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Review Article

Communication protocols for wireless sensor networks: A survey and comparison

Lucia Keleadile Ketshabetswe, Adamu Murtala Zungeru [*], Mmoloki Mangwala, Joseph M. Chuma, Boyce Sigweni

Department of Electrical, Computer and Telecommunication Engineering, Botswana International University of Science and Technology, Private Bag 16, Palapye, Botswana

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ABSTRACT

Studies conducted on resource management in wireless sensor networks have identified energy efficient routing protocols as one of the energy saving mechanisms that can be used to manage the consumption of networks' available energy and extend network lifetime. Routing protocols assist in finding paths for transmission of sensed events, and they must be able to extend the lifetime of a network despite some of the limitations of sensor nodes in a network and the harsh environments in which the sensor nodes are to operate. In this paper, we survey and compare existing routing protocols in wireless sensor networks. We start by introducing the different solutions that can be used to improve the network lifetime and focus on energy efficient routing protocols as the area of the survey, in addition to network topology modeling. We also model the network regarding energy consumption, sensing and event extraction analysis in the network. Categorization of the routing protocols into homogeneous and heterogeneous was performed, for which, sub-classification into static and mobile and other behavioral patterns of the routing protocols was done. The second phase of the paper presents models and simulations of selected routing protocols and comparisons of their performances. We conclude this paper by discussing future work directions with highlights on some futuristic applications.

1. Introduction

A SENSOR network is a collection of a large number of wireless sensing nodes that are spatially dispersed in a sensor field. Sensor nodes act as data generators and network relays, and they can sense (measure), process data, and communicate with other sensor nodes. The end users of the data or administrators can then be able to make observations and respond to events in a particular environment [1, 2, 3]. Wireless sensor nodes are very tiny and very cost effective. They can measure environmental conditions or other parameters including air quality, temperature, sound, pressure, and humidity and send that information to a common base to be processed appropriately.

A biological structure, the practical world, or background of information technology (IT) may be the typical environment. Advanced networking protocols of mesh topology enable the sensing nodes to build a wide connectivity area and connect the cyberspace to the practical world. The sensor module measures environmental parameters that surround the sensor and transforms the ambient energy into electric signals. Information on events that are happening within the vicinity of the sensor is obtained through the processing of the information by the processor module, and the data is transmitted through a radio transmitter to a destination node. Technological advances have led to reduced size and cost of the sensors and hence have fueled interest in the possibility of using large sets of disposable unattended sensors. Exhaustive research on the possible collaboration of sensors in the data collection and computation, the control and administration of the sensing activity and flow of data to the destination node has been going on in the past few years. Sensors communicating through wireless communication links can form a network in an ad hoc manner, a natural design for such collective sensors that are distributed [4].

A wireless sensor network (WSN) should be able to deploy a large number of very small nodes that can assemble and configure themselves for a common purpose. Applications of WSNs include but not limited to battlefield surveillance, environmental monitoring, disaster detection and rescue, precise and intelligent agriculture, medicine and health care, environment-friendly buildings, traffic control, and object tracking. Examples of environmental monitoring and object tracking could be monitoring underground mines for any trends to ensure the safety and

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[*] Corresponding author.
E-mail address: zungerum@biust.ac.bw (A.M. Zungeru).

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location of miners always. WSNs are deployed at minimum costs as compared to wired networks. They can dynamically adapt to changes in the environment they are deployed in, and actively respond to network topological changes. Major parts that make a wireless sensor network are;

1. The Sensor module
2. The Processor module
3. The Power source module
4. The Transceiver

Actuators, analog to digital converters (ADC) and monitors may be added depending on the application. Fig. 1 shows the different elements that make a wireless sensor node [4].

A wireless communication network is formed in an ad hoc manner where sensor nodes can organize themselves with no proper coordination, this is found in most WSNs applications. The source of power for the sensor nodes is a battery, which is usually not re-chargeable or replaceable especially when the sensor nodes are expected to operate with no human intervention for a longer period during the application [3, 5]. Careful resource management is a prime concern in the design of wireless sensor networks. It can be achieved through energy saving techniques such as Radio Optimization, Data Reduction, Sleep or Wake-up methods, Energy Efficient routing protocols and Energy Harvesting [6].

The role of wireless sensor nodes is to detect and gather information from a sensor field or area of interest, computes the information and forwards it through a radio module back to a central point or destination [2, 4, 7, 8, 9]. This study is focused on energy efficient routing protocols, an energy saving method that is needed to discover routes for transmission of data between the sensor nodes and the destination node. Some of the recently published articles that address energy efficiency in communications are reported in [10, 11, 12, 13]. The design of the routing protocols should, therefore, cater to the trade-offs that may arise at the expense of energy efficiency for different applications of the networks.

A survey on wireless sensor networks [14] reveals many desirable properties of social insect communities. The environment of a sensor network may be its architecture or effects of the physical layer on the communications links as well as network traffic patterns. Biological networks differ from planned networks in that the biological ones have a cooperative incentive that evolves naturally, while the latter may require some initiatives to energize nodes to cooperate [15, 16]. The four principles that social insects rely on to be able to self-organize are randomness, multiple interactions, positive feedback, and negative feedback. Stigmergy emerges as a product of these four principles [17]. The ability to self-organize is termed swarm intelligence and is comparatively a unique field that was originally defined as “the design of protocols through the inspiration of the collaborative behavior of social organisms and other animal societies” [18]. It is currently defined as the study of the collaborative behavior of systems that are made of several components and can coordinate through non-centralized controls and self-organization. Engineers interpret swarm intelligence as an emphasis on a design that starts from the bottom to the top with scattered systems that are self-sufficient and demonstrate characteristics of adaptability, robustness, and scalability. Some of the examples of natural species social communities are ant colonies [19], honey bees [20], termites [21], bats [22] and spider monkeys [23].

An important factor in wireless sensor networks is the way in which data and queries are relayed from the source node to the sink node. Research has in the past focused on investigating the possibility of sensors working together collecting data, processing it, coordinating, and managing the extracted information traffic to the destination [1]. To accomplish this task, a single hop communication approach, where each sensor node directly transmits to the sink node can be followed. An alternative approach is a multi-hop communication, where intermediate nodes are used to forward data packets towards the sink node [2, 9]. It is the function of a routing algorithm to decide on the selection of the sets of intermediate nodes that establish routes to forward data packets to the sink. Routing protocols can be classified according to the different ways in which data is forwarded from the nodes to the sink.

Different research work in the field of sensor networks classify the routing protocols based on some metrics. Most research papers focused their survey on either the conventional communication protocols or nature inspired communication protocols. Only a few protocols compared both conventional and biologically inspired routing protocols. This paper outlines a recent review and comparison of communication protocols in WSNs. The initial phase of this work introduces different energy saving mechanisms in WSNs and identifies routing protocols as an area of focus for this work. It further acknowledges that sensor networks can either be homogeneous or heterogeneous depending on the type of sensor nodes deployed in the network. The routing protocols for both homogeneous and heterogeneous networks are classified depending on whether their sink nodes are static or mobile. The different categories of the routing protocols are presented according to their computational complexity, network structure, energy efficiency, and path establishment. The second phase of the paper compares a selected number of protocols. The last part of the paper discusses analytical models of two selected protocols: Ad Hoc On-Demand Distance Vector (AODV) and Termite Hill and re-simulates them. Simulation results for standard simulation and performance metrics are used to compare the performance of the routing protocols.

A review of previous surveys on routing protocols in WSNs is presented in section 2.1 of this paper, while Section 2.2 outlines the important factors that should be considered when designing sensor networks and routing protocols. Section 2.3 presents the wireless sensor networks modeling while Section 2.4 is a discussion of the categorization of routing protocols in WSNs. Analytical models for selected investigated routing protocols are presented in Section 2.5, and the experimental comparison is discussed in section 2.6. Section 3 concludes the paper and highlighting some futuristic applications of WSNs as future work directions.

2. Main text

2.1. Previous work on the survey of wireless sensor network routing

Routing plays a major role in the design of WSNs. Several research papers and surveys have proposed different routing protocols in wireless sensor networks. In one survey [3], discussed a few conventional routing protocols and the way they forward information. A short review period (1999–2000) informed this study. Authors in [1] surveyed a selected number of conventional routing protocols, which is a similar survey to

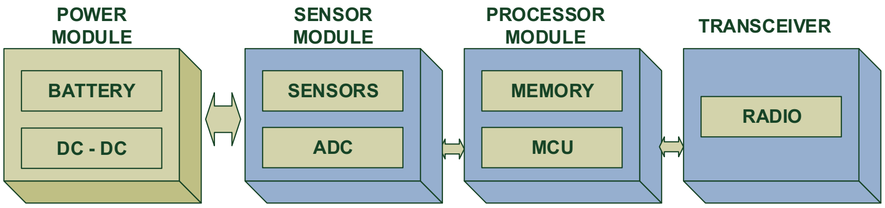


Fig. 1. A structure of a WSN Node.

the extensive survey made by [24]. The protocols in the survey were based on a single sink node, and only a few of them were energy aware. In 2007 [25], focused their survey on clustered algorithms only and discussed their objectives, features, and complexity. An extensive study on Nature-inspired routing protocols is presented by [26] and [14]. It discusses the principles and applications of the protocols and their simulation environments. Authors in [4] also surveyed and compared conventional routing protocols, and Nature inspired routing protocols in WSNs. Categorization of the protocols is presented according to how complex processing of information is, the structure of the sensor network, path establishment and how efficient the network energy is. Results from the analytical and experimental comparisons highlighted some shortcomings in the evaluation of routing protocols in WSNs and provided a benchmark for future comparisons. In 2014, in their top-down survey [6], reviewed methods that permit the trade-offs between application requirements and energy efficiency that arise during the design of WSNs. Previous work on mWSNs was presented by [27] and classified routing protocols with mobile sinks. In 2016, a review of energy efficient routing protocols was discussed by [28] and categorized the protocols based on the characteristics of the sensor nodes. A recent survey of network lifetime maximization techniques was presented by [29], reviewing new trends in wireless sensor networks covering applications, design constraints, and lifetime prediction models. However, these surveys are way behind the recent advances, in addition to the missing detailed performance results and models. As such we then see the need to present and discuss some important models like the energy consumption and detailed analysis and simulation results of the recent communication protocols in WSN. Some design guidelines for the design of maximum lifetime applications are also discussed and presented. A summary of previous research work surveyed in this paper is shown in Table 1.

2.2. *Critical factors in the design of wireless sensor networks and routing protocols*

Some important factors are to be considered when designing wireless sensor networks and routing protocols because of the challenges that may arise as a result of the characteristics of the environment in which these networks are deployed in and the requirements of the network applications. Issues concerning power usage and management, tolerance to faults, the ability to be scalable, network connectivity, QoS, data aggregation, congestion, latency, and production cost need to be addressed in the design of routing protocols for wireless sensor networks. This will help to overcome the following challenges that affect the design of these networks [4];

A. Limited energy capacity: sensor nodes are very small and their main source of power is a battery. The batteries have limited capacity, and

Table 1
Previous work on WSN routing protocols based on surveys.

Authors	Title	Year of Survey	Survey Approach
1. Akyildiz, Su, Sankarasubramanim and Cayirci.	Wireless Sensor Network: a survey.	2001	The survey focuses on conventional routing protocols only. Presents sensing tasks and applications of WSNs and reviews factors that affect the design of the routing protocols.
2. Karaki and Kamal.	Routing techniques in WSNs.	2004	A survey of conventional routing protocols; categorized the protocols into flat, hierarchical, location-based and Quality of Service (QoS). Compared to the classes depending on whether they are multi-path based, query-based, negotiation based, or coherent based.
3. Akkaya and Younis.	Survey on routing protocols for WSNs.	2005	A review of conventional routing protocols; classified the protocols into location-based, Network Flow & Quality of Service (NF & QoS), data aggregation (D-A), data-centric and hierarchical.
4. Abbasi and Younis.	A survey on clustering algorithms for WSNs.	2007	A survey of clustering algorithms for WSNs based on convergence rate, the stability of clusters, overlapping of clusters, node mobility support, and location awareness.
5. Saleem, Di Cairo, and Farooq.	Swarm Intelligence based routing protocol for WSNs: a survey and comparison.	2010	A survey of swarm intelligence-based routing protocols. Presents a critical discussion on the scientific soundness on the survey of routing protocols in WSNs.
6. Zungeru, Ang and Seng.	Classical and swarm intelligence-based routing protocols for WSNs: a survey and comparison.	2012	A survey and comparison of conventional routing protocols and swarm intelligence-based routing protocols. Presents performance metrics and basic simulation parameters that can be used to compare routing protocols.
7. Rault, Bouabdallah, and Challal.	Energy efficiency in WSNs: a top-down survey.	2014	A top-down survey of energy conservation mechanisms, outlining the trade-offs between application requirements and network lifetime.
8. Sheng Yu, Zhang, Li, and Mouftah.	Routing Protocols for WSNs with Mobile sinks: A Survey.	2014	A classification of existing mobile wireless sensor networks (mWSNs) routing protocols according to design criteria. A survey of the state of art routing protocols for mWSNs.
9. Priyanka Sharma and Inderjeet Kaur	A Comparative Study on Energy Efficient Routing Protocols in Wireless Sensor Networks.	2015	Categorization of routing protocols into path establishment, network structure and protocol operation. Path establishment protocols further classified as proactive, reactive and hybrid. Network structure routing protocols are further classified into data-centric, hierarchical and location-based while protocol operation ones are further classified into query based bio-inspired, negotiation coherent, non-coherent, QoS, multipath and mobility. Discussion of the merits and demerits of the routing protocols.
10. Hassan Echoukaira, Khalid Bourguiba, and Mohammed Ouzzif	A Survey on Flat Routing Protocols in Wireless Sensor Networks	2015	A survey of flooding data-centric and forwarding routing protocols based on network structure. Comparison of some flat routing protocols with highlights on their associated problems and application types.
11. Jingjing Yan, Zhou and Ding	Recent Advances in Energy Efficient Routing Protocols for Wireless Sensor Networks: A Review.	2016	A classification of WSNs based on two categories: homogeneous and heterogeneous sensor networks. Further classification into static and mobile networks and discusses various routing protocols under these categories.
12. Maya M. Warrier and Ajay Kumar	An energy efficient approach for routing in wireless sensor networks	2016	Compares Modified Low Energy Adaptive Clustering Hierarchy (LEACH) and Mobile Sink improved energy efficient Power Efficient Gathering in Sensor Information Systems (PEGASIS) using Matrix Laboratory (MATLAB).
13. Yetgin, Cheung, EL-Hajjar, and Hanzo.	A survey of Network lifetime maximization techniques in WSNs.	2017	A review of network lifetime maximization techniques and the lifetime estimation models. Provides some design guidelines that can be used to improve the different design approaches.

therefore careful consideration of energy conservation and transmission range planning must be exercised. Suitable routing protocols should be employed for relevant applications at the best interest of energy saving in the network.

B. Hardware resource constraints: sensor nodes are limited in their ability to process information as well as in data storage. The limitations must be considered alongside the energy limitations in the network and protocol design.

C. Dynamic network: Frequent changes in the structure of the network must be catered for in the design of routing protocols. It is vital to keep the routing data stable in a network where one or more components of the network are mobile.

D. Node deployment: It depends on the desired application and can greatly affect the performance of the routing protocol. A node deployment must suit a specific and relevant application to maintain connectivity and energy efficiency in the network.

E. Sensor Location: It has to be urgently managed especially at the initial discovery of routes when sensor nodes need to gain information on their environment and surrounding to get the position of other nodes.

F. Fault tolerance: Network connectivity and operation must be maintained even in the event of sensor node failures that may occur because of power failures, mechanical damage or any interference in the environment. Routing protocols should be designed to respond quickly and discover new routes for the transmission of data in case there are failures in the network.

G. Latency: Is a measure of the amount of time it takes to send information from one node to the sink or destination node. It is also termed as an end-to-end delay in wireless sensor networks.

H. Data aggregation: It describes the way data is collected in a sensor network which can either be event-driven, time driven query driven or both time and event (hybrid) driven. Collection of data or reporting relates to an event happening in or around the sensor network. It reduces the number of transmissions to the sink node by aggregating similar data packets from multiple source nodes and thus eliminating data redundancy.

I. Scalability: For applications where tens of thousands of sensor nodes are deployed in a network, routing protocols should be designed in a way that they will be able to handle and respond to such greater number of events [4].

Many different routing protocols have thus been developed for wireless sensor networks by researchers around the globe. Routing in sensor networks is different from routing in ordinary networks because of the nature of sensor networks to attract many challenges. Since sensor nodes are deployed in large numbers, it is impractical to assign global addresses (classical Internet Protocol (IP) based) protocols to sensor networks. In sensor networks, sensed information flows from multiple sources to a destination point or sink, unlike in typical communication networks. There is a high probability of redundant data being generated by multiple sources and will require efficient routing protocols to improve energy efficiency in the network. Careful resource management is required to alleviate the sensor nodes constraints of energy available onboard, communication power and the ability to process and store energy. To overcome these many challenges for wireless sensor networks, researchers have been designing and proposing new routing algorithms over the year by considering sensor nodes characteristics, network structures, and path establishment and application requirements. In addition to the ordinary or conventional routing protocols, another class of protocols has been explored by [14, 21, 22, 23] that is inspired by the social behaviors of some biological organisms like ants, bees, termites, spider monkeys, and others. This class of protocols provides natural models that solve global problems with no central coordination and is termed Nature inspired routing protocol.

2.3. Wireless sensor networks' systems modelling

It is observed from surveyed work that most surveys on wireless sensor network routing focused their work on the traditional routing protocols only. Authors in [14] reviewed Nature inspired routing protocols while [4] covered both conventional and Nature inspired routing protocols in their survey work. In the evaluation of their reviewed work [14], identified a gap in the scientific soundness of the presentation and evaluation of routing protocols for wireless sensor networks. This paper intends to fill some of these gaps by presenting analytical models for selected routing protocols and defining their simulation environment and eventually comparing their performances with relevant protocols. The next subsections discussed the models.

2.3.1. Description of the wireless sensor network environment

A wireless sensor network consisting of fixed sensor nodes S, ranging from $1, 2, 3 \ldots S$, having a destination node Q, distributed over a sensor field is considered. The sensor nodes can detect the sensor field and be able to locate the position of the sink and its entire surroundings. It is assumed that each node generates m-bits sized data packets each time and can forward its sensed event in a single hop fashion (directly to the sink) or in multi-hops (routing the sensed events through other sensor nodes to the sink node). As it is the case in typical sensor networks, the main source of power supply for the sensor nodes is a non-rechargeable battery with limited energy. Some part of the battery energy is consumed whenever an event is transmitted or received by a sensor node. It is assumed in this model that the sink node has an infinite amount of energy source. A grid-based network that is spatially distributed is considered. The following fundamental models are required to represent and define the bandwidth and limited energy constraints in the sensor network: 1. Analytical (mathematical) model for node distribution and connectivity. 2. A model for network lifetime using the energy consumption of the network nodes. 3. A model for the reliability of the system [30].

This network has S sensor nodes that are autonomously and spatially distributed over a two-dimensional simulation area F. Considering a uniform random distribution with many nodes S, and a wide space area F, the node density in the network can be given as $\rho = S/F$. This translates to the expected number of nodes for an area.

In the analysis of the connectivity between the nodes in the network, it is assumed that a simple radio link model exists where each node in the network has a certain communication range d_{tx}, using Omni-directional antennas. The communication range is limited, and this represents the bandwidth constraints of the sensor networks. Fig. 2 demonstrates that two nodes can communicate with each other over a wireless communication link, as long as they are within each other's communication range; otherwise, communication fails. The communication is bidirectional.

Considering a propagation model with a certain signal path loss with a transmitted signal power at the source node, $P_{tx} = P(d = 0)$ and received power at the receiving node, $P_{rx}(d)$ of distance d from the source (sender), the received power can be denoted as $P_{rx}(d) \propto d^{-\gamma} P_{tx}$ where γ is the path loss exponent, and typically depends on the environment ($2 \leq \gamma \leq 4$). The wireless transmission range d_{tx} can be mapped to the equivalent transmission power P_{tx} using a threshold for

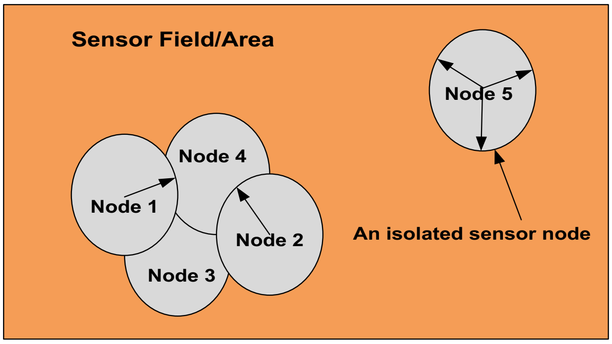


Fig. 2. Modelling the structure of the wireless sensor network.

receiver sensitivity$P_{rx(s)}$. A node in the network can adequately receive information from other nodes only if $P(d = d_{tx}) \geq P_{rx(s)}$. In this system, all nodes in the network area are static but the sink node may move in the system area based on some application requirements. The basic attributes and parameters that make the network structure need to be explored to handle this type of network. This refers to the possible connectivity, reliability and behavior of the operating protocols, and most importantly, the energy consumptions of the participating nodes [30].

2.3.2. Description of the structure (topology) of the wireless sensor network

The structure of the network also known as the network topology refers to the arrangement of the sensor nodes in a given sensing area to form a network. The topology discussed in this paper is a rectangular *x-y* grid. Different properties like the grid spacing, grid size, number of bits, number of packets, grid density and other parameters are used to determine different network topologies. Some of these parameters are defined to gain more insight into the rectangular grid based topology discussed in this work. Grid spacing or distance *(dx, dy)* refers to the spacing between the grid points in the *x* and *y* directions of the network area *Axdx * Aydy*. Grid size *(Ax, Ay)*refers to the number of grid points in the *x* and *y* directions. Grid density *(Ex, Ey)* is the number of nodes in each row and each column from one end of a grid point to another. They amount to a total of *AxAy * (Ex + Ey -1)*.

