to various proposals which simply used greedy forwarding schemes without any guarantees for successful delivery of packets in a network [66]. Face-routing algorithm is among the first geographic routing algorithms that provide guaranteed delivery of packets [65], [67]. Geometric graphs can be used to model WSNs, with geographical position of each sensor node representing a node on the network graph. In face-routing, a geometric planar graph is partitioned into faces bounded by polygons comprising the edges of the graph. The edges of a planner graph do not intersect, except at the endpoints (nodes). The main objective in face-routing is to forward data packets along the interior of the faces intersected by a straight line segment between a source node and a destination node. The boundaries of the faces in the graph are traversed by applying the right-hand rule (counterclockwise traversal) or the left hand-rule (clockwise traversal). In the right-hand rule, the packets are forwarded along the next edges counterclockwise from the edges where they arrived, until the destination node is reached. Traversing the first edge of current face traversal twice in the same direction indicates disconnection between the source node and the destination node, in which a loop is created. There are variants of face-routing algorithms proposed in literature. Adaptive face routing (AFR) uses restricted search areas in order to avoid exploring all the boundaries in a face, using eclipse area for restrictions [61]. An eclipse area is set to an initial value of the optimal route length in a network. If the destination node is not reached whiles exploring the faces, the algorithm restarts with the bounding eclipse area of double size. As an extension to AFR algorithm, other adaptive face routing (OAFR) always selects the boundary point closest to the destination node instead of changing the next face at the intersection of the face boundary with the line-segment joining the source and destination nodes. In addition, greedy other adaptive face routing (GOAFR) algorithm which combines both greedy-routing and face-routing algorithms was proposed in [68].

(f) **Greedy-face-greedy (GFG)**: The GFG algorithm presented in [69] is a combination of both efficient greedy forwarding and face routing. In GFG algorithm, routing can be performed through either right hand rule or left hand rule upon the edge intersecting the source and the destination line segment. The greedy forwarding approach is used as long as possible (*i.e.* until it fails), hence face routing is used for recovery from link failures. On failure of the greedy forwarding, a node enters a recovering mode by using face routing, whereby the distance d_r of the first relay node to the target and the first edge e_r along which the packet is transmitted are stored in the packet header. If the edge is revisited for the second time, the destination is considered to be unreachable and the packet is simply dropped. The relay node distance d_r is used to check if the next hop node is closer to the destination node than the node entering the recovery mode itself. On finding such a node, the greedy forwarding approach can be resumed rather than using the face routing. In GFG algorithm, the greedy forwarding is performed using the links of a unit disk graph and face routing using a planar graph (*i.e.* a graph where no two edges cross) as described in [64]; which also provides a detailed analysis of the protocol, illustrating that it does not provide energy-efficiency but guarantees delivery of packets on any planar graph.

(g) **Location based routing protocol (LBRP)**: The work in [70] proposes a reactive location based routing protocol (LBRP) which aims to achieve minimized routing latency by extracting optimum topology information from dynamic and irregular MANETs topology. This protocol consists of three main phases: *location discovery*, *location management* and *data packets transmission*. The location discovery involves flooding of location request packets for discovering a destination node location. The location request packets are propagated through a network from a source until a node which has the location information is reached or the destination node itself. These packets collect the identity information of every node through which they traversed, which is used to return the location reply packet to the source node. The location management uses a location system to periodically gather current location information for each node in a network. The location system calculates the nodes position coordinates and the speed vector simultaneously. The data packets transmission phase is simply a procedure to execute sending of data packets by a source node. The source node includes the destination node location information into the data packet header and broadcast the packet to its neighbors. Any node with more recent information about the destination node location updates the packet on reception. The LBRP has three main properties: short-delay, loop-free and robust [70]. A possible optimization for the LBRP can be introducing a TTL variable to each location request packet to reduce the associated flooding overhead.