A wireless sensor network can be modeled as an undirected graph $J = J\ (M, N)$ based on the basic graph theory and interconnection networks concept. The graph has *m* sensor nodes (vertices) and *n* set of node pairs (edges).

$M\ (J) = \{m1, m2, m3, \ldots.mn\}$is the set of nodes analogous to wireless sensor networks enabled devices. $N\ (J) = \{n1, n2, n3, \ldots.nz\}$ is the set of node pairs analogous to the wireless communication links. A vertex of *J* or node is an element in *M (J)*. An edge of *J* or link is an element in *N (J)*.

For any pair of nodes to be connected, they must lie within the communication range of each other, otherwise, there is no communication link between the pair of nodes. However, channel errors and contention may also be responsible for broken communication links despite the availability of communication links between pairs of nodes. If at least one path is available for each pair of nodes or vertex in a graph, the graph is considered to be connected otherwise it is termed a disconnected graph. Fig. 3 shows that for every pair of nodes to be connected, there have to be at least ***k*** mutually independent paths connecting them and the graph is considered to be *k*-connected *(k = 1, 2, 3, ….k)*. The number of nodes connected to a node (neighbors) is the degree of that node *u, d (u)*. An isolated node is one with a zero degree *d (u)* = 0 as shown in Fig. 2.

The minimum node degree of a graph (M, N) as borrowed from [30] is expressed as:

$$\text{degmin (J)} = min_{\nabla a \in J}\{\text{deg (u)}\}$$

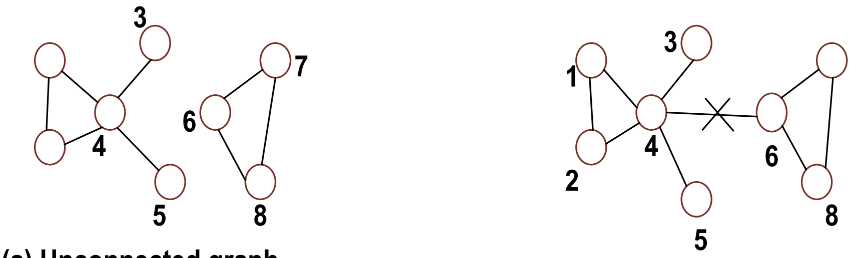
The average node degree of J is

$$d_{avg}(J) = \frac{1}{k}\sum_{a=1}^{k} d(u)$$

In an undirected path,
$d_{avg}\ (J) = d_{avg}(J) = \frac{2m}{k}$

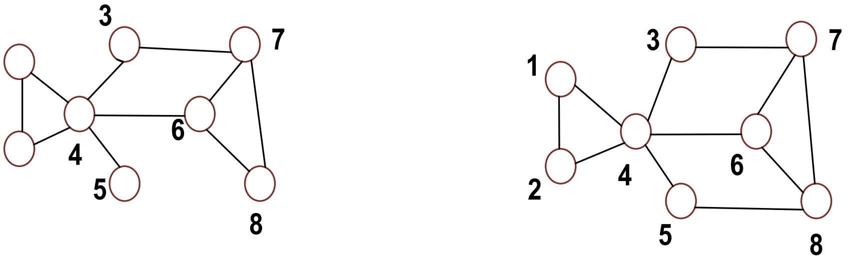
2.3.2.1. Grid distance. Sensor nodes are randomly placed across a network area with a grid size Ax, Ay in the x and y directions. As the sink node queries all the sensor nodes in the network through broadcasts and the source node that has the desired information receives the query, the source node will forward the information to the sink node. The information can be forwarded directly to the sink in a single hop fashion, or it can be forwarded in a series of relays or multiple hops. A source node can be any node in the monitored area of the network grid that has information that can be sent to the sink or destination node. Grid nodes from source nodes to sink node form a grid-based topology to forward or route events to the destination node. Fig. 4 is an illustration of a rectangular grid topology.

Regarding Fig. 4 and reported in [30], to determine the distance that separates two sensor nodes lying close to each other in a rectangular grid-based topology, there has to be a trade-off between distance and energy consumption of the sensor nodes. When two selected nodes are closer to each other, the distance between the nodes will be short resulting in an increased number of hops towards the destination node (sink). If the distance of the selected nodes is longer, the sensor node will need additional energy to forward the information to other neighboring nodes in the grid. For a grid node to forward events in a single hop transmission, the energy needed amounts to the energy dissipated by the participating nodes in the network for transmission and reception of sensed information as Etx and E_{rx} respectively, is given as:



(a) Unconnected graph

(b) 1- connected graph



(c) 2- connected graph

(d) 3- connected graph

Fig. 3. Demonstrating the connectivity of the graph.

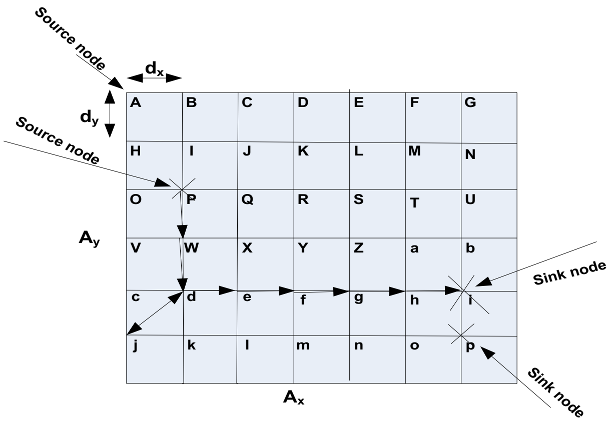


Fig. 4. A rectangular x/y grid-based structure of a wireless sensor network.

$$E_p = E_{tx} + E_{rx}$$

Typically, a grid topology network is shown in Fig. 4. The network is having a sink node at point p away from source node A, for which the number of hops from the sink to the said node is 11 for whichever path is taken, and having a grid distance d_y and dx in the y and x respectively, the distance between two separated nodes D is:

$$D = \left((d_{x1} - d_{x2})^2 + (d_{y1} - d_{y2})^2\right)^{\frac{1}{2}}$$

With the assumption of using a grid topology having A_x as the width, and A_y, as height, we can define the number of rows and column for horizontal (X), and vertical (Y) hops respectively as $\frac{A_x}{dx}$ and $\frac{A_y}{dy}$ respectively. The average transmission cost, T_{cav}, is defined as:

$$T_{cav} = \frac{\sum_{(X+Y)hops}(E_{tx} + E_{rx})}{D_d} \tag{1}$$

Also,

$$D_d = \left((DX)^2 + (DY)^2\right)^{\frac{1}{2}} = D\left(X^2 + Y^2\right)^{\frac{1}{2}}$$

where D_d is the direct transmission path and using the standard radio model, shown in Fig. 5, E_{elec} *(J/bit)* is the radio dissipation energy and E_{amp} *(J/bit*m^2)* is the transmission amplifier energy which is needed for during sending information. For the receiver, only the radio energy, E_{elec} is needed.

It is assumed that channel transmission also introduces energy loss D^2. To send m bits (packet size) of information over a distance D using the simple radio model, the energy dissipated for a single hop transmission is $(E_{tx} + E_{rx})$, and

$$E_{tx}(m, D) = E_{tx-elec}(m) + E_{tx-amp}(m, D).$$

or

$$E_{tx}(m, D) = mE_{elec} + mD^{\lambda}E_{amp}$$

$$E_{tx}(m, D) = n\alpha E_{amp} + mD^{\lambda}E_{amp}$$

Where λ represents the path loss exponent, such that $(2 \leq \lambda \leq 4)$. Assuming $\lambda = 2$ for a single hop transmission with minimum loss or transmission cost;

$$E_{tx}(m, D) = mE_{amp}\left(\alpha + D^2\right) \tag{2}$$

Where α represents the amplification factor such that $\alpha = \frac{E_{elec}}{E_{amp}}$. At the receiver side, to receive the m-bit of information, the radio energy expended is:

$$E_{rx}(m) = E_{rx-elec}(m) = mE_{elec} = \alpha mE_{amp}$$

The average energy expended per unit distance in (1) can then be expressed as;

$$T_{cav} = \frac{\sum_{(X+Y)hops}(E_{tx} + E_{rx})}{D_d}$$

$$= \frac{(X + Y)\left[\alpha mE_{amp} + mD^2E_{amp} + \alpha mE_{amp}\right]}{D^*(X^2 + Y^2)^{\frac{1}{2}}}$$

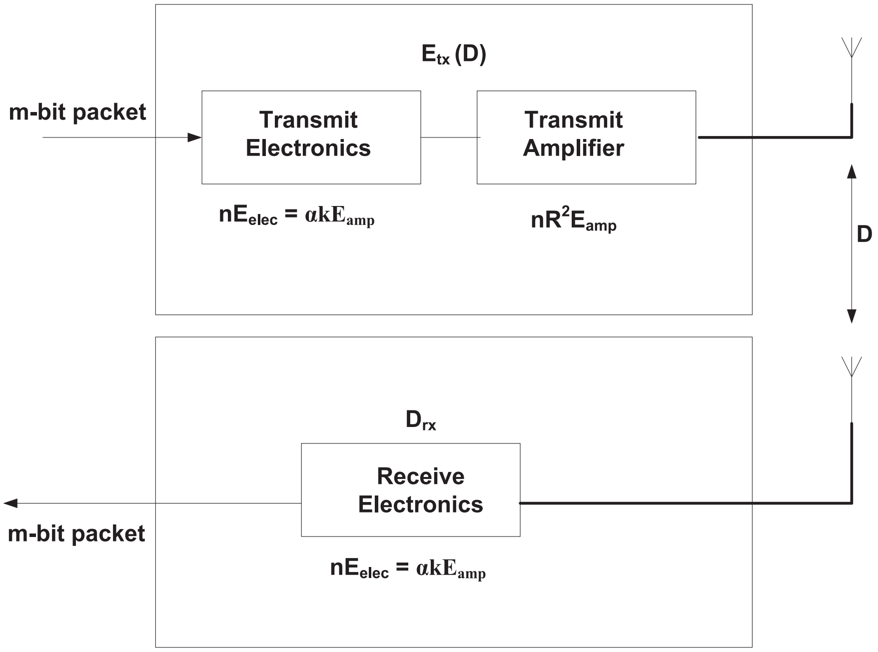


Fig. 5. A model of a single hop transmission radio model.

$$= \frac{(X + Y)\, mE_{amp}\, (2\alpha + D^2)}{D^*(X^2 + Y^2)^{\frac{1}{2}}} \tag{3}$$

The static grid-based network *x, y, m* and E_{amp} are constant along the *Ax* by *Ay* grid topology. If Eq. (3) is expressed in the worst-case scenario as below, the upper ceiling for energy consumption can be achieved.

$$[\![T^{'}_{cav} = \frac{d}{dD}\left[\frac{(X+Y)mE_{amp}(2\alpha+D^2)}{D^*(X^2+Y^2)^{\frac{1}{2}}}\right] = 0$$

That is,

$$\frac{(X+Y)mE_{amp}}{(X^2+Y^2)^{\frac{1}{2}}}\left[\frac{d}{dD}\left[\frac{(2\alpha+D^2)}{D}\right]\right] = 0$$

Or $\frac{d}{dD}[2\alpha D^{-1} + D] = 0$
And

$$-2\alpha D^{-2} + 1 = 0 \tag{4}$$

$$\rightarrow \qquad -2\alpha = -D^2$$

$\therefore D = (2\alpha)^{½}$
Implying that the average transmission cost occurred when $D = (2\alpha)^{\frac{1}{2}}$

2.3.2.2. Analysis of energy consumption per distance of a grid-based WSN. In this sub-section of the paper, we analyze and show the effect of a change in parameters on transmission cost of a wireless terrestrial sensor network. From Figs. 6, 7 and 8, which is a result obtained from the computational analysis of Eq. (12). Fig. 6 describes the behavioral pattern of the effect of transmission distance on energy consumption per unit meter. It is evident that when the transmission distance (*D*) is increased, energy consumed per node also increase. The sharp increase in energy consumed per unit meter (transmission cost) is due to the proportionality between the energy consumed per unit meter and the transmission distance (*D*) as can be seen in the expression (12). For a well-known wireless sensor node produced by Libelium (Waspmote), a node can transmit information up to a maximum distance of 500 meters. For Crossbow MICAz, a maximum of 100 meters is expected and for the Intel product (Intel IMote2), we expect a maximum of 30 meters. This simply means that a multi-hop or relaying method should be encouraged for even distribution of energy in the network and for prolonging the network lifetime. Shown in Fig. 7 is a behavioral pattern of the effect of an increase in packet size in bits on the energy consumption per unit meter. In this behavior, it was also observed that for every bit of packet increase, the energy consumed per unit meter (increase in transmission) increases linearly as well. This idea can be coined from expression (12), of which the energy consumed per unit meter also depends on the number of bits of information (*m*) transmitted in the network. It should be noted that a typical sensor node has low memory in addition to low or limited storage capacity, of which each frame of sensed data or event occupies an average of approximately 100bytes (800bits). Waspmote sensor nodes having a low memory of 8KB SRAM necessitated low overhead transmission. This is to give enough space for data or message transmission. Fig. 8, shows the behavioral pattern of the effect of an increase in the number of nodes in the network on the energy consumption per unit meter. The increase in the network nodes density considered both X and Y directions on the topology. It is also seen that, as the number of nodes participating in the sensing and forwarding of information in the network increases, the energy consumed per unit meter (transmission cost) increase as well. This evidence as can be seen in expression (12), is because, the energy consumed per unit meter (transmission cost), also depends on the number of hops in the *X* and *Y* directions on the topology. This sensor network deployment analysis provides insight into the optimal placement of nodes in the wireless sensor networks. The environment considered is a terrestrial which acts as a grid-based topology with sensor nodes randomly distributed in the environment. We, therefore, addressed the need for a systematic placement of the nodes in the network considering minimum transmission cost, which is the energy consumed in sending a sensed event in joules per unit distance. In the course of the analysis, it was observed that the average transmission cost (average energy consumed per unit distance) has a strong relationship with nodes' distance apart, size of packets of information and the

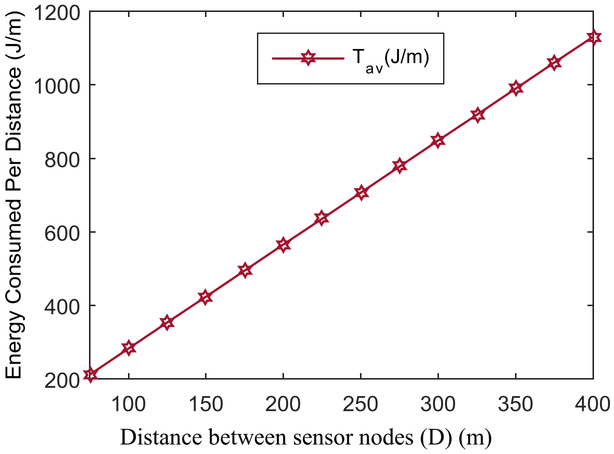


Fig. 6. Effect of Transmission distance on the energy consumed in joules per unit meter.

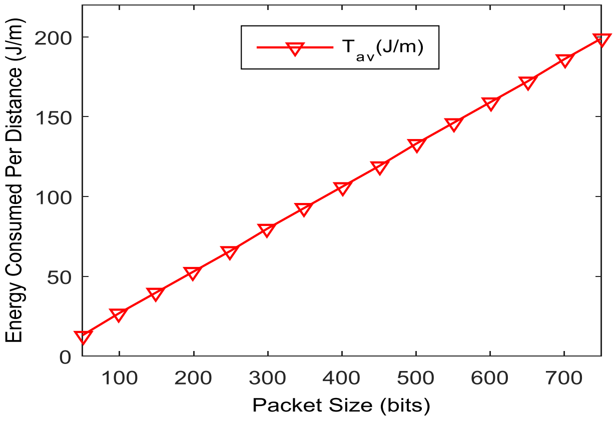


Fig. 7. Effect of Packet Size on the energy consumed in joules per unit meter.

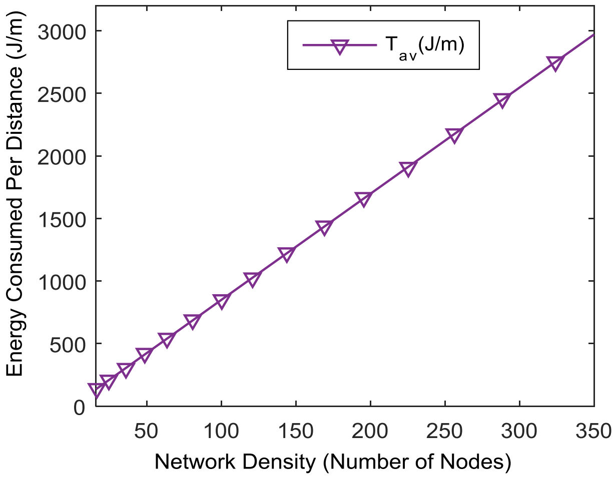


Fig. 8. Effect of Number of Nodes on the energy consumed in joules per unit meter.

network density (number of nodes) in both X and Y axis in the grid-based network. Furthermore, in Fig. 6, it is observed that for an increase in distance between nodes from 200m to 325m, the energy consumed per meter of nodes in the network increased linearly from about 566J/m to 990J/m. It is also evident from Fig. 7 that, as the packet size increases from 200 bits to 600 bits, energy consumed per meter increase from 53 J/m to 159 J/m. Also, from Fig. 8, when the number of nodes in the network increase from 150 to 300 nodes, energy consumed per meter increase from about 1230 J/m to about 2460 J/m.

2.3.3. Energy model

Network reliability can be improved by reducing the energy consumption of the wireless sensor network. This can be achieved by analyzing the system from known theories and mathematical formulations of all components in the system or network. It is therefore vital to investigate all components of the wireless sensor network to discover the different ways in which the limited sensor nodes energy is consumed in the network. The energy expended during transmission and reception of events in the network should also be investigated. In light of this, the behavior of the network and its routing protocols are analyzed by altering some parameters in the system that contribute to energy consumption to optimize energy consumption for the network.

2.3.3.1. Basic static energy consumption for a wireless sensor network – single hop and multi-hop routing. In single hop routing, sensor nodes forward information directly to the destination node in one hop. In the case that the destination node is far from the source node, more energy will be needed to transmit a single packet of data and avoid losing the data along the long transmission path hence reducing the lifetime of the network. The lifetime reduction comes as a result of the battery of the sending node being drained at a fast rate as the distance D in Eq. (9) is large. In the case of multi-hop transmission, source nodes also act as routers as information is forward in a relay of nodes through neighbor nodes to the sink node. The three different ways for route selection are proactive, reactive and hybrid [4, 14].

In reactive routing, routes are computed only when they are needed and sensor nodes store routes for their neighbors only. In proactive routing [30] routes are computed even when they are not needed and stored in a routing table at every node. Routing table maintenance overhead is difficult due to the increasing rate of a large number of messages exchanged. This limits the scalability of the routing protocol. The combination of proactive and reactive routing through the utilization of either of the two for a given radius and the other outside the radius leads to hybrid routing. Fewer control packets are realized with reactive routing resulting in improved energy efficiency. This paper concludes by presenting an analysis of the performance of reactive routing protocols (Termite Hill and AODV).

2.3.4. Sensing models

Each sensor node in a wireless sensor network can sense the environment and detect the events in its surroundings. The sensing range and accuracy of a sensor node limits its ability to sense the physical environment. Sensing models are used to address issues of sensor field coverage, a lifespan of the coverage and coverage redundancy in sensor networks. The two classes of sensing models are deterministic or binary and probabilistic sensing model [31].

In deterministic or binary sensing model, a node can only sense events at locations that fall within their sensing range. Any point outside the node's sensing range is invisible to the node. It is assumed that the sensing range for every node is a uniform circle with a sensing radius *D*. If at point z, an event occurs within the sensing range of node *(a)*, it is assumed that the probability *P*, that the event is detected is 1, whilst the probability of any event outside the sensing range is assumed to be 0. This means

$$= \begin{cases} 1, & \mathit{if}\ D, \geq d(a,\ z) \\ 0, & \mathit{otherwise} \end{cases}$$

where, *d (a, z)* is the Euclidean distance between ***a*** and z.

To set up the least number of active nodes and at the same time meeting the coverage requirements, the tuneable sensing model can be used as an expression of the deterministic model. This means that the sensor field can be adequately covered with minimum overlaps when different sensing radii for different sensor nodes ($D1 \leq D2 \leq D3$) are used. The lesser the number of active nodes in the sensor field, the lower the energy consumption [31].

In probabilistic sensing model, the ability of the sensor node to detect the environment decreases with increase in the sensing range. This approach is more realistic

$$\begin{cases} 1, & \mathit{if}\ D - r \geq d(a,\ z) \\ e^{-\lambda x^{\beta}} & \mathit{if}\ D - r \leq d(a,\ z) \leq D + r \\ 0 & \mathit{if}\ D + r \leq d(a,\ z) \end{cases}$$

Here r represents the amount of uncertainty in the sensor node's radius of detection.

x = d (a, z) – (D - r)

λ, *and* β are parameters used for detection.

Examples of sensor nodes whose behavior can be illustrated using this model are ultrasound and infrared sensor nodes. Environmental factors like noise, interference, and obstacles can affect the sensitivity of the sensor nodes [31].

2.3.5. Analysis of events extraction in wireless sensor networks

This section describes the optimization method for data collection using relay nodes in wireless underground sensor network (WUSN). It is expected that maximum transfer of data is disseminated from the relay nodes to the collection center (sink node) for a network whose energy resource is limited (WUSN). In this network, we assume that all the sensor nodes including the relay nodes are randomly placed on the given environment as shown in Fig. 9. The sensor node including the relay and forwarding node carries a limited energy supply E_{sp}. The respective distance between each pair of sensor nodes on the underground environment is r_{ij}, where r_{ij} is the actual distance between nodes *i* and *j* on the sensor network environment. With the assumption that, much data needs to be captured and transferred to the end node (sink) via the relay and forwarding nodes, it is worth knowing that the source and relay nodes are energy constraints nodes, though the sink node is of sufficient energy source as can be charged through plugging into the power mains. For the network, each node consumes E_{rc} of energy for every bit of received message, and E_{tm} of energy for every bit of transmitted message, and E_{sm}

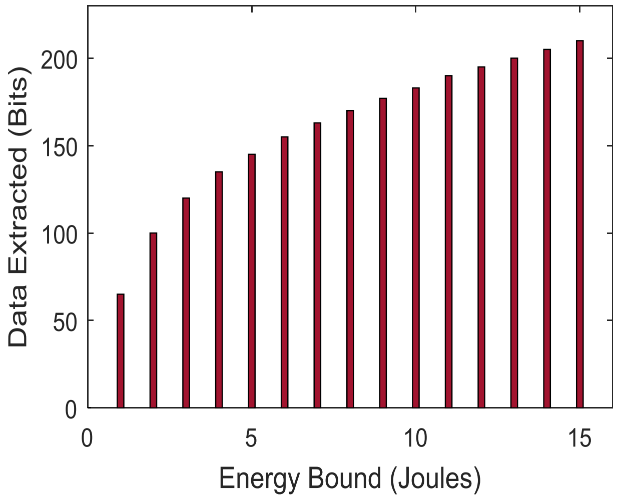


Fig. 9. Maximum energy bound with data extraction.

of energy for every bit of sensed message. For sensor nodes having a transmission energy per unit time and information flow rate E_{ij} and I_{ij} respectively and links between the nodes i and j respectively, the expression relating the information transfer per unit time and that of energy transmission per unit time on a path is described in [32] and governed by Shannon's capacity, which is an expression for an additive white Gaussian noise (AWGN) channel. For setting information flow rate along with transmission energy per unit time, it is necessary to find the coordinated operation of all nodes in the network to maximize the information transmitted to the sink node via the relay and forwarding nodes. As in [33], and also reported in [34], we followed the same trend and assumed that there is no data aggregation in this network, meaning, all events are relayed to the sink node via relay and forwarding nodes. If the sum of energy consumed by node i is E_i, which comprises of both receiving, sensing, and transmitting energy, the same energy E_i should not be more than the amount of energy available for the node i.

Following these assumptions, we can then represent the problem as a nonlinear program as:

$$Max \sum_{j=1}^{K} I_{jK+1}$$

Such that,

$$\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji} \ \geq \ 0$$

$$for\ i = 1 : K$$

That is,

$$\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji} \leq M \sum_{j=1}^{K} I_{jK+1}$$

K is the available bits of data sent via the relay node to the sink that is generated from the source node. For a signal decay constant of d_{ij}^{-2} and a communication channel noise of ζ, we assumed that all transmissions are with the scheduled process which is either through FDM, where FDM stands for frequency-division multiplexing or TDM, and TDM represents time-division multiplexing, and that there is no interference, we then model the network environment in such a manner that the energy consumed at node i, is such that, $E_i \leq E_{sp}$, similar to the work reported in [30], that is:

$$\left(\sum_{j=1}^{K+1} E_{ij} + E_{rc}\sum_{j=1}^{K} I_{ji} + E_{sm}\left(\sum_{j=1}^{K+1} I_{ij} + \sum_{j=1}^{K} I_{ji}\right)\right) \leq E_{sp} \tag{5}$$

$$for\ i = 1 : K$$

and

$$I_{ij} \leq log\left(1 + \frac{E_{ij} d_{ij}^{-2}}{\zeta}\right)$$

$$for\ i = 1 : K,\ j = 1 : K+1$$

such that,

$$I_{ij} \geq 0, \ \ E_{ij} \geq 0$$

$$for\ i = 1 : K,\ j = 1 : K+1$$

The expression (5) defines the total energy consumed in the network. The expression constitutes the energy used during sensing of information transferred to the sink node through a relay node as "E_{sm}", and the energy consumed during the transmission of events among nodes i-j, which depends on energy node i spent in transmitting sensed events as (E_{ij}), and that of node j used in receiving the information $E_{rc}I_{ji}$. As seen in expression (5), it is expected that the total energy for every participating node should be of higher value than the whole sum of energy used in receiving, transmitting information and sensing the events. The total energy expended at a sensing node in the network is represented as:

$$\sum_{i=1}^{N} E_i = \sum_{i=1}^{K}\left[E_{sm}\left(\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji}\right) + \sum_{j=1}^{K+1} E_{ij} + \sum_{j=1}^{K} E_{rc} I_{ji}\right]$$

$$= E_{sm}\sum_{i=1}^{K} I_{iK+1} + \sum_{i=1}^{K}\sum_{j=1}^{K+1} E_{ij} + E_{rc}\sum_{i=1}^{K}\sum_{j=1}^{K} I_{ij}$$

$$= \sum_{i=1}^{K}\left(E_{sm} I_{iK+1} + E_{iK+1}\right) + \sum_{i=1}^{K}\sum_{j=1}^{K}\left(E_{rc} I_{ij} + E_{ij}\right) \tag{6}$$

The expression in (6), clearly shows that the maximum message or events that can be gotten or sensed by the sensor network are dependent on the amount of energy available at each of the sensor nodes in the network. That is, to achieve maximum throughput regarding message extraction from the network, we can look at the network having at least I_{min} message received by the sink node. This statement can be used to replace expression (5) by a more generalized expression as:

$$min \sum_{i=1}^{K}\left(E_{sm} I_{iK+1} + E_{iK+1}\right) + \sum_{i=1}^{K}\sum_{j=1}^{K}\left(E_{rc} I_{ij} + E_{ij}\right)$$

such that,

$$\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji} \geq 0$$

$$for\ i = 1 : K$$

and,

$$\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji} \leq M \sum_{j=1}^{K} I_{jK+1}$$

$$for\ i = 1 : K$$

That is,

$$\sum_{j=1}^{K} I_{jK+1} \geq I_{min} \tag{7}$$

$$for\ i = 1 : K$$

It then implies that,

$$I_{ij} \leq log\left(1 + \frac{E_{ij} d_{ij}^{-2}}{\zeta}\right)$$

$$for\ i = 1 : K,\ j = 1 : K+1$$

Such that,

$$I_{ij} \geq 0; \ \ E_{ij} \geq 0$$

$$for\ i = 1 : K,\ j = 1 : K+1$$

The computational results of Eqs. (5) and (7) are shown in Figs. 9 and 10 respectively for maximum energy bound variation from $\mathrm{E_{SP}} = 1$ Joule to $\mathrm{E_{SP}} = 15$ Joules, and minimum data bound varied from $\mathrm{I_{min}} = 0$ to $\mathrm{I_{min}} = 170$ bits. The network is randomly distributed with 100 nodes

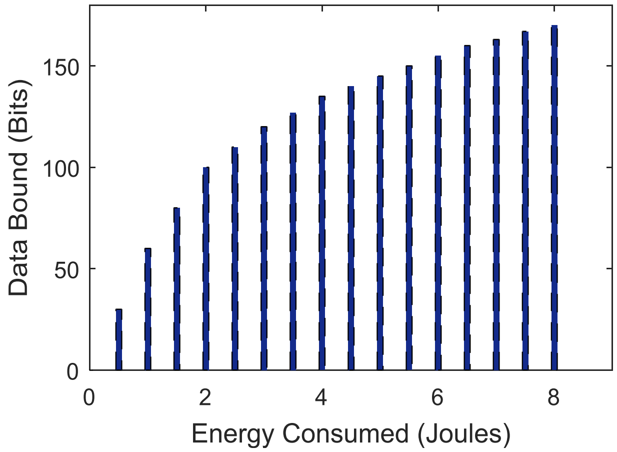


Fig. 10. Minimum data bound with energy consumption.

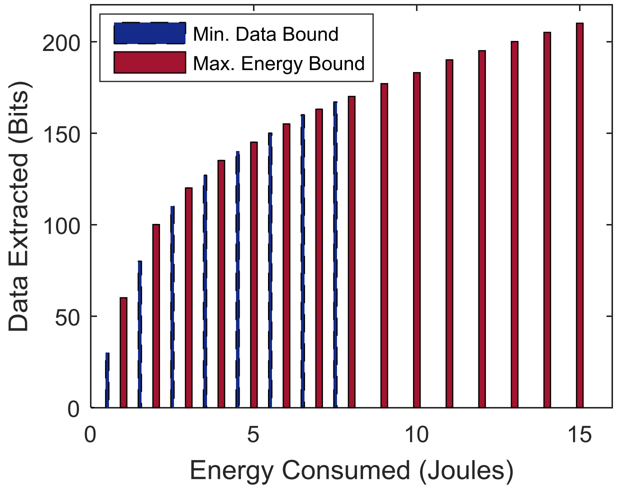


Fig. 11. Optimal Data extracted versus Energy consumed.

with $E_{rc} = 500\mu J, E_{sm} = 1mJ$ and$M = 20$ *bits*and the relationship between Eqs. (5) and (7) can also be observed computationally as shown in Fig. 11. As can be seen in Fig. 11, the minimum data bound corresponding to the problem in Eq. (7), converge faster than the problem with maximum energy bound in Eq. (5).

2.3.6. *Wireless underground sensor networks*

This subsection describes the underground environment as possible environment for wireless sensor network applications.

2.3.6.1. Electromagnetic (EM) wave signal propagation in underground environment. Signal propagation in the underground environment deals with signal transmission from sensor nodes to the sink node using WSNs. Fig. 12 shows Node deployment in the underground environment with signal propagation in the underground medium.

Generally, this environment is a constraints environment which requires knowledge of the properties of the medium, which is either soil or water. With the use of Friis equation [35]; we can derive the level of the signal received in a free space which depends on the distance of transmission as:

$$P_{tm} + g_{rc} + g_{tm} - F_{PL} = P_{rc} \tag{27}$$

The Eq. (27) is in the logarithm form, where $P_{tm}$is the transmitted power, P_{rc} the power received by the receiving antenna,F_{PL} the path loss in decibel (dB)that occurs in free space, g_{rc} and g_{tm} are the gains of receiving and transmitting antennas respectively. The path loss is represented by the equation:

$$F_{PL} = \left({}^{1}\!/_{10}\right)(324 + 200\log(R) + 200\log(Q))$$

Moreover, R stands for the transmitting distance between transmitting and receiving nodes, whereas Q is the frequency of operation of the transmitting antenna. Considering the underground environment, it is necessary to add into the expression (27) a parameter that will reduce error in transmission and reception of the signal, such that the Eq. (27) becomes:

$$P_{tm} + g_{rc} + g_{tm} - (F_{PL} + S_{PL}) = P_{rc} \tag{8}$$

Where S_{PL} represents the losses in the paths (links) of transmission in the soil medium. But S_{PL} is the summation of transmission loss in soil medium due to attenuation (S_{PLA}) and loss due to the difference between the electromagnetic wave signal propagation in the soil medium and that of the terrestrial medium (S_{PLW}). This then implies that Eq. (8) becomes:

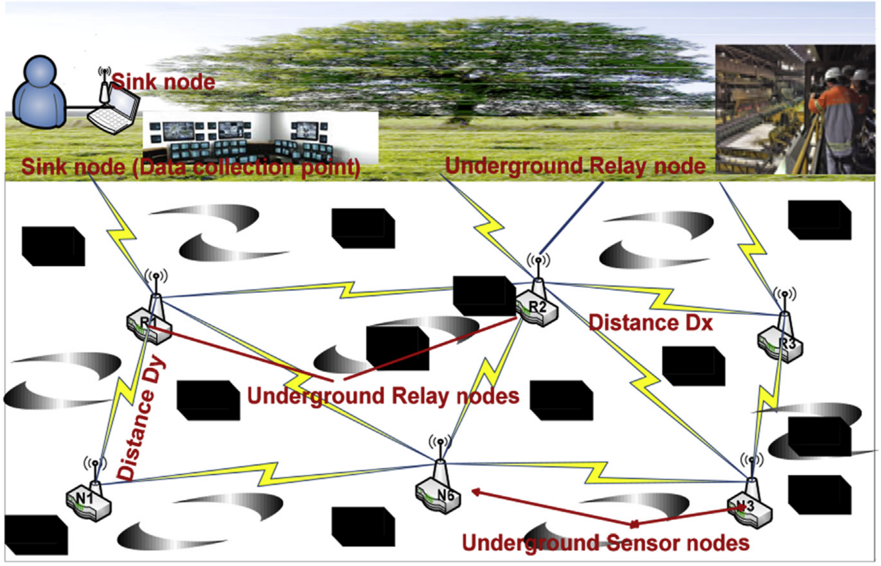


Fig. 12. Node deployment in an underground environment.

$$P_{rc} = P_{tm} + g_{rc} + g_{tm} - (F_{PL} + S_{PLA} + S_{PLW})$$

In an extension of [29], we adopted the path loss of EM wave communication technique in the soil medium as:

$$S_{PL} = \left({}^{1}\!/\!{10} \right) (64 + 200\log(R) + 200\log(Q_S) + 86.9KR) \tag{9}$$

Where K is the attenuation constant, and Q_S is the phase shifting constant.

In [36], a detailed model of the underground environment is given. However, most of the underground environment deals with either water, rocks and or soil. This implies that properties of the medium, in this case, the soil along with the electromagnetic propagation in the soil medium is needed for better understanding of the wave propagation and information transfer from sensors to sink nodes. As in [35, 37], a semi-empirical dielectric property and mode of soil is presented, which utilizes the radio frequency of ranges 300KHz-1.3GHz.

Authors in [35] have derived a model for propagation in the underground environment using EM waves, which was coined from the Fourier transformation approach of Maxwell's equations. We adopted a similar approach in our analysis, though, details of the mathematical derivations can be found in [35]. Since we are considering underground, of which soil is the medium of interest, we can as well consider a transmitting antenna buried at the surface of the soil and of the infinitesimal dipole with six (6) main components of the EM field wave. Thus, the six (6) components can is expressed as a function of Bessel in the integral form. It then implies that using EM wave, we can arrive at the Poynting vector in the time-average, which relates to the power density of the transmitting nodes at a particular point, and can be expressed as:

$$\rho_{av} = (0.5) \times R_e \left[\hat{\dot{E}} \times \widehat{H}^{*} \right]$$

$\hat{\dot{E}}$, represents the intensity of the electric field and $\widehat{H}^{*}$ is the magnetic field intensity conjugate. However, detailed derivation can be obtained in [37, 38]. Considering a simple and less computationally complex model of WUSN as shown in Fig. 13, we can analyse the EM wave transmitted in the soil. The model has a transmitter and receiver separated by distance R_d, and depth from the surface, h_{dt} and h_{dr} for transmitter and receiver respectively. If we consider the different waves in the underground as: Lateral wave, direct wave and reflected wave, we can devise the poynting vectors for the three (3) waves as components of the EM wave in the soil medium. These three (3) components of the EM wave are the results of either reflected signal in the air-soil interface (reflected wave), of which part of the signal still get propagated through the soil, or as a result of line-of-sight (direct wave) propagation of the signal between the transmitting node and receiving node through the soil medium, or propagation of signal in air and penetration of the same signal in soil (Lateral wave).

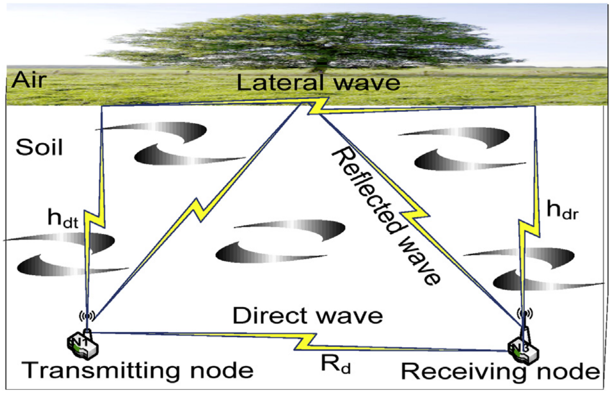


Fig. 13. EM wave propagation in the underground environment.

Considering the direct wave of EM field at the underground point, the wave is spherical and travel radially outward from the transmitting antenna of the transmitting node to the receiving node along the line-of-sight. Due to the constraints medium of operation (underground environment), the direct wave is usually attenuated, and the attenuation is much more pronounced in wet soil than in dry soil, which is due to the conductivity of soil when wet. The direct wave time-average Poynting vector as reported in [37, 39], and adopted in this work is represented as:

$$\rho_{av}^{dw} = \left(\frac{S_{Dp}}{4\pi (r_{d1})^2} \right) M_1$$

where

$$M_1 = \left(e^{i2N_s r_{d1}} \right) G_{tx}$$

$$N_s = \left(\beta_{ps} + i\alpha_{as} \right) = 2\pi f \left(\left(\mu_s \varepsilon_s \right)^{1/2} \right)$$

and

$$r_{d1} = \left[(h_{dt} - h_{dr})^2 + R_d^2 \right]^{0.5}$$

Where N_s represents the wave number in the soil medium,α_{as} the attenuation constant in the soil, β_{ps} the phase shifting in the soil, G_{tx} the antenna gain, S_{Dp} the permittivity constant, M_1 the phase shifting and attenuation of wave propagation in soil medium, $\mu_s = \mu_0$ the permeability in soil and equals to that of vacuum as soil is nonmagnetic. The received signal in the soil is a product of the poynting vector and the receiving area (A) such that:

$$A = (\lambda_{ws})^2 G_{rx} (4\pi)^{-1}$$

$$\lambda_{ws} = 2\pi \left(\beta_{ps} \right)^{-1}$$

where G_{rx} is the gain of the receiving antenna, λ_{ws} is the wavelength in the soil medium and A is the receiving area. Detailed mathematical derivations can be found in [30, 32]. For an angle related to the line of a dipole (α), we can compare the EM wave with the direct gain of an antenna as:

$$G_{tx} = Sin\alpha$$

For the reflected wave in the underground environment, it is observed in Fig. 13 that the traveling wave is incident to the air-soil surface and reflected the original medium (underground).

For a flat air-soil surface, we can arrive at the relationship between the Poynting vector in time-average (ρ_{av}^{rfw}) and other factors like the work in [37, 39] as:

$$\rho_{av}^{rfw} = \left(\frac{S_{rp}}{4\pi (r_{d2})^2} \right) M_2$$

Where

$$M_2 = \left(e^{i2N_s r_{d2}} \right) G_{tx} C_{rf}$$

$$C_{rf} = \frac{\left(\left(\frac{1}{N} Cos\varnothing_{ri} \right) - Cos\varnothing_{rt} \right)}{\left(\left(\frac{1}{N} Cos\varnothing_{ri} \right) + Cos\varnothing_{rt} \right)}$$

$$r_{d2} = \left[(h_{dt} + h_{dr})^2 + R_d^2 \right]^{0.5}$$

For r_{d2} representing the reflected path length, C_{rf} the reflected constant, $\varnothing_{rt}$ and $\varnothing_{ri}$ refracted and incident angles respectively, and N the refraction index.

Also, according to Snell (Snell's Law),

$$Cos\varnothing_{ri} = \frac{(h_{dt} + h_{dr})}{r_{d2}}$$

$$Sin\varnothing_{ri} = \frac{R_d}{r_{d2}}$$

$$Sin\varnothing_{rt} = NSin\varnothing_{ri}$$

$$Cos\varnothing_{rt} = \left(1 - \sin^2\varnothing_{rt}\right)^{0.5}$$

and

$$N = \left(\frac{\left(\varepsilon^{'2} + \varepsilon^{''2}\right)^{0.5} + \varepsilon^{'}}{2}\right)^{0.5}$$

Where $\varepsilon^{''}$ and $\varepsilon^{'}$ represents the imaginary and real parts of the permittivity of soil respectively.

For the Lateral wave in the underground environment, we can get the relationship between the Poynting vector and receiving node as:

$$\rho_{av}^{Lw} = \left(\frac{S_{Lp}}{4\pi(R_d)^4}\right)M_3$$

Where

$$M_3 = \left(e^{i2N_s(h_{dt}+h_{dr})}\right)\left(e^{i2C_oR_d}\right)G_{tx}\left(C_{rfL}\right)^2$$

$$C_{rfL} = \frac{2Cos\varnothing_{Li}}{NCos\varnothing_{Li} + Cos\varnothing_{Lt}}$$

Where C_{rfL} the coefficient of is a refracted wave in the soil medium and S_{Lp} is the constant of diffusion on the air-soil interface.

Combining the three (3) EM waves in the underground environment, and similar to the analysis in [37, 39], we can have the total power density in the underground as:

$$\rho_{T(av)} = \rho_{av}^{Lw} + \rho_{av}^{dw} + \rho_{av}^{rfw} \tag{10}$$

It is worth knowing that Eq. (10) is a vector sum of all the three (3) components of the EM wave in underground as they have the three directions (x, y, and z), this is similar to the analysis in [37, 39], such that:

$$\rho_{T(av)}^{X} = \left(\rho_{av}^{dw} \times \frac{R_d}{r_{d1}} + \rho_{av}^{rfw} \times \frac{R_d}{r_{d2}} + \rho_{av}^{Lw} \times Sin\varnothing_{Lt}\right) \times Cos\theta$$

$$\rho_{T(av)}^{y} = \left(\rho_{av}^{dw} \times \frac{R_d}{r_{d1}} + \rho_{av}^{rfw} \times \frac{R_d}{r_{d2}} + \rho_{av}^{Lw} \times Sin\varnothing_{Lt}\right) \times Sin\theta$$

$$\rho_{T(av)}^{z} = \left(\rho_{av}^{dw} \times \frac{|h_{dt} - h_{dr}|}{r_{d1}} + \rho_{av}^{rfw} \times \frac{(h_{dt} + h_{dr})}{r_{d2}} + \rho_{av}^{Lw} \times Cos\varnothing_{Lt}\right)$$

Whereby θ represents the azimuth angle in the cylindrical coordinates of the receiving nodes/antenna.