(h) Distance routing effect algorithm for mobility (DREAM): The DREAM protocol proposed in [71] is built on two observations. The first being the *distance-effect*, which is based on the fact that network nodes appear to move slowly with respect to each other as the distance separating the nodes increases; whereby the location information is also updated as a function of distance separating the nodes without disrupting routing accuracy [71]. Therefore the nodes which are located far apart are required to update each other less frequently than the nodes which are closely separated. The second idea is based on nodes mobility rate, which triggers the sending of information updates autonomously as the nodes move. Therefore the nodes communicate their location information more frequently as they move faster in the network, which allows each node to self optimize the frequency of disseminating the message updates. Each node knows its location coordinates through a GPS. The location coordinates are exchanged periodically between the nodes and stored in a location table maintained by each node. The key advantage of exchanging the location information in DREAM protocol instead of exchanging the complete link-state or distance-vector information is that it consumes less bandwidth, hence more scalable. Moreover, the frequency at which message update packets are exchanged is proportional to the relative mobility of the nodes and the distance effect, which results in reduced routing overhead. Thus, the stationery nodes no not necessarily have to send any routing update messages.

Cross-Layer Design Techniques in WSN Communications

The necessity for a different design criteria and paradigm is justified by the fact that the applicability of strictly layered techniques based on the OSI protocol architecture is hardly sufficient and greatly questioned in the case of WSNs [26], [28], [29]. The CLD technique emerged as an effective approach that is widely adopted and applied in WSNs to meet their unique application requirements. Consequently, recent research work in WSNs has been directed towards adaptation and optimization across various layers of the conventional OSI protocol stack by exploiting their interdependencies in a cooperative and opportunistic manner [5], [27], [72], [73], as illustrated in Figure 2-3. Energy-efficient communication in WSNs is a crucial optimization task drawing attention from various fields in hardware, communication protocols and algorithms design. This includes diversity and coding at the

PHY layer, modulation techniques at the link layer, power adaptation and scheduling for medium access control (MAC) layer, efficient and effective routing at the NET layer, and QoS provisioning for APP layer [17], [27]. With CLD, optimization techniques in research exploit traditional architectural designs by not only focusing on different layers in isolation.

The core objective in the CLD paradigm is to understand and exploit the interaction and share of information across multiple layers [6]. For instance, CLD can be employed to compensate for different timescale variations associated with each layer in the protocol stack by handling them at appropriate layers but with flexible information flow. At the PHY layer, variations in SNR may be instantaneously fast in a scale of microseconds, as directly dictated by physical environmental conditions. At the NET layer, topology changes may occur at the slower rates affected by sensor nodes mobility, power failure and when new nodes join the

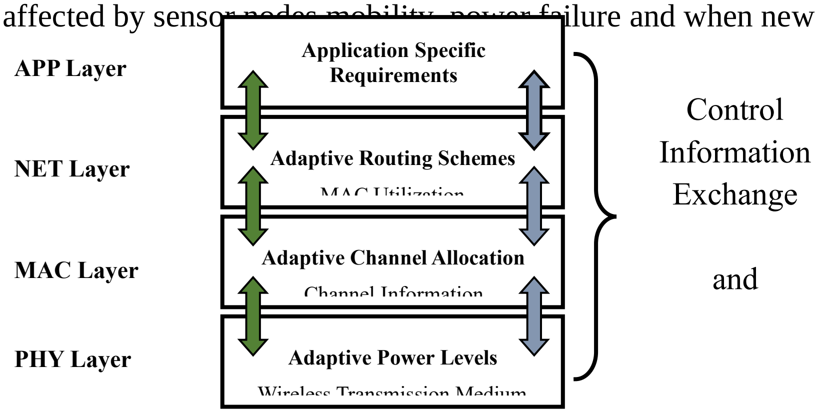

Figure 2-3: Example of CLD architecture, [72].

network, which may be in a scale of seconds. Also, traffic-pattern variations may occur in a scale of minutes at the APP layer, depending on the application for which a WSN is deployed. In adaptation to time scale variations of the wireless channel conditions, each layer should locally attempt to handle the variations with flexible information exchange to other layers of the protocol stack.

Cross-Layer Design Techniques for Routing Protocols in WSNs

Energy-efficiency and performance of routing protocols in WSN communications can be enhanced by employing CLD techniques [73]. There is a substantial amount of research in design of routing protocols for WSNs, mainly targeted at the interdependency between MAC and NET layers [74]-[75]. The authors in [74] carried out experimental study to exploit the effects of link quality indicator (LQI) in WSN communications. Through their experimentation, they found out that LQI alone cannot be a good metric for routing, thus good when combined with other routing metrics. They also illustrated that LQI is a function of both the external (physical environment) and internal (operational characteristics local to each sensor node, such as TPL) phenomena of the sensor nodes. The authors in [75] propose a novel link quality assessment (LQA) based on CLD, combining information sources from different layers in on order to improve performance at higher layers. Their work illustrates that CLD improves end-to-end network throughput and transmission delays without introducing any overhead. Most importantly when applied at the NET layer to make fast and better routing decisions in order to adapt quickly to time-varying conditions of the wireless communication channel.

Moreover, localization can play an important role in routing decisions as nodes would be able to determine their neighbors with their relative positions. Based on CLD methodology again, Blumenthal *et al.* [76] proposed weighted centroid localization (WCL) which is based on received signal strength indicator (RSSI) and the LQI to determine the positions of sensor nodes in a network. Their work shows that in practical scenarios, RSSI has a high variance and low entropy. This is the result of the time-varying characteristics of the radio channel, such as reflections, polarization and refraction of radio signals to mention a few; most significantly when using un-adapted MAC protocols. In [77], the authors present a CLD methodology for improving network lifetime by exploiting interdependency between the PHY layer, MAC layer and NET layer; in which case they compute lifetime optimal routing flow, link schedule, and link transmission powers for all active time slots. Furthermore, the work in [78] proposes a cross-layer medium access control (CLMAC) for improving energy-efficiency in WSN communications, with wake-up nodes that are part of a route between a source node and destination node, while giving other nodes more time to be in a sleep state for longer periods. However, the proposed CLMAC protocol is contention based, with the use of more routing control packets wasting the scarce energy available from sensor nodes' batteries.

The work in [79] proposes adaptive low power listening (ALPL), which is a cross-layer framework for optimizing global power consumption and load balancing in WSNs. ALPL enables each node to make use of its local state and neighborhood information in making routing decisions. The advertisement of state information with neighbor nodes is based on the exchange of beacons, increasing communication overhead in the process. In [80] and [81], a load-balancing scheme is proposed, which sends traffic generated by each node through multiple routes to minimize energy-consumption and improve lifetime of the individual nodes in a WSN. The authors in [82]-[84] also proposed adaptive routing schemes to achieve load balancing in WSNs. These works consider residual energy for the sensor nodes along the routes used for data packet transmissions, using routes with maximum residual energy for delivery of packets. A cross-layer protocol (XLP) is proposed in [85]. This work introduces *initiative determination*, in which each node makes use of its current state to decide on participating in communication. A unified cross-layer framework which replaces the entire conventional layered protocol architecture to achieve a highly reliable communication with minimum energy consumption is also proposed, whereby communication and networking functionalities from PHY layer, MAC layer, NET layer and APP layer are implemented in a single protocol to achieve the reliability. Further, the work in [86]-[88] also exploits the interaction and share of information across multiple layers in an effort to improve energy-efficiency at the network layer.

Recent developments on routing protocols and algorithms for ad hoc and sensor networks also include modifications to the standard DSR algorithm [28], [89], [90], [91], [92], [93], [94]. The work in [28] proposes a hierarchical-DSR protocol, separating the sensor nodes into two categories: one category for performing the actual sensing of data in the network and the other for forwarding the data to the sink node. The mechanism combines the advantages of both reactive and proactive routing techniques. However, this introduces a single point-of-failure in case the forwarding node fails in a group of other sensor nodes, whereby the network may be divided and become dysfunctional. Moreover, network connectivity depends largely on the operation of the forwarding nodes. In [89] also, the authors proposed an extended-DSR protocol, which records the last RSS of a packet from a source node. The RSS value is used to assess wireless channel link conditions, including congestion; and to determine if the receiver node would be out of transmission range from the source node in a mobile network scenario. The major problem with this approach is the reliance on possibly stale RSS values from the received packets, which may lead to routing inconsistencies.

More versions of the modified standard DSR algorithm for congestion control in ad hoc networks are proposed in [90], [91], [92]. The nodes locally monitor their received packets' queue to determine if they are about to experience congestion, and broadcast notifications if congestion is about to occur. Thus broadcasting is a problem is WSNs as it increases traffic flowing in the network, which degrades performance. The authors in [93] proposed a DSR based routing scheme whereby TPL is included in the RREQ packet. The TPL and RSS are used by the receiving nodes to calculate the power required by the transmitting node for successful delivery of packets. Before relaying the RREQ packet, the receiver node inserts the power requirements into the RREQ. On receiving the RREQ packet, a destination node inserts the TPL information for each hop in the RREP packet, which will be used for selection of routes with minimal energy requirements. Further, the authors in [94] also present their work whereby they exploit the interaction between MAC layer and the DSR algorithm in an effort to improve performance of the DSR algorithm. However, the authors in [27] argue that even though CLD methodologies have the potential to improve performance and efficiency in WSN communications, they can also bring undesirable results if not approached with careful analysis and proper design; such as leading to a *spaghetti* design with unintended interactions, loops and hard-to-maintain and upgrade code. Hence, the disadvantages of CLD may outweigh the advantages in not carefully approached.