The analytical results of our model similar to the work in [36], showing the effects of operating frequency on the path loss for various distances between nodes using Eq. (9), is shown in Fig. 14 through Fig. 16. The model was simulated in MATLAB. Fig. 14 shows the effects of varying operating frequencies for different internode distance on path loss in the underground environment. From the result, it is clearly shown that even with the an increase in operating frequency, the path loss is not as high as when the distance between nodes is increased for different operating frequencies. To decrease the path loss, antenna size needs to be increased to shorten the transmission distance. We also show the impact of internode distance on the path loss for various operating frequencies in Fig. 15. In Fig. 15, when the distance between transmitting and receiving nodes is increased, a high increase in path loss is noticed, and this further strengthens the results in Fig. 14, showing that, for the decrease in path loss, large antenna size is needed for underground transmission using electromagnetic wave communication technique. In Fig. 16, we show a 3D representation of Figs. 14 and 15 to further explain the effect of both operating frequencies and internode distance on path loss in an underground environment.

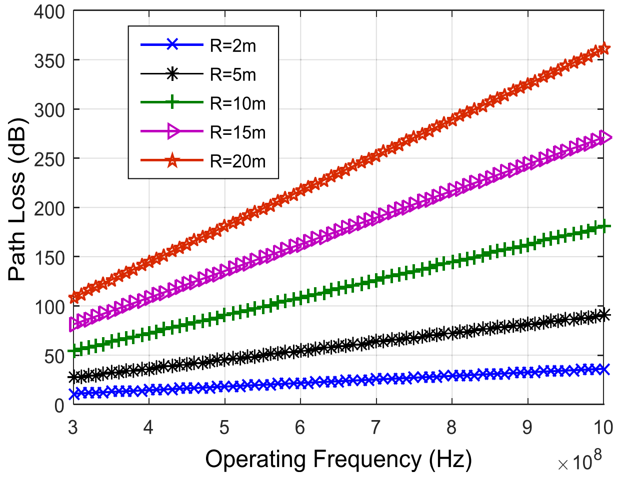


Fig. 14. Path loss versus operating frequency for different internode distance.

2.3.6.2. Pulsed power magnetic induction (PPMI) communication. Figs. 17, 18, and 19 shows a system of magnetic induction (MI) in its schematic form, a model of magnetic induction communication and a system showing the equivalent circuit of magnetic induction respectively. In Fig. 20 and Fig. 21, we show the technology of magnetic induction pulsed power and its circuit model system used in wireless sensor networks respectively. Fig. 20 shows the technology on how series or relay nodes are employed in the underground environment to send and relaying sensed information from a sensing node to the receiving node (Sink node). In Fig. 21, we give the circuit equivalent of the proposed pulsed power magnetic induction system whereby the transmitter first charges the first capacitor (C_P) to attain a very high value of the input voltage V_S, of which after fully charged, the capacitor will have to dissipate the energy to the transmitter coil (L_P) for relaying the signal to the next circuit. The effect of electromotive force (*emf*) of the LC circuits helps in the oscillation of the circuits and in-turn, promotes the relaying effects of each of the series LC circuits until the signal gets to the destination (Sink

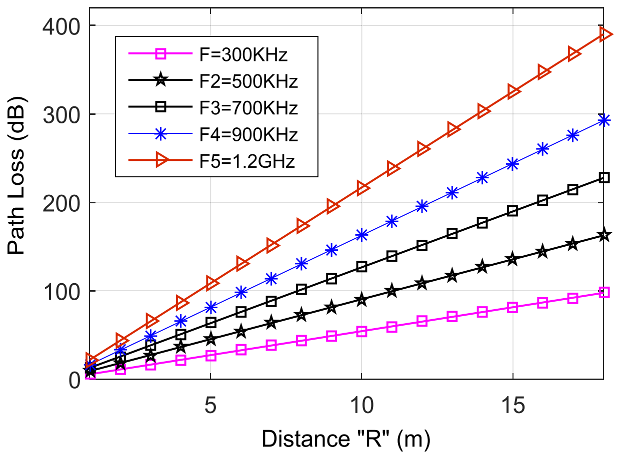


Fig. 15. Path loss versus distance between nodes for different operating frequencies.

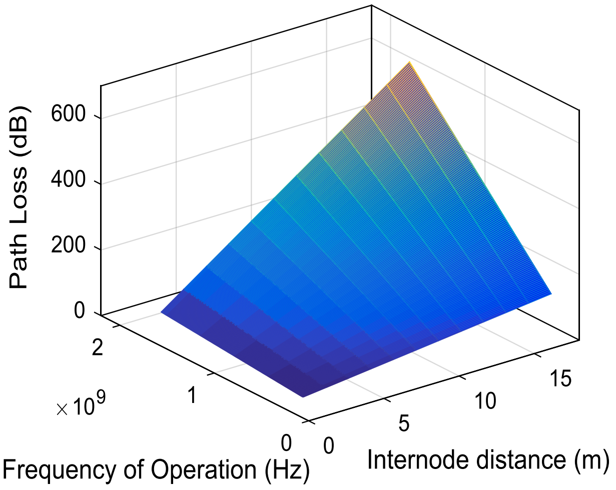


Fig. 16. Effect of both operating frequencies and internode distance on path loss in an underground environment.

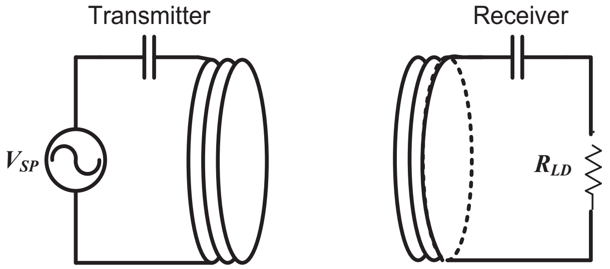


Fig. 17. Schematic of magnetic induction system.

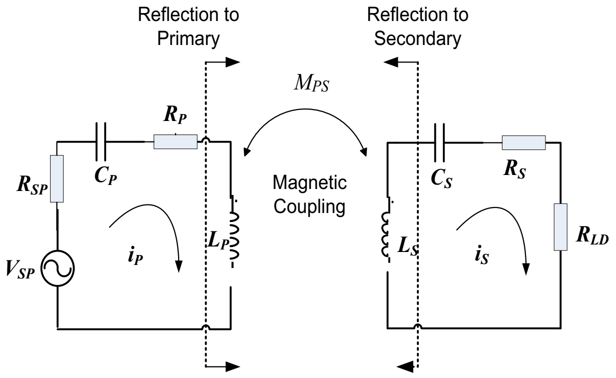


Fig. 18. Magnetic Induction communication model.

node). This system uses a similar principle as described in work [41, 42], and [43]. With this action, the transmission range is increased, and solve the need for a large antenna size for an increase in transmission range as proposed in Fig. 17 through Fig. 19 for an increase in transmission range. If we consider Fig. 21 and apply Kirchhoff's voltage law, we will have:

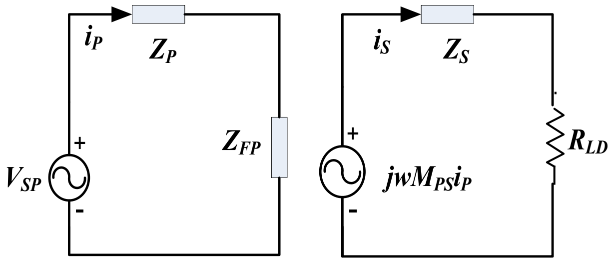


Fig. 19. Equivalent circuit of MI.

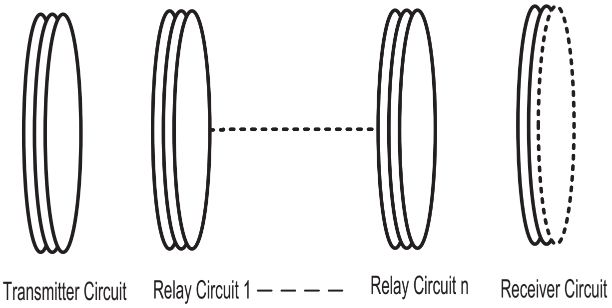


Fig. 20. PPMI communication technology.

$$V_{SP} + jwM_{PS}I_S - I_P\left(R_{SP} + R_P + jwL_P + \frac{1}{jwC_P}\right) = 0$$

$$I_S\left(R_{LD} + R_S + jwL_S + \frac{1}{jwC_S}\right) - jwM_{PS}I_S = 0$$

Hence, getting the equivalent circuit model analysis from Fig. 21, we have:

$$Z_P = R_{SP} + R_P + jwL_P + \frac{1}{jwC_P}$$

and

$$Z_S = R_S + jwL_S + \frac{1}{jwC_S}$$

where also,

$$Z_{FP} = \frac{w^2(M_{PS})^2}{Z_S + R_{LD}}$$

If we consider $Z_{FP} << Z_P$, it will mean that the current i_S in the receiver circuit will not have much effect on the transmitter circuit, hence, Z_P can be neglected, which implies that:

$$P_{rc}l_{w=w_0} = \frac{1}{2}|i_S|^2 R_{LD}$$

$$= P_{tm}\left[\frac{2wM_{PS}}{(R_{SP} + R_P)(R_{LD} + R_S) + w^2(M_{PS})^2}\right]^2 R_{LD}R_{SP}$$

also, for maximum power transmission, we have:

$$P_{tm} = \frac{(V_{SP})^2}{8R_{SP}}$$

hence,

$$w_0 = resonant\, frequency = \frac{1}{\sqrt{L_P C_P}} = \frac{1}{\sqrt{L_S C_S}}$$

For the pulsed power magnetic induction technique with multiple relay circuits, we can deduce the current in the transmitter circuit using Kirchhoff's current law as:

$$i_P(t) = \frac{v(0)}{L_P w}e^{-\sigma t}\sin(wt)$$

where

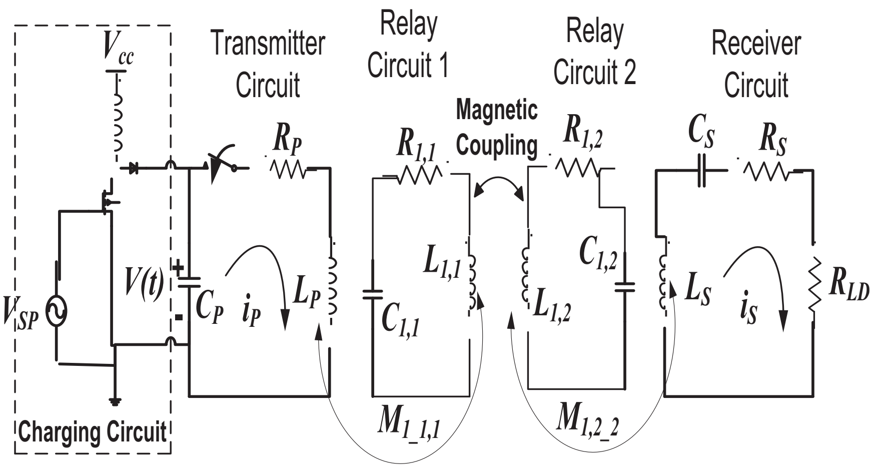


Fig. 21. Circuit of pulsed power system for WUSNs.

$$\sigma = \frac{R_P}{2L_P},\ w = \frac{1}{2}\sqrt{\frac{4}{L_P C_P} - \frac{R_P^2}{L_P^2}} = \frac{1}{\sqrt{L_S C_S}}$$

The quantity of magnetic flux in the circuit represented as B at a distance R away on the axis of the radiating coil is given by:

$$\mathrm{B}(R) = N_P \frac{\mu_0 i_P r_P^2}{2R^3}$$

If we substitute the emf as used in [14] into the power ratio, we have:

$$\frac{P_{rc}}{P_{tm}} = \frac{\max(i_S)^2 R_{LD}}{\max(i_P)^2 R_P}$$

$$= \left(\frac{\mu_0 N^2 A^2}{2\pi R^3}\right)^2 \frac{1}{L_P C_P} \frac{R_{LD}}{R_P\left[(R_S + R_{LD})^2 + \left(wL_S - \frac{1}{wC_S}\right)\right]} \tag{11}$$

where N = N$_P$ = N$_S$, and A = A$_P$ = A$_S$, and R is the transmission distance. Due to the resonant nature of the circuit, we can simplify Eq. (11) as:

$$\frac{P_{rc}}{P_{tm}} = \left(\frac{\mu_0 N^2 A^2}{2\pi R^3}\right)^2 \frac{1}{L_P C_P} \frac{R_{LD}}{R_P (R_S + R_{LD})^2}$$

2.3.6.3. Pulsed power magnetic induction channel characteristics. For both MI and PPMI techniques, we can derive the path loss (PL) of the system. The path loss is further shown in Fig. 22 for varying distance between nodes. The expression for the PL, similar to that of the work in [36], is as:

$$P_L = -10\log\frac{P_{rc}}{P_{tm}}$$

Furthermore, Fig. 23 shows the Signal to Noise ratio (SNR) with varying distance between nodes, and the ratio of transmitted signal to the noise in the system termed as signal-to-noise ratio for both the MI and PPMI is as:

$$SNR = P_{tm} - P_{NS} - P_L \tag{12}$$

Where P$_{tm}$ is the transmitted signal, P$_{NS}$ the noise signal and P$_L$ represents the path loss in the system. Also, the bit error rate (BER) of the system is related to the *SNR* as:

$$BER = \left(\frac{1}{2}\right) f_{C(er)}\left(\left(\frac{1}{2}\right)\sqrt{SNR}\right)$$

Where $f_{C(er)}$ represents the error function.

We adopted the resistance of the system coil and self-inductance of the system as in [44], which gives:

$$L = \frac{\mu_0 \pi N^2 r}{2}$$

where

$$R = \rho 2\pi r$$

And

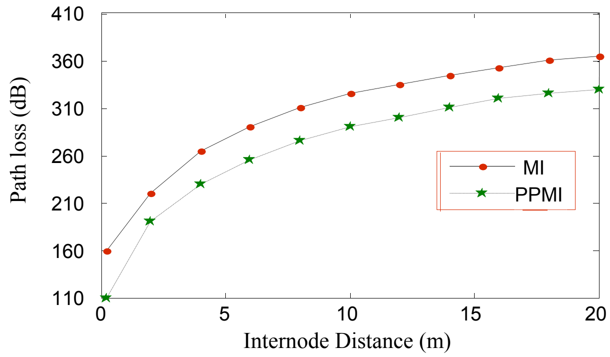


Fig. 22. Effect of varying internode distance on path loss for different communication techniques.

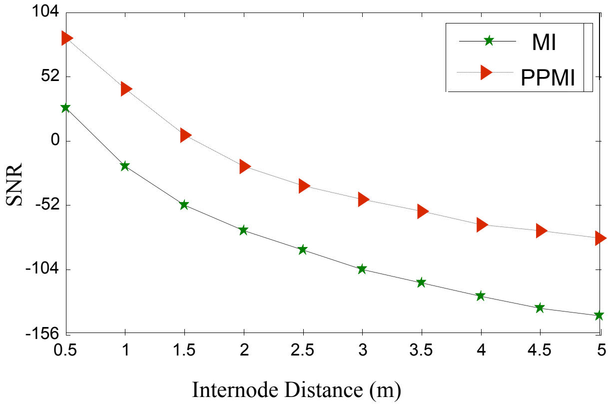


Fig. 23. Effect of varying distance on SNR for different communication techniques.

$$\frac{P_{rc}}{P_{tm}} = \frac{\mu_0}{32\pi R^6 C_p}\frac{N^2 r^5}{\rho^2} \propto \frac{N^2 r^5}{\rho^2}$$

N is the number of turns of the coil, r the radius of the coil, where ρ is the resistivity of wire used for the coiling. From Eq. (12), the SNR can then be represented as:

$$SNR = \frac{4v(0)^2}{\frac{\mu_0 N^2}{C_P \rho} - R} + 10\log\frac{\mu_0}{32\pi C_P R^6} + 10\log\frac{N^2 r^5}{\rho^2} - P_{NS}$$

2.4. Categorization of energy efficient routing protocols in wireless sensor networks

The main function of a routing protocol is to determine paths for sensor nodes to transmit data in a network while achieving maximum network lifetime. The lifetime of a network depends mostly on the lifetime of the sensor nodes in the network. The different types or characteristics of sensor nodes that can be deployed in a wireless sensor network have prompted classification of sensor networks into either homogeneous or heterogeneous. Homogeneous wireless sensor networks consist of nodes that are similar or are of the same type. The similarity can be regarding communication bandwidth, their source of power, computation capability or storage capacity. Cluster heads (CHs) selection is randomly assigned in a homogeneous WSNs. Heterogeneous sensor networks, on the other hand, are made up of nodes with different computing capabilities or power and different sensing and communication range. Fig. 24 illustrates the categorization of the surveyed routing protocols.

A structure of a heterogeneous wireless sensor network is as illustrated in Fig. 25.

Routing protocols for both homogeneous and heterogeneous networks are classified into static and mobile. Mobile wireless sensor networks are more scalable and flexible. They are commonly made up of static sensor nodes that are responsible for sensing while one or more mobile sink nodes are used to gather data. The mobility of sink nodes shortens the transmission range and thus saves energy for the network. The energy consumption among the nodes can also be easily balanced in the network. Homogeneous routing protocols are broken down into data-centric, hierarchical, location-based and NF & (QoS) awareness depending on the network structure. On the other hand, the static homogeneous routing protocols can also be classified as Nature inspired, cross-layer, opportunistic and cooperative routing. Depending on the type or characteristic of the sensor nodes and the number of mobile nodes in a network, mobile homogeneous routing protocols are divided into a mobile sink, mobile sink, and source and multiple mobile sinks. Static heterogeneous networks are expressed regarding energy heterogeneity and cost, sensing & transmission range heterogeneity while mobile heterogeneous ones are defined regarding energy heterogeneity and energy, transmission range and data range heterogeneity. Table 2 illustrates the categorization of the surveyed routing protocols. For ease of reference, reference numbers are indicated for each protocol. Discussions on the reviewed routing protocols follow after that.

2.4.1. Routing protocols for homogeneous wireless sensor networks

Homogenous routing protocols have equal capacities of computation, power, and communication. They are discussed under different categories, such as data-centric, hierarchical based, and location-based, or network flow and quality of service.

2.4.1.1. Data-centric routing protocols. In data-centric routing protocols, all sensor nodes play similar roles. Data is forwarded to neighboring nodes within the sensor field by each node [47]. The sink node forwards data through queries to some particular regions in the network and waits for an acknowledgment. The properties of data are identified through data attribute naming [24]. The different routing protocols under this category are:

2.4.1.1.1. Data- flooding and gossiping (F & G). The use of complex algorithms of routing and topology maintenance is not observed when sending data in F & G [24, 45]. Data is broadcasted to neighboring sensor nodes after being received from other nodes. The process continues until the data packet reaches its limit of the number of hops or until the destination node is reached. Duplication of data arriving at a single node results in implosion, overlapping and resource blindness. These drawbacks are avoided in Gossiping whereby a data packet is forwarded to one neighboring node that is randomly selected by the use of a neighboring table that tests the capability of all the nodes. The node that is chosen

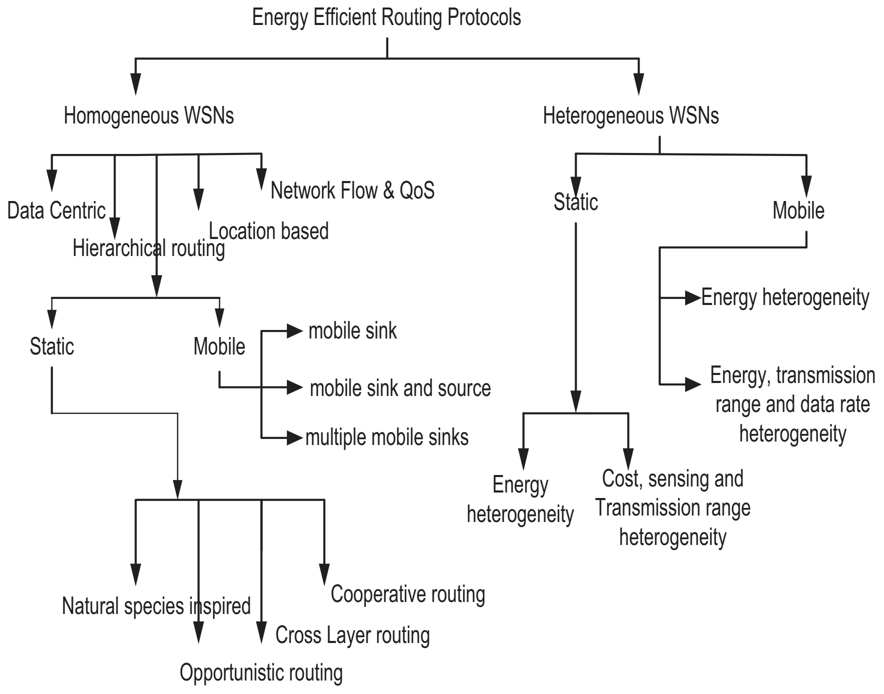


Fig. 24. Categorization of reviewed routing protocols in wireless sensor networks.

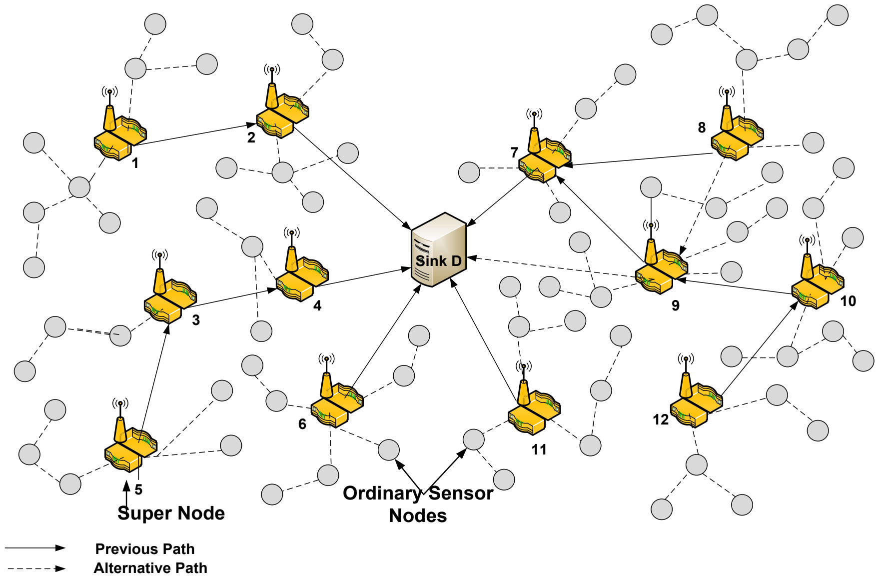


Fig. 25. A structure of a Heterogeneous wireless sensor network.

Table 2
Classification of reviewed routing protocols for wireless sensor networks.

Energy Efficient Routing Protocols							
Homogenous WSNs				Heterogeneous WSNs			
				Static		Mobile	
Data Centric	Hierarchical	Location Based	Network Flow & QoS Aware	Energy Heterogeneity	Cost, sensing & transmission range Heterogeneity	Energy Heterogeneity	Energy, transmission range & data range Heterogeneity
F & G [45, 46] SPIN [47] DD [48, 49] GBR [1] EAR [50] RR [1, 51, 52] CADR [53] ACQUIRE [54] COUGAR [55] EAD [56] Mcfa [57]	LEACH [58], LEACH-C, LEACH-MF, MODLEACH [59] PEGASIS [60] SOP [61] TEEN [1, 62, 63], APTEEN [63] HEED [64] EAR-CSN [65] BCEE [66] CEBCRA [67] HERO [68, 69] ECPF [70] FSC [71] NEECP [72]	GAF [73] GEAR [74] MECN [75] SMECN [75] TBF [76] EAGRP [77] Span [78, 79] BVGF [80] GeRaF [81] LUCA [82, 83]	MLDG [84] SAR [85] MLER [86] SPEED [87] EAQSR [1] MCBR [88] SL-QoS-MS [89] AODV [90]	ECDC [91], EEMHR [92] LE-MHR [93]	CSLRP [94]	HARP [95] RAHMoN [96]	HSN [97]

Energy Efficient Routing Protocols							
Homogenous WSNs							Heterogeneous WSNs
Static				Mobile			
Nature inspired	Cross-Layer	Opportunistic	Cooperative	One mobile sink	Mobile sink and source	Multiple mobile sinks	
PSO [98, 99], PEADD [100] CRP [101], SC [102], SDG [103], EBAB [104], ACO [105, 106], ACO-C [107], ACALEACH [108], MACS [109], AntChain [110], PZSWiD [111], ACMRA [112], ACMT [113], ACLR [114], MSRP [115], JARA [116], ACOLBR [117], EEABR [118], IEEABR [119], FF [120], FP [120], E-D ANTS [121], AR and IAR [122], Beesensor [20], Beesensor-C [123], *i*ACO [124], ACO-QoSR [125], MO-IAR [126], Ant-aggregation [127], ASAR [128], BABR [18, 129], ACO-EAMRA [101], EAQR [130], IACR [131], QDV [132], AntSenseNet [133], BIOSARP [134], Bat Algorithm [22]).	JRPRA [135] LMCRTA [136] CLOD [137]	ExOR [138] MORE [139] EEOR [140] E^2R [141] K-S [142].	RBCR [143] EBCR [144] *mp*-MILP [145]	Termite Hill [21, 146, 147] LURP/ALURP [148], DDRP [149] WARP [150] λ-Flooding [151] PredQoSR [152]	TARS [153]	MobiCluster [154], W-L [155] ER [156] AVRP [157] MDRP [158] Dream [57, 159]	

randomly selects another neighbor to forward the data packet, and the cycle is continually repeated. In this scenario, the amount of delay to arrive at the destination may increase.

2.4.1.1.2. Sensor protocol for information via negotiation (SPIN) protocol. SPIN [47] transmits data in a sensor network through a negotiation model where sensor nodes negotiate the data description in their possession and the one they need to get amongst themselves. Meta-data attribute naming is used to concisely describe the sensor data. The meta-data negotiation saves energy as it avoids the demerits of flooding such as data redundancy and congestion. Data transmission is achieved through advertisement data (ADV), a data request (REQ) and the real data (DATA). SPIN operates as shown in Fig. 26.

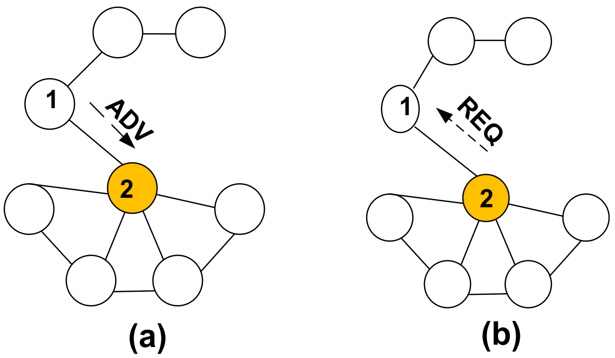
2.4.1.1.3. Sensor directed diffusion (DD) protocol. In DD [48, 49], the sensor nodes are given attribute value pairs names. These can be names of some objects, it may be names indicating geographical locations or duration of some events. The sensor nodes are queried to send data only when there is a demand for the data [4]. Four elements are found in DD: Interest, data, gradient, and reinforcement. Interest data packets describe an assignment that the network has to do. Upon receiving an interest, a sensor node that is interested in it forms a gradient (routing information) with every neighboring node that has sent the interest data packet and saved it in its memory. When sensing data is transmitted, a gradient represents a state of routing geared towards the destination node. Every node that receives the data packet repeats this process, sending the data packets on multiple paths to the sink node. The sink node reinforces the path from which the first data packets were received. Global network topology maintenance is not a concern in DD. Directed Diffusion is not well suited for applications where there is a need for a continuous flow of data [38, 160]. Fig. 27 is an illustration of the process of data in Directed Diffusion routing protocol.

2.4.1.1.4. Sensor gradient based routing (GBR) protocol. DD routing is enhanced in GBR where the hop number is maintained while the interest is diffused into the network [1]. The minimum number of hops taken to arrive at the destination node denotes the shortest possible route to the destination node. This helps every sensing node to identify the least number of hops to the sink also termed as the height node. To calculate the gradient, the difference between the height of the node and that of its neighbor is found. The link with the largest gradient is chosen as the receiving node for the forwarded data packet. The traffic is uniformly distributed over the network by using mechanisms that spread traffic. Data combination is performed at a relaying node when several routes pass through that node. GBR performs much better than DD considering the energy consumed during communication. In the protocol, a query (about an event) is forwarded based on the information gradient in the sensor nodes [160].

2.4.1.1.5. Energy aware routing (EAR). Protocol. EAR [50] is an algorithm that aims to prolong network lifetime by keeping a set of partially optimal routing paths at different times using a chosen probability. It is assumed in this protocol that an addressing scheme that is class-based can be used to address each sensor node. Discovery of routes and formation of routing tables are realized through localized flooding at the set-up phase of this approach. Each node will then be able to calculate its total energy cost in this manner: For a request sent from node X_i to node X_j, X_i calculates the cost of the path as shown in Eq. (13).

$$C_{Xj,Xi} = \mathrm{Cost}(P_i) + \mathrm{Metric}(X_j, X_i) \tag{13}$$

The sensor node energy level determines the routing decision on the transmission path. Paths deemed as high cost are eliminated. Each node



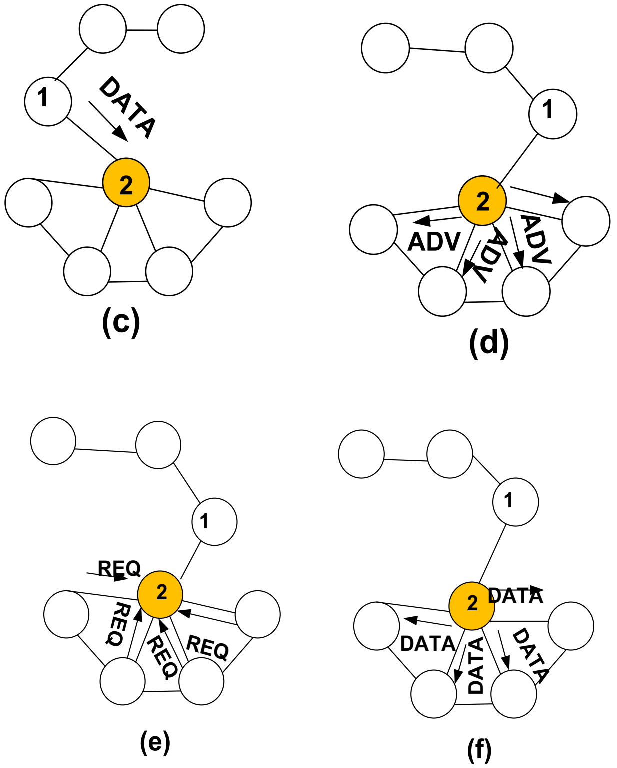


Fig. 26. Steps that show the operation of SPIN. (a) Node 1 advertises its data to node 2. (b) Node 2 replies with a request message. (c)Node 1 sends data to node 2. (d) Node 2 advertises its data to its neighbors. (e)Neighbors respond with a request for data. (f)Node 2 sends data to its neighbors [4].

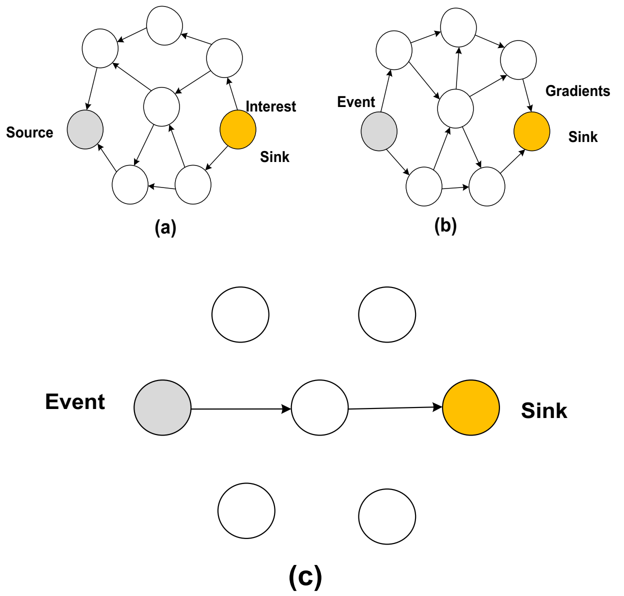


Fig. 27. Illustration of DD routing protocol (a) Interest Flooding (b) Establishing starter gradients (c) Transmission of messages.

assigns neighbor nodes a probability in a routing table in respect to the paths created [4].

$$P_{Xj,Xi} = \frac{{}^{1}/C_{Xj,Xi}}{\sum_{k\in FTj} {}^{1}/C_{Xj,Xi}};$$

X_j then processes the average cost of arriving at the destination through the neighbor nodes in the forwarding table as:

$$\mathrm{Cost}(X_j) = \sum_{i\in FTj} P_{Xj,Xi}\mathrm{C}_{\mathrm{Xj,Xi}}.$$

In the data communication phase, using probabilities, sensor nodes are randomly selected from the forwarding tables for each node to forward the data packets. To sustain the lives of all routing paths, localized flooding is performed at the route maintenance phase. Energy Aware Routing (EAR) performs the same way as Directed Diffusion in that they discover potential paths from source nodes to the destination node, but it showed a 21.5% improvement in energy conservation of nodes, and 44% extension of network lifetime [4].

2.4.1.1.6. Energy rumor routing (RR) protocol. RR [1] is another enhancement of DD that brings a balance between query flooding and event flooding. Flooding of events is performed when there are a small number of events, and there are a huge number of queries. Queries are only routed to nodes that have sensed certain events but not to the whole network. A list of neighboring nodes and events are kept by each node as well as forwarding information to all nodes it is aware of. A broadcast request can actively create a list of neighboring nodes or just overhearing broadcasts from other nodes. A static network structure was used to test RR whereby every sensor node broadcasted its identity during the initial stage of routing. It works efficiently with less amount of data [4].

2.4.1.1.7. Constrained Anisotropic Diffusion routing (CADR) protocol. CADR is yet another variant of Directed Diffusion, and it is made up of Information-driven Sensor Querying (IDSQ) and Constrained Anisotropic Diffusion (CAD) routing [53]. CADR outperforms DD in energy efficiency as reported in [4].

2.4.1.1.8. Active query forwarding in sensor networks (ACQUIRE). Authors in [54] proposed a technique that collects information in a sensor network that is energy constraint and named it ACQUIRE. It works by regarding a query as an active element that propagates through the network randomly or in a controlled fashion searching for a solution [160]. ACQUIRE functions with single-shot, complex queries for data where a huge number of sensor nodes can respond. Efficient querying is demonstrated where the value of the look-ahead parameter, a, is modified, signifying that the sensors can be requested for data by each sensor some hops away from them. The algorithm behaves as flooding [4].

2.4.1.1.9. Cougar. In [55] a Cougar approach to In-Network Query Processing in Sensor Networks is proposed. The protocol incorporates a new layer of queries between applications and the sensor network. To save energy, declarative queries are utilized by this layer to process queries from the functions of the network layer which include relevant sensors selection and utilization of internal network data aggregation [160]. Sensor nodes elect a leading node responsible for data aggregation and transmission of data to the destination node. The sink node produces query layout which informs the incoming query of the data flow and in-network processing and forwards the information to the related sensor nodes. The procedure detailing the choice of a query leader is also provided as shown in Fig. 28. The main setback experienced in Cougar is the additional overhead to the sensor nodes introduced by the extra query layer that tends to increase energy consumption and storage [4].

2.4.1.1.9.1. Energy aware data-centric routing (EAD) protocol. EAD [56], is a distributed routing protocol that aims at building a virtual backbone, for which active sensors are involved in the routing process perform in-network data computation and transmission of traffic. The size of the backbone formed by the active sensors is reduced by an optimal spanning tree made of fewer leaves, which is approximated by the broadcast tree that the protocol has created. Neighboring broadcast scheduling and distributed competition among neighbors are the two concepts demonstrated. However, the concepts do not take into consideration the mobility of sensor nodes in the network, where a tree is dissolved before a round is completed, particularly in a densely populated mobile environment.

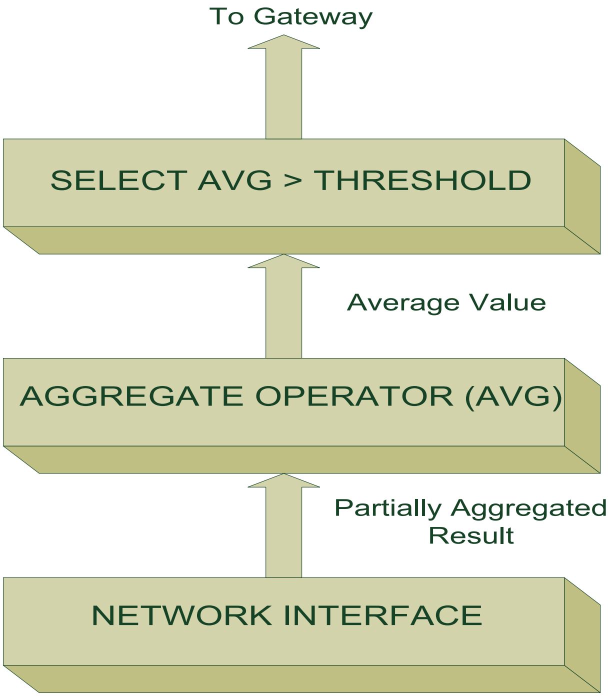


Fig. 28. Query plan at a leader node.

2.4.1.1.10. Minimum cost forwarding algorithm (MCFA). The MCFA algorithm sets up a cost field using routing. Data is then forwarded along the minimum cost path, which is followed by the battery life and hop count as well as the energy consumption count. A sensor node sends its cost to the sink node. The sink node floods an advertisement (ADV) message. The sensor node that receives the ADV message floods it further to its neighboring nodes and attaches the ADV cost to its cost, hence establishing the cost field. MCFA is a very simple protocol and avoids forwarding table maintenance. However, it has a challenge of limited network size and load imbalance [57].

2.4.1.2. Hierarchical routing protocols. Hierarchical routing protocols operate by clustering sensor nodes. This refers to sensor nodes forming groups and assigning a cluster head to aggregate the cluster group data and forward it to the destination node. This causes a reduced number of transmissions to the sink, and hence minimum congestion at the sink node and the energy consumption is thus reduced. Multi-hop communication is exercised in these protocols. The different protocols in this category are:

2.4.1.2.1. LEACH protocol. LEACH [58]is a commonly known clustering algorithm that operates in a single hop transmission among cluster heads (CHs) and adopts random selection of the cluster heads. This is not suitable for large scale networks and if a low energy sensor node is selected as a cluster head, the lifetime of the network may be jeopardized as this node may die as a result of energy depletion. In LEACH centralized (LEACH-C), the destination node is the decision maker in cluster formation and selects CHs per energy levels of the sensor nodes and their distance to the base station. Every node in the network after calculating its energy level forwards this data accompanied by its location to the destination node. The destination node, in turn, averages the energy levels of the nodes and identifies a sensor node with an energy level above this average which it will select as a CH for that cycle. LEACH-MF is another enhancement of LEACH that utilizes clusters of multiple layers and reduces the range between the sink nodes and the CHs and ultimately reduces energy consumption in the network. The ordinary CHs create a set of super CHs and they, in the long run, transmit data to the destination. This improves the scalability of the network as well as the network lifetime (an energy efficient approach). An effort to eliminate unnecessary overheads that are introduced by the selection of CHs in different rounds in LEACH is demonstrated by an algorithm that efficiently replaces cluster heads. This is realized in Modified LEACH (MODLEACH) where nodes nearer and far away from the destination node send their data at varying power levels creating a balance of energy in the network. A technique utilizing a dual transmission power level is also included in this algorithm.

2.4.1.2.2. PEGASIS protocol. PEGASIS proposed by authors in [60] and also discussed in [4], is another enhancement of the LEACH protocol. In PEGASIS, combined data is propagated from one node to another, aggregated and forwarded to the sink. The use of multiple nodes is avoided so that no clusters are formed. Setbacks of PEGASIS are that transmission of data to distant nodes introduces excessive delay and the single node that is selected for transmission of data can deplete its energy due to regular transmissions. A better variant of PEGASIS, termed as Hierarchical-PEGASIS was developed to overcome the delay challenge experienced during packets transmission to the sink node. It works by incorporating energy x delay metrics, involving [4]. Even though PEGASIS suffers from data transmission redundancy leading to more energy being consumed in the network [120], it is more energy efficient than LEACH.

2.4.1.2.3. Self-organizing protocol (SOP). The SOP developed by [61] discusses how the sensor forwarding nodes are self-organized and how they create routing tables in the four stages of discovery, organization, self-reorganization, and maintenance. In the first stage, neighborhood sensor nodes are discovered. Formation of groups which merge by building a hierarchy for addressing nodes depending on where they are in the hierarchy is realized in the organizing stage deals with re-organization of groups and responding to failure in the partitioning of nodes. However, the organization phase of the algorithm comes with additional overhead [4].

2.4.1.2.4. Threshold sensitive energy efficient sensor network (TEEN). TEEN, a protocol proposed by [1] intends to react to sudden changes in the parameters that are detected such as humidity. It brings together the hierarchical approach with that of the data-centric protocol. In TEEN, the formation of clusters together with cluster leaders is realized. Cluster leaders are responsible for broadcasting two starting points of the sensor nodes, which are hard and soft starting points. Minimum values of a parameter make the hard threshold and help to initialize the sensor nodes to energize their transmitters to be able to send data to the cluster head. TEEN does not work well for applications that demand continuous data flow [4].

2.4.1.2.5. Adaptive periodic (APTEEN) protocol. As a variant of TEEN, APTEEN [63], is a protocol that aims to acquire periodic data and respond to events that rely on time. It is also responsible for cluster formation. Cluster leaders in APTEEN are responsible for data aggregation and energy saving. The protocol supports three types of queries, which are persistent for events monitoring. Simulation analyses indicate that it performs better than LEACH, with the challenge of overhead and complex multiple levels cluster formation as well as utilization of threshold-based functions [4].

2.4.1.2.6. Hybrid energy efficient distributed clustering (HEED) protocol. HEED [64] another improved version of LEACH utilizes sensor node remaining energy as well as node density as a metric for selection of clusters with the intention to balance the energy in the network. Three phases define the HEED operation process. The initialization phase marks the selection of cluster heads depending on their remaining energy and intra-cluster communication cost. The second stage is the repetition phase. It provides the repeated cluster head selection which arises due to some parameters if they were not selected at the first stage. The finalization phase completes and finalizes the cluster head selection. However, it is worth noting that some parameters that may be considered by the cluster head selection may impose some setbacks on the network, even though the protocol is well suited for improving network lifetime.

2.4.1.2.7. EAR for cluster based sensor networks (EAR-CSN). Proposal of this protocol [65], was based on cluster formation, architecture, and selection of cluster heads which are less energy constrained and are aware of the locations of other nodes location. The protocol is also able to maintain the states of the sensors while establishing multi-hop routes gathering of information in the network. A Time Division Multiple Access (TDMA) based Medium Access Control (MAC) is used for communication with cluster heads. Sensor nodes inside a formed group of nodes can be in a state of detection, forwarding, relaying detection or that of not being active. Performance parameters that define a cost function between any pairs of nodes could be throughput, delay optimization, energy consumption, and many others. EAR-CSN is limited in transmission distance, and also adds overheads due to multiple cluster heads and hence consumes much energy [4].