Critical Review for Preferred Routing Algorithm

This section provides a detailed review about the preference on the DSR algorithm among many other routing algorithms discussed in Section 2.4 of this chapter. A good routing protocol can be described as the one with minimal routing overhead without creating loops, good recovery from link failures, and most importantly energy-efficient in the case of WSNs. As mentioned in the previous sections already, the DSR algorithm is a simple and efficient routing scheme that establishes routes between a source node and destination node only when the need arises *(i.e.* reactive protocol). This supports for reduced communication overhead and scalability in network deployments . In contrast, table-driven (*i.e.* proactive) protocols generate routing tables and maintain them continuously irrespective of the need. Latency for route acquisition is therefore less for the proactive routing approach. This might be necessary for certain applications but the cost of communication incurred might not be feasible in WSN, where energy-efficient communication is of utmost importance. Also, the proactive routing approach requires more memory due to significant increase in the size of routing tables, which may limit the size and density of networks due to memory limitations associated with sensor nodes in a WSN. As a result of the reactive nature of the DSR protocol, periodic routing updates and neighbor discovery procedures are automatically eliminated to restrict the energy and bandwidth associated with the routing control packets [19]. Further, the routing control packets overhead scales automatically to what is required to react to topological changes for the routes which are currently in use during packet transmissions.

Furthermore, the DSR protocol ensures that a network is completely self-organizing and self-configuring, without the requirement of an existing network infrastructure or administration [24]. Being source-based, one of the advantages of the DSR protocol is that intermediate nodes do not need to maintain up-to-date routing information in order to route the packets they forward. During data transmission, source nodes explicitly specify the entire hop-by-hop route information to a destination node. Hence, routes are maintained only by the source nodes from which packets are originated, reducing routing the overhead for intermediate nodes. Through route caching, the intermediate nodes also utilize the route cache information efficiently to reduce routing overhead. The performance evaluation conducted on both proactive and reactive protocols [19], [20], [21], [22], [23], showed that the DSR protocol performs better than the AODV and other proactive protocols in terms of throughput, end-to-end delay, and packets drop. The DSR protocol performance is attributed to its characteristics of having multiple routes to destination nodes. In case of link failure, it does not require a new route discovery processes. Because of this, end-to-end delay is reduced, fewer packets are dropped and less energy consumed. The DSR protocol has therefore been chosen as the basis for the presented research work. In conclusion, the next section presents summery for the work discussed in this chapter.

Chapter Summary

The work in this chapter presented the investigation conducted in survey of the research accomplishments in WSN communications, mainly focusing on routing protocols and CLD methodologies. The major portion of the research efforts has been directed towards design techniques aiming to improve energy-efficiency in WSN communications by exploiting the interaction and share of information across multiple layers of the OSI protocol stack, which is found to be the most viable solution thus far for overcoming the inherent design challenges and performance improvement in WSNs. In as much as WSNs share similar characteristics with wireless ad hoc networks, majority of communication protocols and standards which have been proposed for wireless ad hoc networks do not offer best solutions when applied directly (*i.e.* when used without modifications) in WSNs, which results from the fact that WSNs have unique design constraints with scarcity of resources imposed by the decreasing size of the sensor nodes.

Most of the recent works on routing protocols try to minimize energy consumption in WSNs. Nonetheless, unlike the work on routing protocols proposed in Chapter 3 and Chapter 4 of this dissertation, the discussed protocols do not take into consideration, checking of network and channel status before transmission of routing control packets in a network. In WSNs, the energy associated with the exchange of routing control packets has a significant impact on energy consumption, which may lead to faster depletion of energy. Therefore the cross-layer framework proposed in this dissertation goes further to check network and channel status, together with the quality of wireless channel links before transmitting any routing control packets in an effort to improve energy efficiency. Hence this chapter provided the core pillars and foundations which were concisely reviewed as a preamble to the ideas and contributions presented in the following chapters.

Chapter 3

Conclusion and Future Work :

Chapter 4

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