2.4.1.2.8. A balanced-clustering energy-efficient (BCEE) hierarchical routing protocol. BCEE [66] intends to balance energy dissipation or wastage in sensor network nodes to improve the network lifetime. The protocol adopts a combination of ant-based routing method and the hierarchical approach. As in other algorithms that are hierarchical, there are two phases of routing in BCEE. K-means algorithm is used in phase one to select cluster heads from an unknown location of sensor nodes but adopts the concept that uses Receive Signal Strength Indicator (RSSI) for cluster formation. The second phase; steady state, adopts optimization techniques that which are based on ant colony to set-up an ideal multi-hop path from CHs using techniques that are rational and selects hops to arrive at the destination node. In comparison to LEACH through simulation, BCEE performs better per energy consumption of nodes. However, network overhead increases in cluster formation, in addition to delayed data transmission to the sink [4].

2.4.1.2.9. Cost based energy balanced clustering algorithm (CEBCRA) [51]. Authors in [67] proposed CEBCRA with the intention to increase network lifetime. It operates in three phases which are: selection of cluster leaders, the establishment of clusters and forwarding of data. Based on the remaining node energy and cardinality of the neighboring nodes, the cluster leaders are chosen in a distributed fashion. Sensor nodes are affiliated with cluster leaders within their transmission range in the establishment stage according to the cost value of the cluster leaders. In the data routing stage, CEBCRA initially uses single hop transmission mode within every cluster and after that uses multi-hop transmission mode amongst the clusters. In the data routing, a cluster leader calculates the cost of every route between the sink and itself, while choosing forwarding nodes along those routes. The protocol was compared with LEACH in MATLAB simulation, and results indicate that it performs better regarding energy consumption of nodes [34].

2.4.1.2.10. Hierarchical and reliable routing protocol for WSNs and actor networks (HERO) protocol [68]. HERO efficiently forms clusters by use of meta-data pre-definitions. Routing tables are formed from this data for efficient communication amongst the sensor nodes. Data can be transmitted from a sensor node to cluster head and similarly from cluster head to a sensor node in a multi-hop and fault tolerant manner. The desired level of reliability can be defined achieved between two nodes which are distant from each other in a more significant measure [69]. HERO was compared with the direct query (Traditional), indirect Query protocol (IQ) and MuMHR protocol in a lifetime model (remaining lifetime of a wireless sensor network, RLSN). It was found that the HERO lifetime was far greater than that of the other protocols.

2.4.1.2.11. An energy aware distributed clustering protocol in WSNs using fuzzy logic (ECPF) [70]. Non-probabilistic cluster head selection, fuzzy logic, and on-demand clustering are the three techniques that are found in ECPF [69]. The main parameter in ECPF that ensures the selection of cluster leaders in a non-probabilistic manner is the residual energy of the sensor nodes. The residual energy is achieved by introducing a delay that is inversely proportional to the remaining energy of every sensor node. Fuzzy logic is applied in assessing the state or value of a node and make a final selection of a cluster leader from a group of possible cluster leaders. A sensor node can join a cluster leader closer to it that has the lowest fuzzy cost. Choosing cluster leaders is not done at every round in ECPF. In consideration of energy conservation and network lifetime, ECPF performs better than LEACH, and HEED.

2.4.1.2.12. Fan shaped clustering (FSC) protocol [71]. Different shapes can be obtained from sub-dividing clusters and then be defined and have an impact on the performance of a sensor network. FSC divides a large-scale network into rings that have a common center. Different parts are then formed from the rings, creating fan-shaped clusters. In this clustering, techniques of selecting cluster heads, sub-dividing clusters and forwarding data are then developed to enhance the lifetime of sensor networks through reduction of information routing cost and network overload. FSC performance shows lower energy consumption than HEED routing protocol [161].

2.4.1.2.13. A novel energy efficient clustering protocol (NEECP) [72]. NEECP cluster head selection is achieved by the use of an adjustable sensing range. Data aggregation is achieved through the formation of chains. Three parameters that support the adjustable sensing range are the distance between the farthest node to the sink and the sink, the distance between the closest node to the sink and the sink and the constant maximum sensing range of the nodes. Using an adjustable sensing range is a solution to the energy hotspot problem and minimizes the energy consumption. Data redundant transmission is avoided through redundancy check techniques. The protocol implementation can be made with or without data aggregation, and its performance is way better than that of LEACH and HEED [72].

2.4.1.3. Location-based routing protocols. Location information is used to address sensor nodes by calculating the distance between the nodes to determine the energy consumption and also to request for information to send data (query) from certain regions of the network [79]. These protocols assume that the source nodes are aware of the position of the sink node and that each node in the network knows the position of its neighbor. The protocols can function with no routing tables with the ability to localize data. The routing protocols are:

2.4.1.3.1. Geographic adaptive fidelity (GAF) protocol. Authors in [73] developed GAF which was originally made for MANETs, but it can also apply to sensor networks. This protocol deactivates nodes that are less participating in the routing decisions in the network with no impact in the routing performance, and hence save energy in the network. A Global Positioning System (GPS) sensor is attached to every node to indicate its location, which will enable the nodes to remember itself with a point on the virtual grid [1]. In GAF, states of nodes are changed between active and sleeping status, which tends to balance its load. The only difference from the hierarchical protocol is that the leader does not perform any fusion or data aggregation [4].

2.4.1.3.2. Geographic and energy aware routing (GEAR) protocol. GEAR [74], is a routing protocol that routes queries to some particular regions of a sensor network. For purposes of location identification, each sensor node in GEAR has a GPS sensor [162]. Energy-aware heuristics that rely on geographic information are used to select nodes to forward data to the sink. They use geographically recursive forwarding protocol to disseminate data within the area of interest. Unlike in DD, the number of interests is restricted by concentrating on a region and not sending the interests to the entire network. In this way, energy conservation is more realized in GEAR than in directed diffusion. Each node keeps an estimated cost and learning cost for arriving at the destination through neighboring nodes. The algorithm operates in two phases [4]:

- Sending or relaying data packets toward the region of interest;
- Propagation of data packets within the region [163].

2.4.1.3.3. Minimum energy communication network (MECN) protocol. MECN [75] is a protocol designed to achieve the least energy in an ad-hoc, unsystematically deployed sensor network that uses GPS. It is best suited for static sensor networks. For efficient utilization of MECN, a topology with minimum power for static nodes as well as supernodes is used. It sources for a sub-network with a few nodes and requires low power to transmit between sets of sensor nodes in the network. Global minimum power paths are thus discovered without involving all the nodes in the network. A localized search for each node depending on its relay region is carried out. The protocol has a fast response to sudden changes in the network like dynamically adapting to node failure or the deployment of new sensors. This is because it can re-configure itself and it uses a localized search for every node depending on its relay region. MECN relies on the node positions on the plane and is made up of two main phases; MECN assumes that there is a possibility that any node in the network can send data to any other sensor node at every point in time, a very unrealistic condition.

2.4.1.3.4. Small MECN (SMECN) protocol. Authors in [75] also proposed an improved version of MECN and named it SMECN. SMECN considers potential obstacles between pairs of sensor nodes against MECN with the unrealistic assumption that any node in the network can send data to any other sensor node. SMECN has a fully connected network like MECN. SMECN however, produces a sub-network for minimum energy relaying that is smaller considering the number of edges. Results obtained through simulation indicate that minimum energy is used in SMECN and maintenance costs of links at the lower end are also less when compared to MECN. However, more overhead may be added to the algorithm due to the introduction of sub-network with smaller edges [4].

2.4.1.3.5. Trajectory based forwarding (TBF) protocol. TBF [76] uses a densely populated network with a coordinate system that helps the sensor nodes to position themselves to estimate the distance to their neighbors. A source of an event specifies a trajectory in a packet, but the path on a hop-by-hop basis is not given. A sensor node that forwards data greedily decides to find the nearest trajectory that the sensor node at the source has fixed. There is a possibility of the creation of multipath in TBF. Route maintenance is not affected by the mobility of the sensors.

2.4.1.3.6. Energy aware WSN geographic routing (EAGRP) protocol. A multi-hop energy aware routing protocol, EAGRP [77] operates with the energy level and location of every node in the network. The location and energy levels of neighbor nodes are known by each node to enable them to forward packets. The typical range to all neighbors of the source or forwarding node is calculated, and levels of their energy are checked as well as selecting the lively neighbor based on the energy level. A lively neighbor is one that has its energy level exceeding the set starting point value and has more energy. Its range amounts to or is shorter than the arithmetic means the value of all its neighbors. Comparing the results from simulation to those of AODV and DSR, EAGRP performs better based on delay, the rate of data delivery, throughput and power dissipation [4].

2.4.1.3.7. Span protocol. Span reduces energy consumption by using sensors to relay the data between the source node and the sink node [79]. SPAN: An Energy-Efficient Coordination Algorithm for Topology in Wireless Networks. The algorithm is a power saving technique that reduces energy consumption in the network without much significant reduction in the network capacity or connectivity. It is a distributed and randomized algorithm whereby nodes make local decisions on specific actions to reduce energy consumption which involves sleeping time and or joining in forwarding backbone as a coordinator.

2.4.1.3.8. Bounded Voronoi greedy forwarding (BVGF) protocol. As attractive as greedy geographic routing is in wireless sensor networks, it may take long forwarding routes and suffer failure in some network structures. BVGF [80], was as a result proposed to offer coverage for detection over a geographic field. It is therefore well suited for surveillance and object tracking applications. As a localized routing protocol, BVGF takes greedy decisions of routing within a single hop of the location of its neighboring nodes, selecting a neighbor node with the shortest Euclidean distance towards the sink node. It uses a Voronoi diagram for geometry computation and is only interested in neighbor nodes that have their Voronoi regions crossed by the line that connects the source node to the sink node. Analysis of the protocol, as well as its simulation on C++, indicates great efficiency for sensing coverage networks [69].

2.4.1.3.9. Geographic random forwarding (GeRaF) protocol. GeRaF [81] is a routing protocol that is based on the geographical position of the sensor node and through the contention between receiving nodes, and the routing node random choice. The protocol focusses on the average count of hops towards a sink node as opposed to the communication range and the average count of existing neighbor nodes. It is analyzed through an analytical model and implemented on a practical scheme. Results show that GeRaF outperforms GAF for a standard deviation that is a considerable fraction of the radius of the field [79].

2.4.1.3.10. Location based unequal clustering algorithm (LUCA) protocol. LUCA [82] is a routing protocol that is based on probability and is intended to overcome the hot spot problem in sensor networks. In LUCA, the cluster size changes in proportion to the distance from the destination node. Smaller clusters are formed nearer the destination, and larger ones are farther away from the destination. During the setup phase, each sensor node has a backoff timer whose value is random. When the nodes receive an advertisement (ADV) message of a cluster head within the time, the ADV message joins the cluster. If their ADV messages are no longer received, the node selects itself as a cluster head and broadcasts to its neighbors as a cluster head. LUCA used Global Positioning System (GPS) to find its location. Since sensor nodes in LUCA are mindful of their location, the protocol is not best suited for real-time applications, and its energy overhead is increased [83].

2.4.1.4. Network flow and QoS-aware routing protocols. These protocols are concerned with the start-up of routing and the delay of data from the source nodes to the destination as well as bandwidth and energy. A balance between energy consumption and quality of data must be met to achieve improved energy efficiency. Routing protocols under this category are:

2.4.1.4.1. Maximum lifetime data gathering (MLDG). The system lifetime is defined by a routing protocol called Maximum Lifetime Data Aggregation (MLDA) [84] as the count of sporadic message records obtained out of the sensor until the primary sensor died. It uses a technique that specifies how for every time, a message can be acquired and forwarded to the destination. This protocol aims to increase the schedule network lifetime, because the network lifetime is dependent upon the time that the schedule stays valid. Data aggregation is considered during the establishment of the maximum network lifetime route. Maximum Lifetime Data Routing (MLDR) applies in cases where data aggregation is not attainable. MLDA, as well as MLDR, perform better than H-PEGASIS when considering network lifetime [84]. When considering a delay in data packet delivery, Hierarchical-PEGASIS is better than MLDA. Cluster-based MLDA (CMLDA) [84], a better version of MLDA and MLDR was designed to overcome the challenge of delay in MLDA.

2.4.1.4.2. Sequential assignment routing (SAR). A protocol proposed by [85], SAR is the original algorithm design for routing that considered QoS in making decisions for routing. It is a multi-path routing protocol that is table driven and aims to achieve network fault tolerance while at the same time preserving energy for the sensor network. Failure recovery in SAR is achieved by ensuring that there is consistency in the routing table for both downstream and upstream nodes on every routing path. It takes into consideration the QoS metric, the priority level of each packet and the energy resource on each path while creating trees rooted at a single hop neighbor to the sink [1]. In SAR multiple paths are built from sink to sources. Its main drawback is the introduction of overhead during table route and states maintenance at every sensor node.

2.4.1.4.3. Maximum lifetime energy routing (MLER). Another network flow based protocol MLER [86] is proposed to solve the challenges of routing in sensor networks and aims to improve network lifetime. In MLER, the cost of a link is defined as a product of the remaining energy of a sensor node. When energy is required for the transmission of data, the link is used. MLER establishes traffic distribution by maximizing network lifetime. In comparison to the MTE algorithm, it is only the energy that is consumed during a packet transmission as the link cost that performs better. This is because relative residual energy that reflects the predicted energy consumption rate was taken into consideration [4].

2.4.1.4.4. A stateless protocol for real-time communication in sensor networks (SPEED). A routing protocol that uses real-time unicast, real-time area-multicast and real-time area-any cast communication methods is SPEED [87]. To identify routes, it makes use of geographical forwarding, and it requires that every node should keep its neighbor's information. As a localized protocol, it purposes to possess minimum control overhead. An integration of feedback control and non-deterministic geographic forwarding assist in maintaining a delivery speed of interest across the network, hence providing harmonized real-time communication from one end to another. This protocol is very efficient and scalable particularly for sensor networks with sensor nodes that have scarce resources. SPEED performs much better than Dynamic Source Routing (DSR) [164] and AODV [90] regarding data delay from one end to another and the consumption of energy by sensor nodes [4].

2.4.1.4.5. Energy aware QoS routing (EAQSR). EAQSR [1] is a multi-path routing protocol that incorporates QoS in its routing decisions and is also table driven. The main goal is to discover an optimum route to the sink in consideration of error rate and usage of energy at the same time satisfying the requirements of delay from one end of the network to another. It considers the routes that satisfy the instantaneous traffic requirements and maximizing the throughput for non-real time traffic. The protocol is not flexible enough to allow adjustments of bandwidth sharing for different links. This is because the bandwidth ratio is uniformly distributed over the sensor nodes in the network [4].

2.4.1.4.6. Message initiated constraint based routing (MCBR). This is a wireless ad-hoc sensor network routing protocol MCBR [88] that is based on a constrained message-initiation. MCBR explicitly encodes routing objectives.

An MCBR protocol has specifications for every message or event m received and is expressed as $(U_m^o, C_m^d, C_m^r, Om)$ where U_m^o represents the source of the information, C_m^d is the set of sink referred to as the destination, C_m^r represents the set of route constraints and $\mathrm{O_m}$ is the objective.

2.4.1.4.7. Smart routing with learning based QoS aware meta-strategies $(SL-QoS-MS)$. SL-QoS-MS is an MCBR [70] framework. This algorithm is made up of sets of QoS-aware meta-strategies and QoS specifications. In the algorithm, learning is experienced in all phases. Each node sends out a packet with its current Q-value for the type of message attached. All the participating sensor nodes are set to be in a promiscuous listening mode. Upon overhearing a packet of type k, a node updates the corresponding cost function value known as CQ-cost and makes another approximation of its own cost (Q-value) with the use of the expression as shown in (14), irrespective of whether it is the designated receiver or not.

$$Q_k = (1-\alpha)Q_k + \alpha\left(O_k + \min_c NQ_k(c)\right) \tag{14}$$

Here α is the learning rate, O_k represents the current local objective function value and n this node's neighbor.

Instantaneous search forwards the message to the "finest" neighboring node using the Q-value, according to the estimates. For decisions on when to re-broadcast the packet, constrained flooding is utilized per the approximations on cost. The packet is relayed to its parent through adaptive spanning tree. The parents periodically point to a neighboring node that has the finest Q-value to change roles. Advantages of this routing protocol are: (1) explicit destination utilization and QoS specifications for discovering optimal routes; (2) Extra maintenance packets are not required; (3) Different routes automatically adapting to changes in network conditions; and (4) If a path to the destination exists, infinite looping does not occur. The simulation environment was Prowler Routing, Modelling, Application and Simulation Environment (RMASE). Regarding success rate and low energy consumptions, the protocol performed well when compared to AODV.

2.4.1.4.8. AODV protocol. Large scale sensor networks are susceptible to link failures due to long transmission range and deployment of many sensor nodes. With this in mind together with the ad-hoc nature of deployment of sensor nodes in sensor networks, AODV [90] is a suitable communication protocol for these networks. AODV allows sensor network to adapt to dynamic link states quickly. Sensor nodes can respond timely to frequent changes in network topology and breakages in link connectivity. This is made possible using destination sequence numbers that always ensure free loops in the network. Routes in AODV are discovered only when they are required. Periodic HELLO messages are utilized in the original AODV, to assess if links to neighboring nodes are valid. In AODV, RREP packets are not generated by forwarding nodes even if they have valid routes and hence avoid adding multiple replies overheads. Cross-layer techniques that help to avoid high packet loss paths are also included in this version.

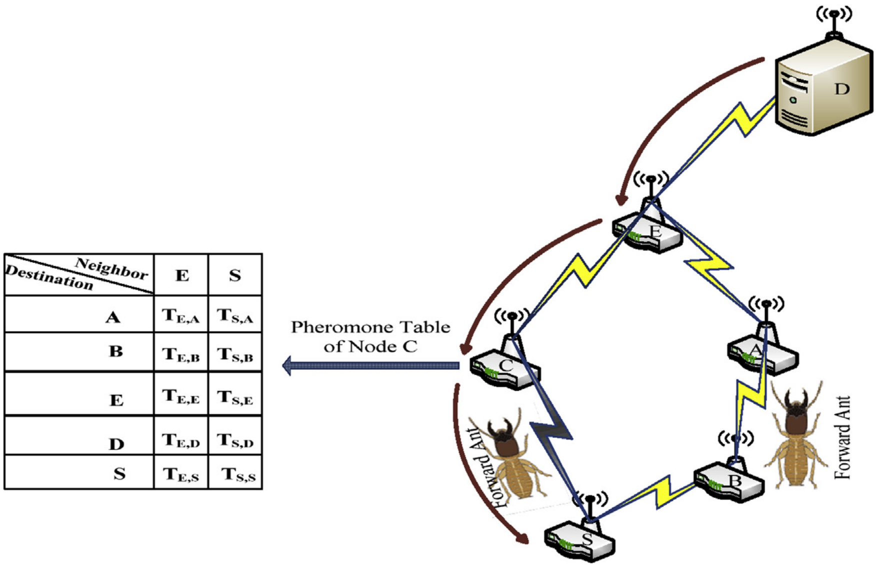
2.4.2. Routing protocols for static homogeneous wireless sensor networks

These are the homogenous class of routing protocols. They are protocols that have equal capacities of computation, power, and communication but having all the nodes in the network as being static in their mode of applications.

2.4.2.1. Nature inspired routing protocols. They solve complex problems with no centralized planning by emulating the social behaviors of natural creatures such as ants [165], bees [20], termites [21], spider monkeys [23] and bats [22]. The protocols demonstrate self-organization properties which are Stigmergy, multiple iterations, positive feedback, and negative feedback. Stigmergy is when social creatures like ants, indirectly use the environment to communicate. When insects go hunting for food, the secret chemical agents called pheromones from their bodies and deposit them onto the ground, leaving a trail which releases a scent in the air. Other insects are attracted by the scent and follow that trail, dropping pheromones while doing so. This continues until there exists, an established path from the colony to the food source. Positive feedback is when the pheromone amount increases due to an increased number of insects along the shortest path. Negative feedback reduces the pheromone by evaporation due to a small number of insects visiting the trail [4]. In [165] a study of ants' behavior and the way in which a group of ants (swarm) communicate amongst themselves by the adoption of the pheromone that the ants deposit along the paths while searching for food was conducted. Foragers follow the path to where other ants discover the food by sensing pheromone trails. This behavior of ants has influenced the study of ant colony optimization and the design of ant algorithms. The double bridge is an experiment that ant algorithms use to explain the inspiration of this initiative. Two paths of different lengths connect an ant home to a source of food. Initially, all ants are freely moving in and around their nest. One of the two bridge branches is the only way that can be used by the ants to reach the food. The ants start by moving randomly and can choose to follow either the shorter branch or, the lengthier one with the same probability. While moving along the paths, ants leave a track of pheromone on the ground. On selection of paths, they choose paths that are marked by a large pheromone quantity with higher probability. Each node uses a pheromone table to get guidance for path selection. The table records data that is collected by the onward or forward ant. The quantity of pheromone along the path is recorded and kept in a table at every node for its neighbor node. The node has a unique odor of pheromone, and the table is in matrix form, having destination nodes registered on the sides while neighbor nodes are registered running across the top. Rows represent destinations while columns represent neighbors. A pheromone table entry is identified by $T_{n,\ d}$ where n is the neighbor key and d is the destination key. The selecting probabilities of each neighbor are calculated from the values in the pheromone table. As illustrated in Fig. 29, as a packet reaches node G from an earlier hop S, the source, the pheromone decay of the source and pheromone are added to linthe k $\overrightarrow{SG}$. There is a high probability of selecting Path G because it is the shortest path leading to the destination, resulting in $\overrightarrow{SGED}$. The node G pheromone table as shown in Fig. 29 has neighboring nodes E and S. Nodes A, F, S, D and E are its promising destinations, bearing in mind that all neighbors are promising destinations.

The pheromone track on the branch that is shorter will rapidly grow and hence increase the likelihood that the branch will be used by ants that will follow. This is because the ants that choose that branch will discover the food before other ants and return to the ants' home base. This process that is auto-catalytic (positive feedback) demonstrates the self-organizing behavior that the ants possess and use to select the shortest path. The selection probability is given as;

$$P_k(r,s) = \begin{cases} \dfrac{[\tau(r,s)]^{\alpha} \cdot [\eta(r,s)]^{\beta}}{\sum\limits_{u \in J_k(r)} [\tau(r,s)]^{\alpha} \cdot [\eta(r,s)]^{\beta}}, s \notin J_k(r) \\ 0, else \end{cases}$$



Destination \ Neighbor	E	S
A	$T_{E,A}$	$T_{S,A}$
B	$T_{E,B}$	$T_{S,B}$
E	$T_{E,E}$	$T_{S,E}$
D	$T_{E,D}$	$T_{S,D}$
S	$T_{E,S}$	$T_{S,S}$

Fig. 29. Description of pheromone table of node G.

where $J_k(r)$ represents a group of nodes which still have to be toured, βdenotes the determining factor for the absolute pheromone as opposed to the one saved along the distance, ηsymbolizes the combined savings of two nodes on a single tour in contrast with savings of both nodes in two different tours, τ is the measure of pheromone on the edge, (r,s,u) denotes the identifier of the node, P_k is the possibility that ant k decides on moving from one node to another, $\tau_o$is the level at which pheromone increases on edge, $\rho=$ local research factor of evaporation and $\alpha=$ global research factor of evaporation. Other nature inspired routing protocols are:

2.4.2.1.1. Particle Swam optimization (PSO) protocol. The algorithm was inspired by the study of the behavior of a flock of birds in search of corn. In PSO [98], some 'particles' are positioned in a problem search area and each one of them investigating the aim of the problem where it is positioned. Particle movements are randomly decided upon from the search area through the combination of part of the history of the best and current positions of every particle with those of other members in the swarm. The swarm ultimately is most likely to collectively move nearer to the best fitness function, in the same way as a flock of birds hunting for food. PSO techniques when applied to WSNs routing and clustering to be able to choose cluster heads in the best manner by considering the remaining energy of sensor nodes [22].

2.4.2.1.2. Pheromone based energy aware DD (PEADD) protocol. PEADD [100] is an improvement of DD [166] in nature-inspired routing protocols that are based on the experimental studies of ant colony optimization. It involves nodes that have higher energy in the process of information collecting with the aim of maximizing the lifetime of the sensor networks. The algorithm uses ants that maximize the amount of pheromone along a path in proportion to the nodes' remaining energy levels. Paths that have a higher amount of remaining energy are augmented, and the rest are decreased. The pheromone quantity decreases as data is being transmitted because the pheromone measure has a connection with the remaining energy. The level of pheromone is updated in proportion to the amount of data transmitted. Simulation results from the proposal of this algorithm indicate that the network lifetime demonstrated by PEADD, for a rising number of dead nodes, is significantly greater than that is demonstrated by Directed diffusion.

2.4.2.1.3. Comprehensive routing protocol (CRP). CRP [101] is an algorithm that also follows after the ant colony protocol. It is a variant of the EAR that uses the probability of selection in its routing decision while considering the rate at which data packets arrive at the sink and network lifetime. The protocol debates that are regularly using the supposedly optimal path may not necessarily be the finest, for the fact that it will result in exhausting all the path nodes energy. It recommends occasionally using less optimal paths instead. Three stages are followed in CRP; Establishment of a routing table, data exchange, and maintenance of routes. In establishing the routing tables, flooding of the searching packet is done locally from the destination up until the source node is reached to discover all the routes. The process starts from the source node to the sink and ensuring that the possibility that everyone is selected based on the concentration of pheromone along every path, nodes residual energy, the square of transmission range along the path and the frequency at which the node acts as a relay or router. All these are obtained from the routing tables that are probabilistic at the time of route discovery and updating stages. In the data exchange stage, the data packet is sent to any neighbor in the forwarding table, choosing the possibility that the neighbor is equivalent to the one in the forwarding table. Every one of the intermediate nodes relays the packet of data to a neighbor that is selected in random in its forwarding table, with the possibility that the neighbor that is being chosen is equivalent to the possibility found in the forwarding table as well. This continues until the packet of data arrives at the sink node. A node that is selected as the succeeding forwarding node during data transmission will have the concentration of pheromone on the branch that separates it with the preceding node refreshed as in (15) and (16).

$$I_{ij} = I_{ij} + \Delta I_{ij}\ , \tag{15}$$

where I_{ij} is the amount of concentration of pheromone on the branch between node i and j. and ΔI_{ij} is the updated amount, and is calculated following;

$$\Delta I_{ij} = \left(1 - D_{jd}^2 \Big/ \sum_{k \in N_i} D_{kd}^2 \right) xT \Bigg) \tag{16}$$

Where D_{jd} represents the range between node j and the sink node d and T stands for a constant. The maintenance of routes shows the real network condition. Flooding locally is infrequently carried out from the sink node to the source node to sustain all the paths and ensure that the routing tables are updated according to the existing conditions. In comparison to the EAR as simulated in NS-2, the algorithm demonstrates a great potential to bring better solutions but is limited in QoS metrics.

2.4.2.1.4. Sensor-driven and cost-aware (SC) protocol. SC [102] assumes that there are sensors which are attached to ants' bodies which enable them to detect food sources at the initial stage of routing to improve their ability to sense the best direction that the ant will initially follow. Every node saves the probability distribution and the cost approximations of the destination from each of its neighbors, in addition to the sensing ability. SC is susceptible to data misleading whenever an obstacle introduces sensing miscalculations. For the cost approximation of Q_n for neighbor n, from the existing node to the sink node, the cost is 0 if it is the sink node, else,$C\ = min_{n \in N}(c_n + Q_n)$, where c_n represents the local cost function [4]. Calculating the initial probability is expressed as;

$$P_n \leftarrow \frac{e^{(C-Q_n)^\beta}}{\sum_{n \in N} e^{(C-Q_n)^\beta}}$$

2.4.2.1.5. Self-organizing data gathering (SDG) protocol. SDG [103] is a routing protocol that intends to gain sensor networks' reliability and scalability. In SDG, another sink is used by a node in case a sink node failed. The use of one sink node which denies a sensor network the ability to handle draining sensor nodes energy, is the strong basis for SDG protocol. This is justified by the fact that is positioned close to a sink exhausts all of its energy, the sink becomes detached from the network turning the sensor network into being useless since it will no longer receive data packets. To reduce the overhead of routing, only backward ants are produced by sink nodes. The usual Ant Colony Optimization (ACO) techniques of stochastic forwarding are used by sensor nodes to communicate event and data information to the sink node. Clustering of nodes in SDG is inspired from the behaviors of ant colonies whereby eggs and larvae come into groups. Ants continuously pick up and drop eggs depending on how similar they are. Sensor nodes on the edges of the clusters can vigorously change cluster associations based on a probabilistic technique which favors clusters with greater amounts of pheromone in their cluster. SDG was investigated by simulation in NS-2 using metrics of reliability. It dissipates a noticeable measure of energy because of hello packets exchange and its proactive characteristic. It was not compared with other existing protocol.

2.4.2.1.6. Energy balanced ant based (EBAB) routing protocol. EBAB [104] is a vigorous and adaptive communication protocol that is also based on optimization techniques of an ant colony. It is divided into intra-cluster and inter cluster to achieve a balance in energy consumption in the network and improve the lifetime of the network. In the intra-cluster, the protocol is divided into clusters and rounds that were formed when routing started. A cluster is established after choosing cluster leaders, and cluster leaders forward a sequence of data packets, alerting other sensor nodes. An "ACK" response is forwarded to gain membership of the cluster. If a node receives messages exceeding one, it will select the finest cluster leader based on the energy and distance. When the energy of the cluster leader decays below a certain threshold, data on gathering rest energy and the range of a cluster member is broadcasted, and the fitness calculations for all nodes are made. The node with the highest fitness level will become the succeeding cluster leader.

In the stage of data propagation, all the nodes switch the receiver on at the start of every cycle. Information on time slots for Time Division Multiple Access (TDMA) is then broadcasted. Every member of a cluster will maintain the transceiver in the off position until its appointed time comes. When it comes, members of a cluster forward the detecting data to the cluster leader. The improved ACO algorithm was used in the Intra-cluster section. In comparison to LEACH, EBAB shows through simulation that it has improved and better survival of sensor nodes, increased amount of information arriving at the destination [4].

2.4.2.1.7. ACO protocol. ACO routing algorithm was proposed by [106] to solve routing and load balancing challenges in WSNs. It adapts well to the ever-changing and static network topologies. The algorithm helps to find routes from the sending nodes to the destination nodes. The foraging behavior of ants is the inspiration behind the development of ACO. A group of ants depositing pheromone along a path is used to increase the delivery of data between the source nodes and the destination node [14]. The algorithm can be further improved for better performance.

2.4.2.1.8. Adaptive clustering based on ACO (ACO-C) protocol. Authors in [107] proposed ACO-C which is a clustering protocol that is conscious of energy and uses suitable cost functions that are applied at the destination node. The cost of transmitting data at long distances and data aggregation on all sensor nodes is evenly reduced and spread across the network. The problem of routing was accepted as a clustering challenge that aims to pick K from N nodes as cluster leaders and was realized by considering agents that are named software ants. The simulation was performed in MATLAB environment. Analysis and performance comparison with PSO-C, LEACH, and LEACH-C indicated that the protocol performs better regarding delivery of data and network lifetime [4].

2.4.2.1.9. Ant colony clustering algorithm (ACALEACH). ACALEACH [108] is an enhancement of LEACH that is founded on an ant colony. In ACALEACH, the range between the cluster leaders was taken into consideration for cluster leaders' selection in addition to the sensor nodes remaining energy. ACA is applied into routing mechanisms of inter-clusters to lower the energy dissipation of cluster leaders and eventually extend the network lifetime. When its performance was compared with that of LEACH in MATLAB simulation software, it demonstrated better performance in average energy consumptions and nodes survival. However, it did not take delay and throughput in consideration in its routing process, which may add overheads that may lead to poor performance [4].

2.4.2.1.10. Multi-path routing based on ant colony system (MACS). A Multipath routing proposed by [109], based on Ant Colony System. The ant demonstrates a new characteristic and technique of searching. MACS attempts to resolve the challenge of basic ACS getting trapped in the global optimum solution and to do away with the challenge of contingency as soon as it possibly can manage. The protocol outperformed ACS and DD considering average transmission delay when simulated in NS-2 environment [4].

2.4.2.1.11. AntChain protocol. AntChain [110] intends to improve energy efficiency, data integrity, and lifetime parameters of sensor nodes. A near optimal chain is realized through the utilization of ant techniques of colony optimization that run in the base station. The network sensor nodes build a bi-directional chain structure which adapts by itself in response to minor changes that may occur in the network. Instead of having sensor nodes that communicate with each other in establishing a transmission route, like is the case with other routing protocols, sensor nodes in AntChain only get valuable data from the sink node broadcast. The removal of the routing function saves a noticeable measure of energy in the network. In this protocol, sensor nodes need no previous knowledge of the network. The sink starts by sending an enable signal for setup to all the nodes notifying them that the network is initializing. When the notice from the sink is received, the nodes respond with their location along with the ID. They may alternatively send a brief message to confirm that they are still alive. AntChain is centralized and hence is not as robust as fully distributed routing protocols. It is also unrealistic by assuming that each node in the network can directly exchange data with the sink [4].

2.4.2.1.12. Probabilistic Zonal and swarm inspired system for wildlife direction (PZSWiD). PZSWiD [111] is a routing protocol that aims to achieve accurate information that is being transmitted and improving the reliability of the entire network for an extended period, as well as covers the speed of the transmission of the information that is propagated. The protocol emulates a data-centric approach by executing a routing and aggregation technique that is swarm inspired. A probabilistic model which represents data in a sensor network that is data-centric is used. Nodes respond to varying queries that are produced by a destination node and also carry sensed events to the sink. PZSWiD works with applications that are query based as well as event-based. The sensor nodes can generate emergency or periodic reports. The reports depend on how crucial or urgent the sensed data is, and then proactively forwards them to the sink. This is a complex protocol with a vague description of parameters. Probability P_{sd} is assigned, of a query that is relayed from destination s to every node d within the sensor network. The assignment is based on the closeness of the detected data to the requested data, and on the pheromone quantity. Network Simulator (NS)-2 simulations with varying zone radii, while observing its average delay and energy consumption were performed. Performance comparisons were not made with current routing protocols to investigate performance [4].

2.4.2.1.13. Ant colony based multi-path routing algorithm (ACMRA). ACMRA [112] identifies split multi-paths between the source nodes and the destination node. Many paths between source and sink are set up in multipath routing. Two types of ants are produced, namely: the Reinforcement ANT (RANT) and the Search ANT (SANT). SANT collects path information and local information of the intermediate nodes as they propagate along the path. RANT updates the pheromone table using the reverse links and carries path information back to the source node. This can be sensor node residual energy, energy dissipation of the current path or the length of the path itself. ACMRA is a multipath algorithm that is demand driven and uses a communication process that operates in two phases which include stages of building, routing, and transmission of data. For the building routing stage, SANTs are generated by the cluster head in the event region depending on the number of neighboring nodes, and the subsequent node is selected to change to depending on the selection probability. For the data transmission phase, the hop count, minimum energy at a path and energy dissipation is related to the network lifetime. The main and duplication mode of multipath channeling was compared to ACMRA, and it proved to perform better-considering node energy standard deviation and energy consumption. The metrics of quality of service were not considered in the design of this protocol, and the sensor nodes were not sufficiently distributed in the network. The simulation environment was also undisclosed [4].

2.4.2.1.14. Ant colony multicast trees (ACMT) protocol. ACMT is a multicast trees routing protocol based on an ant colony and proposed by [113]. It attempts to extend the lifetime of a network by reducing the process of communication in energy consumption. In ACMT, ants discover trees, which contain all the destination nodes. Current nodes can be any node that has been discovered on the tree. Each ant takes a step to enable the existing tree to grow further. The algorithm only observes the concept of positive feedback for the basic ant colony algorithm. When its simulation results are compared to the YANG model and Flooding, it performs better. The death rate of nodes increases as the network grows at a fast rate [4].

2.4.2.1.15. Ant colony optimization based location aware routing (ACLR) protocol. In ACLR [114], ants select the next hop to a subset of the set of neighboring nodes instead of all its neighbors. This ensures delivery of data packets at the destination at the same time avoiding loops. A formula is proposed that estimates the probability of transition that ants use to select nodes for their next hop. To determine the pheromone that ants deposited, the protocol uses a model. A unique mechanism to vaporize the pheromone on different paths depending on the remaining energy and nodes position was recommended to maximize the variety for the best solution of the ants. The comparison was made with other routing protocols like BAR, SC, FF, and IAR for performance [4].

2.4.2.1.16. Multi-sink swarm based routing (MSRP) protocol. A self-organized routing algorithm for sensor networks MSRP [115] which adapts easily to the environment and is fault tolerant. Slime-mold organisms are the inspiration behind MSRP. They find benefits in their ability to coordinate themselves in groups utilizing the production and evaporation of pheromone. Data traffic is organized towards the destination node by applying the concept of the gradient at the same time demonstrating tolerance to faults and autonomy. MSRP uses Objective Modular Network Test-bed in C++ (OMNET++) in evaluating its performances, adapting to environmental changes and signaling overhead. The phases of the process of signaling in the algorithm are as illustrated in Fig. 30 [4].

2.4.2.1.17. Jumping Ant Routing Algorithm (JARA). JARA [116] combines the merits of both proactive and reactive routing to increase the time it takes for route discovery and decrease the overhead in the route discovery for the wireless sensor network, hence it is referred as a hybrid routing protocol. In JARA, Zone routing protocols (ZRP) is combined with Ant Routing Algorithm for Mobile Ad-hoc networks (ARAMA) by the application of the jumping mode to minimize the proactive overhead. Two parts make up the algorithm. The first one covers the process that nodes use to keep the structure of some hops by using a proactive routing protocol. The second part covers the way each node implements ant routing in discovering paths beyond its zone. Therefore, every node keeps a zone, and each ant can jump a zone. According to simulation results, JARA minimizes route discovery overhead and shortens the route finding time particularly in heavily populated structures when compared to ARAMA [4].

2.4.2.1.18. ACO based load balancing routing (ACOLBR) protocol. ACOLBR [117] was proposed for Wireless Multimedia Sensor Networks to solve WSNs challenges. It first forms routing within clusters by a lowest spanning tree mechanism that has a cluster leader as the base. The routing between clusters is then formed by ACO to find the finest path from cluster leaders to the destination. The protocol utilizes the positive feedback of the message to get the remaining energy of the node, the propagation range and the delay in transmission as the heuristic index which ensures the transmission of the network has QoS. When compared to M-IAR and AGRA, it performs better with regards to energy efficiency and end-to-end delay [4].

2.4.2.1.19. Energy efficient ant based routing (EEABR) protocol. EEABR [118] is a routing protocol that is based on Ant Colony Optimization (ACO) meta-heuristic. In the protocol, a forward ant is launched at a regular interval by each node in the network to find a route to the sink. Every ant conveys the location of the node that was checked last, implying that forwarding nodes carry in the tables, kept data of ants that were received and forwarded. The contents of the table for each node show the previous and forward node, timeout value and identification of the ant. However, each node ant maintained a forwarding table which helps intermediate or receiving nodes to look up to the table to order to determine possible loop. The table is normally a pheromone trail of the path taken, and the measure of such is as:

$$\Delta\tau = \frac{1}{C - \left[\frac{EMin_k - Fd_k}{EAvg_k - Fd_k}\right]}$$

For an update of the routing table, expression (17) is utilized, such that:

$$\tau(r,s) = (1-\rho)^{*}\tau(r,s) + \left[\frac{\Delta\tau}{\varnothing.Bd_k}\right] \tag{17}$$

Where $\rho$is the pheromone evaporation factor, Bd_k, the number of checked nodes due to backward ant k, $EMin_k$ is the lowest value of the vector E_k, $EAvg_k$, the average of the vector values, andϕ a coefficient that force the ant to drop part of the pheromone strength on its way to the

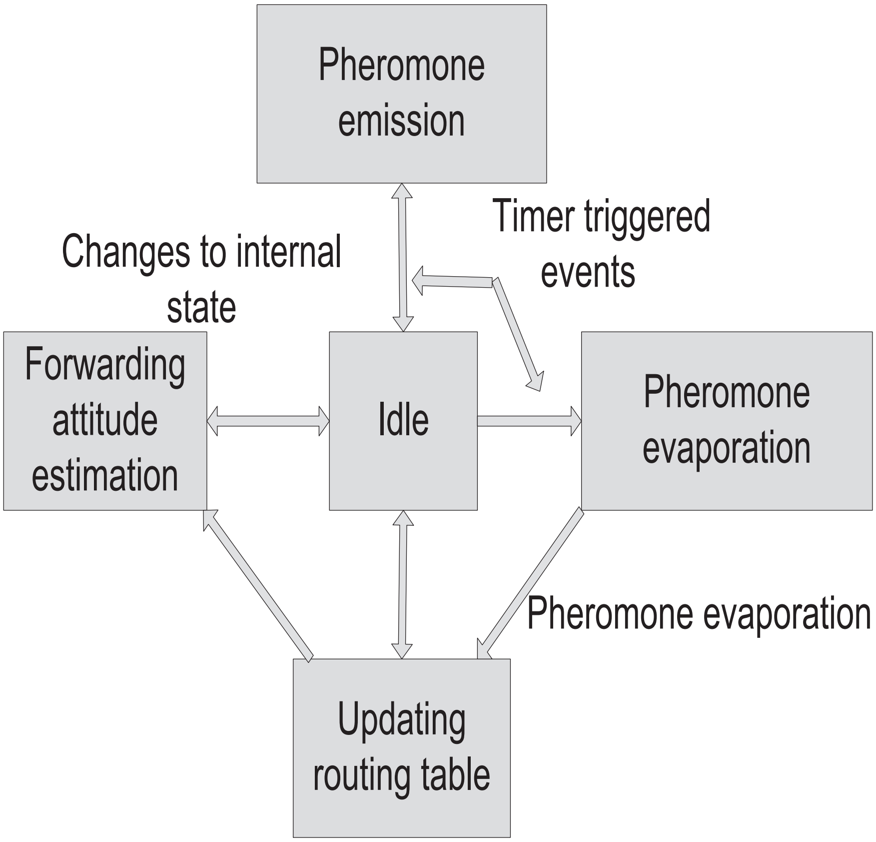


Fig. 30. Phases of Signaling process of multi-sink swarm-based routing.

source node. This kind of behavior is vital when the sink node can move, because it quickens the adaptation of pheromone [84]. In determining the strength of EEABR, it was compared with BABR and IABR and found to outperform the two protocols. The demerits are that it increases the excessive delay in the delivery of packets and also lacks the quality of service [4].

2.4.2.1.20. Improved EEABR (IEEABR) protocol. IEEABR [167] is an improved version of EEABR, which is based on ACO. EEABR was designed with the main objective of reducing the load of communication in a network as well as conserving the energy expended when communicating. The algorithm also introduced methods that can be used to update pheromone tables on the sensor nodes. The agents operating in EEABR are the forward ants and the backward ants. IEEABR enhances this algorithm by considering the energy consumption of each routing path and the energy available for each node in the network. It aims to discover optimal routes from the source nodes to the sink node by utilizing the ability of an ant colony system to self-organize, dynamically optimize and to self-adapt. It does this without wasting the energy of the nodes while improving the network lifetime and maintaining network connectivity.

2.4.2.1.21. Flooded forward ant routing (FF) protocol. FF [102] debates the issue that ants, even those augmented with sensors can lose directions as a result of obstacles or mobile sinks. The protocol uses link estimation probabilities. For the estimation, Link probabilities are used. Thus, a forward ANT will be allowed to broadcast only if $P_k < 1/|M|$, here k is the neighbor the ant is coming from and M denotes the set of neighbors. If there is no clue from the beginning, $P_k = 1/M$ for all k, a single broadcast only, will be realized from every node. Secondly, each transmission will have a random delay added to it, allowing the utilization of the delayed transmission. If the same ant from other nodes is heard by a node, the node will stop broadcasting [4].

2.4.2.1.22. Flooded piggyback ant routing (FP) protocol. FP [102] introduces a different species of ants called data ants to forward ants. Data ants transport the forward list. The flooded forward ants are controlled in the same way as in FF. The protocol managed to combine data ants with forwarding ants through controlled flooding to forward messages and identify the finest routes as well. This was intended to lower energy dissipation in the network having the data ants transporting the forward list. The protocol as compared to SC, FF, and BABR as demonstrated using RMASE environment, FP showed a higher success rate than all the protocols, but its energy consumption was relatively high [4].

2.4.2.1.23. Energy delay ant-based routing (E-D ANTS). E-D ANTS [121] is a routing protocol that is designed to reduce the time delay in the transmission of fixed packets. Here, Energy-Delay, named E and D ants' model was proposed. This protocol aims to enhance network lifetime and service transmission of real-time data for sensor networks. It is a reactive routing protocol that relies on the repetitive production and unicast transmission of many forward ants to find less energy and paths of delay, which is the same as AntNet. In E-D ANTS, each ant saves the level of the remaining node energy and the hop delay incurred while hopping from one node to another in its memory. OPNET simulation environment was used. Results show that E-D ANTS converges faster than AntChain and AntNet. The routing protocol, naturally flat would not easily handle large network structures, except when hierarchical techniques are included in its design [4].

2.4.2.1.24. Ant colony based reinforcement learning algorithm (AR and IAR). Like other ant-based routing protocols, AR & IAR [122] makes use of probability distribution for decision making when discovering routes. It differs with other protocols in the reinforcement learning algorithm that backward ants implore to get a more optimal path than the one the forward ant had taken. An evaluated heuristic correction index $A_{i,d}$ is utilized in the improved version called IAR. The routing protocol was compared with FP, SC, and FF and outperformed them based on energy usage of the network nodes, which in turn increases the network energy efficiency. The algorithm also shows better output regarding low latency and high success rate [4].

2.4.2.1.25. Beesensor. Authors in [168] and [169] discuss this algorithm which finds route only when they are needed. The hunting pattern of honey bees inspires the algorithm. The protocol operates with three kinds of natural organisms called packers, scouts and foragers. Packers identify suitable foragers at the source node, responsible for the data packets. Scouts' main role is to use the broadcasting principle to discover the routes to a new destination. Key agents of this communication protocol are foragers. They assume a line of sight type of propagation of data and transport the information to a destination node. When a source node senses an event, and it lacks a valid path to the destination node, it sends off an onward or forwards scout and stores events in its memory. The onward scout is transmitted to all neighbors of a node using the broadcasting principle. Each forward scout has attached to its payload a unique identification as well as the detected event. While the rest of the nodes stochastically decide whether to broadcast the forward scout further or not, neighbor nodes continually broadcast the forward scout at a range of two hops or less. Forwarding scouts do not make a source header which saves the whole range of sensor nodes that are propagated to the destination nodes. Their size is therefore fixed and is not dependent on the path length that was followed. Beesensor depends on the collaborations of routing at the source and scouts were on the return of the scouts, the creation of minor forwarding tables is done. It was analyzed on RMASE simulator and compared with EEABR, FP, and AODV. As an on the demand-based routing protocol, it is not suitable for applications of security or where information has to be regularly updated.

2.4.2.1.26. BeeSensor C. As an improvement to the BeeSensor routing protocol, it is inspired by the behavior of bees in a beehive colony. BeeSensor-C [123] operates through a dynamic clustering technique to reduce energy consumption and increase the network lifetime. It achieves an energy balance in the network by using a multipath formation technique. In addition to four agents (packers, scouts, foragers, and swarms) utilized in the original BeeSensor protocol, it introduces Hive Header, a fifth agent that claims the need to be selected as a cluster head when it senses an event. BeeSensor-C uses a free space model when it sends or receives a single bit packet [28].

2.4.2.1.27. Improved ACO (iaco). Authors in [124] proposed iACO, a routing protocol which is based on a technique of ant food hunting behavior. It partially relies on the efficient Max-Min algorithm and shows to be a perfect fit for flexible structures in wireless sensor networks. Each data packet in this proposed algorithm is regarded as a separate ant exchanging information with another one through values of pheromone that are saved in each routing table for every sensor node. The algorithm is executed in three main steps: production of local solution depending on the routes; update of pheromone; and deciding on updating the pheromone table. In addition to the pheromone update rules, there is a mutation factor in which a threshold is set to raise the speed of convergence of the protocol. The mutation factor is partially dependent on Best Worse Ant Algorithms (BWACA) and Max-min ant system. No performance analysis was done on the algorithm. It was however observed that as the network grows, the throughput reduces, making the algorithm poor in QoS [4].

2.4.2.1.28. ACO-QoSR protocol. ACO-QoSR [125] is a reactive routing protocol which aims to solve challenges of requirements for delay, limited energy and processing limitations in sensor networks. The challenge it aims to address is discovering routes from source nodes to sink node such that the overall delay from one end to another is less than a boundary value D, while the residual energy ratio, $\mathrm{ERR} = \mathrm{E}_{\mathrm{residual}}/\mathrm{E}_{\mathrm{initial}}$, exceeds a certain threshold value. A selection probability as in [125] is used in the algorithm to broadcast ants in unicast to the subsequent nodes. When a source node needs to send data in its possession, it searches its routing table for a valid route. In failing to find such a path, it initiates a probe stage to look for a new path. Each path probe consists of m forward ants. Max-min ant algorithms for smoothing and boundary techniques are also utilized. Using the unicast ant to discover the paths that are constrained in delay is debatable because the protocol stores the information of routing on the header of forwarding ants as well, hence increasing the energy consumption further. AC0-QoSR suffers delays in packet delivery especially in large networks [4].

2.4.2.1.29. Ant colony based many to one sensory data routing (MO-IAR). MO-IAR [126] protocol operates in two sections. The first section employs onward and returns ants to identify the optimal path amidst multi-hop sensor networks. The second section is where data ants route the real sensory data through the shortest path. The upstream data flow can be routed through the shortest path. The protocol can avoid congestion, and as a result, can handle both sporadic many-to-one sensory and event-based data stream. Ant colony optimization is used in the first section, assuming that each sensor node is aware of its position and that of the previous node which can be tracked with GPS technology. Initially, a single sensor node is deployed, and every node internally announces a HELLO data packet to a neighboring node to create a table for the neighbor. For the second stage, after discovering the optimal route, data ants are employed to forward the real data stored by *x* number of generator nodes heading towards the destination. MO-IAR performs much better than SC, FF, and FP regarding average latency and number of collisions when compared through simulation. Excessive use of energy can result due to the use of source routing and other state information in the forward ants' header. Delay in packet delivery to the sink can also be experienced [4].

2.4.2.1.30. Ant-aggregation. Ant-aggregation [127] is a routing protocol that argues the case that energy consumption can be significantly reduced by a multi-hop structure of communication that works with in-network aggregation and as a result improve the lifetime of a network. The protocol attempts to resolve the challenge of an NP-hard problem, which is an optimal aggregation in a multicast tree. The algorithm learns from ACO information of aggregation trees at minimum cost, where onward ants search for the optimal route to the sink node. An onward ant is unicast at every node to the subsequent node with a possibility that the protocol has defined. The ants attempt to get to the nearest point of aggregation for the paths that previous ants searched. The protocol converges to the internal best aggregation tree. Ant Aggregation performs best in reducing the energy that is dissipated in the network when it is compared to greedy algorithms and opportunistic aggregation [4].

2.4.2.1.31. Ant based service aware routing (ASAR) protocol. ASAR [128], is a routing protocol that selects appropriate routes to satisfy various QoS requirements from different types of operations. It is best suited for multimedia sensor networks. The protocol targets two different modes of operating network with various QoS requirements: 1. the query-driven which includes both data query (D-services), and stream query (S-service) S-service does not tolerate errors but tolerates delays more. 2. The event-driven method that consists of R-service only, which adds firm requirements in the delay and reliability for sensing of events and announcements, for example, monitoring older adults. In updating pheromone in ASAR, values of pheromone assume discrete values between 0, and $\tau^{h}{}_{\max,}$ which speed up the rate of convergence and minimizes the number of pheromone updates that are needed. When compared with the performances of DD and simulation results in NS-2 of Dijkstra's algorithm, ASAR outperforms these protocols based on bandwidth, energy dissipation, latency and metrics of the rate of packet loss [4].

2.4.2.1.32. Basic ant based routing (BABR) for WSN. BABR [18] was among the first routing algorithms that take inspiration from the behaviors of ants. It uses Forward ants that are launched regularly from the source to sink nodes, with the intention to find the right path to the sink node. The forward ants use probabilistic mode using neighboring nodes to get to the sink node. However, each of this forward ant tends to gather the information of the path they took to get to the destination node (Sink), this help in future to know the way about of the sink node. When the forward ant gets to the sink node, it is immediately converted to backward ant with the intention to update the path it took to get to the sink node. When it successfully arrived at the source node, it dies off, meaning its mission is accomplished. The link or path taken is normally maintained using:

$$\sum_{i\in N_k} P_{ji} = 1; \;\; j = 1, \ldots, N.$$

The local model of traffic M_k is updated with the values passed in $\mathrm{S}_{\mathrm{s}\to\mathrm{d}}$. The time of the trip $\mathrm{T}_{\mathrm{k}\to\mathrm{d'}}$ employed by $\mathrm{F}_{\mathrm{s}\to\mathrm{d}}$ to move from k to d' is used to update $\mu_{\mathrm{d},}\, \sigma^2_{d'}$ list $\mathrm{trip}_{\mathrm{k}}$ $(\mu_{\mathrm{i},}\sigma_i^2)$ of a function representing an arithmetic mean as μ_{i} with variance as σ_i^2 for perioda of trips taken from node k to all nodes i (i≠k) which is governed by:

$$\mu d' \leftarrow \mu d' \;\; + \eta(Tk \to d' \;\; - \mu d')$$

$$\sigma^2_{d'} \leftarrow \sigma^2_{d'} \;\; + \eta((Tk \to d' \;\; - \mu d')^2 - \sigma^2_{d'})$$

The time for the trip $\mathrm{T}_{\mathrm{k}\to\mathrm{d'}}$, whereas η, stands to represents the trip weight for each trip taken, and for some samples taken for each trip is approximated as $5(1/\eta)$, by which updating the trip by the use of routing table is governed by the following:

The value $P_{kd'}$ (the probability for choosing the neighbor node k, when the node destination is d') is incremented with the expression:

$$P_{kd'} \leftarrow \; P_{kd'} + r(1 - \; P_{kd'}),$$

where r represents a factor of reinforcement showing the quality of the followed path.

The $P_{kd'}$ probabilities linked to the other nodes declines respectively:

$$P_{kd'} \; \leftarrow P_{kd'} \; - \; r\, P_{kd'}. \;\; n \, \in \, N_k, \;\;\; n \, \neq \, f.$$

The reinforcement factor r is calculated having three basic concepts in mind: (i) an increment in the probability of selection which is proportional to routes quality should be added to the routes. (ii) The quality is a state of traffic which is dependent on the quantity that can be guessed by Mk, and (iii) they should avoid uncontrolled oscillations by not allowing all the traffic fluctuations. Setting up a guarantee between stability and adaptability is critical. Amongst several tested options, expression (4) was selected to calculate r:

$$r = c_1 \;\left(\frac{W_{best}}{T}\right) + c_2 \;\left(\frac{I_{\mathrm{sup}-} \;\; I_{inf}}{(I_{\mathrm{sup}-} \;\; I_{inf}) + (T - \; I_{I_{inf}})}\;\right),$$

where W_{best} denotes the best journey taken in the final window of observation $W_{d'}$ [4] by an ant to node d'.

2.4.2.1.33. ACO based energy aware multi-path routing algorithm (ACO-EAMRA). ACO-EAMRA [112] proposed a routing protocol which relies on the accessible energy of sensor nodes and the dissipationn of energy in every path for selection of routes. The routing protocol when compared with DD, performs better considering the ability to save energy. It does not consider QoS in the process of routing [4].

2.4.2.1.34. Energy efficient ACO based QoS routing (EAQR) protocol. Authors in [170] came up with an energy efficient ACO based QoS routing (EAQR) protocol. The protocol gives the provision of QoS and energy depletion balancing over the whole network a priority. Along with its path hop count, reduced path power and through increasing the model of pheromone trace, EAQR creatively offers two experimental mechanisms that rely on the range and the wellbeing of the path to satisfy real-time, and common traffic performance requirements. It, therefore, provides service differentiation between best effort traffic and real-time by including the new model of pheromone heuristic that is two-fold in ant colony system [4].

2.4.2.1.35. An adaptive QoS and energy aware algorithm (IACR). IACR [130], is an improvement to ant colony routing. It takes into consideration QoS and nodes energy balancing with the intention to extend the network lifetime. It is made up of the routes discovery just like in the basic ant routing, as well as maintenance of routes where there is a fast response to sudden changes in the network topology. The protocol addresses instantaneous traffic with high bandwidth demand such as broadcasts of voice and video. Results from simulation on Omnet++

when compared with DD show that it performs best. However, it suffers a delay in forwarding of packets to the sink [4].

2.4.2.1.36. QoS based distance vector routing (QDV) protocol. A distance vector routing protocol based on the quality of service, QDV was proposed by [132] and uses colony optimization of ants for wireless sensor networks. QDV, in its routing decision, is concerned with the quality of service and the network reputation. It highlighted that a dignified node indicates that the node is trustworthy and more dependable for purposes of data transmission. Some indications of misbehaving in a node lower its reputation and eventually has an impact on the value of its security, hence deactivating the mischievous nodes from accessing the network. Every sensor node in the routing protocol contains some information concerning neighboring nodes. Communication between the autonomous nodes depends on their range. Any node in the network can be mischievous, so the protocol is more concerned about separating it from others and ensuring efficient and safe transfer. Simulation results confirm that the performance of QDV is better than that of Sensor Network Encryption Protocol (SNEP), even though it causes excessive delay in delivering data packets to the sink as a result of choosing the most secure node, and hence consumes network energy [4].

2.4.2.1.37. AntSensNet. Authors in [131], proposed AntSensNet, which is a routing protocol for wireless multimedia sensor networks that use several units of quality of service. A multi-path video packet scheduling that is power efficient is utilized in this protocol with the intention to gain less video distortion transmission. To ascertain the quality of service requirement of sensor networks, AntSensNet combines ACO-based routing with a hierarchical structure. It is made up of reactive and proactive components. Its reactive nature is demonstrated by setting up routes only when they are needed, while the proactive side is shown by the fact that, routes are surveyed, maintained, and upgraded proactively by a set of exceptional agents while a data session is in progress, its operation is in three ways; firstly, nodes are formed into colonies by the cluster networks. Then network path amongst clusters which satisfy every application requirements utilizing ants. Lastly, traffic is relayed by using paths that the ants had previously discovered. During clustering, information outside the cluster is transmitted by the channel heads only, avoiding collision amongst sensor nodes inside the cluster. This saves energy and improves latency. NS-2 simulation results show that the proposed technique that reduces distortion and is used to carry video packets has better video quality as opposed to using TPGF, and ASAR [4].

2.4.2.1.38. Biological inspired self-organized secure autonomous routing (BIOSARP) protocol. BIOSARP [134] is inspired by the social behavior of ants and based on ant colony optimization, ACO. It is an improvement of Secure Real-Time Load Distribution (SRTLD) routing protocol which broadcasts data packets in finding neighboring nodes making calculations at each node during the relaying of a packet of data, hence wasting much energy. Unlike SRLTD, BIOSARP has an independent routing scheme in which improved ant colony optimization (*i*ACO) is utilized to achieve the best path forwarding decision. Packet and broadcast overhead are minimized to reduce the loss of power, packet delivery delay at the sink and packet loss in the network. Two kinds of ants namely: forward and backward ants are employed to improve energy efficiency by using end to end delay, residual energy and link quality as parameters that are added to the ant pheromone probability formula. Its superior performance has been proven in real environments to outperform other states of the art protocols like IEEABR, E-D ANTS and STRLD [28]. The best applications of the algorithm include battlefield surveillance and monitoring of buildings or structures and the environment.

2.4.2.1.39. Bat protocol. It is based on the natural social behavior of bats. This refers to their ability to identify their roosting crevices, obstacles and be able to avoid them and to even sense their prey, all in the dark [22]. In the selection of the best cluster leader nodes from a multitude of the species, the protocol best utilizes the network as a nonlinear function. The aim employs a fitness problem to reduce the compactness within clusters with a short range between sensor nodes belonging to one cluster. Simulation of the algorithm in four different WSNs implementations yielded better results than those obtained with the LEACH routing protocol.

2.4.2.2. Cross-layer routing protocols. In this class, parameters of non-adjacent layers of the network are allowed to interact with the intention to achieve improved energy efficiency and longest network lifetime [28]. The routing protocols under this class are:

2.4.2.2.1. Joint Routing power and random access algorithm (JRPRA). JRPRA [171] combines optimal development of the physical, Medium Access Control (MAC) and routing layer to prolong the network lifetime of a wireless sensor network consisting of a single sink. Its power control algorithm works in the physical layer while the routing strategy works in the network layer. JRPRA initially formulates a convex optimization problem with the link access probabilities provided and then proposes a distributed algorithm named Joint Routing and Power Control Algorithm (JRPA). JRPA is developed as a heuristic algorithm since in practical networks the link access probabilities are often indirectly available, so the problem is deteriorated in a non-convex problem. Network lifetime is extended by adjusting the capacity of the link [28].

2.4.2.2.2. A lifetime maximization cooperative routing with truncated automated repeat request (LMCRTA) protocol [168]. This is a distributive algorithm that integrates the physical layer's cooperative adversity with the data link layer's truncated automatic repeat request as well as the network layer's distributed routing strategy. Network lifetime is extended through the integration of the diversity schemes, the application of Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) modulation schemes to allocate power with minimal errors and selection of optimal paths based on the state of the channel and the remaining node energy. Cyclic Redundancy Check (CRC) is used to validate data accuracy instead of the Signal to Noise Ratio (SNR) threshold that is usually used [28].

2.4.2.2.3. Cross layer optimal design (CLOD) protocol. In CLOD [137], task scheduling and reduction of link-level congestion are achieved through appropriate resource allocation at the data link layer, while routing is done at the network layer. A compressed sensing technique that minimize the number of transmitted bits reduces the node level congestion at the transport layer. CLOD assumes a fixed link capacity and is suitable for networks with light loads [28].

2.4.2.3. Opportunistic routing protocols. These protocols reduce the number of unwanted re-transmissions and provide solutions to unreliable link failures. Multiple routers utilize the broadcast property of wireless communication to improve throughput in the network. Examples of these protocols are:

2.4.2.3.1. Extremely opportunistic routing (ExOR) protocol. ExOR [138] is an opportunistic routing protocol that combines routing and MAC technique to gain some cooperative diversity on radio hardware that is standard such as 802.11. Multiple potential forwarders receive ExOR data broadcasts from each packet in which one of them is chosen only after the set of nodes which received the packet is known. ExOR can concurrently try multiple long and rather radio lossy links by delaying decisions forwarding until reception is achieved. This causes high expected progress for every transmission. ExOR is well suited for applications with existing radios since only a single ExOR node forwards each packet, unlike it's the case with cooperative diversity schemes. Its disadvantage is making sure that only the "best" receiver of every packet forwards it, to avoid duplication [28].

2.4.2.3.2. MAC-independent opportunistic routing and encoding (MORE) protocol. MORE [139] is a variant of the original ExOR opportunistic routing protocol. Task scheduling in ExOR is highly structured, introducing a solution to the issue of coordination. This issue is bypassed by MORE through a combination of opportunistic routing with intra-flow network coding. The two routing protocols, however, do not address energy consumption in a network.

2.4.2.3.3. Energy-efficient opportunistic routing (EEOR) protocol. EEOR [140] intends to minimize the cost of energy in selection and prioritization of a forwarder list under opportunistic routing while increasing the network lifetime. It is a multipath routing protocol that investigates its Expected Energy Cost (EEC), rather than it's Expected Transmission Count (ETX) as an initial parameter. Prioritization of a forwarder list then follows based on the EEC. EEOR has adjustable and non-adjustable power models and demonstrates high efficiency when compared to ExOR, considering the throughput, packet delivery, energy consumption, loss ratio, and delay. It is more suitable for unicast broadcast networks [28].

2.4.2.3.4. Energy efficient routing (E^2R) protocol. E^2R [141] presents a self-selection technique for routers at the stage of data delivery and avoids pre-selection of a routing list beforehand. It purposes to utilize the route metric value of a node and compares it with the metric value that is embedded in the data packets that it has received. In the case that the node's metric value is less than the value of its received data packets and it does not overhear any of its neighbors with a higher metric value during the node's back off period, the nodes opt to be a relay or router node itself. E^2R performs better than AODV based on packet delivery ratio, control overhead, and packet delivery delay and energy depletion. It is suitable for large scale networks and can work in mobile environments [21].

2.4.2.3.5. Kaliszan and Stanczak (K-S) protocol [21]. K-S [142] does not use coordination techniques as other protocols do, but rather extends network lifetime by combining opportunistic routing with network coding and avoiding duplicate transmissions. A linear program is formulated by assigning a fixed reception probability. A simple heuristic algorithm is developed to solve the program. When compared to MORE K-S minimizes energy consumption up to 20%.

2.4.2.4. Cooperative routing protocols. High spectral efficiency and channel fading mitigation can be achieved through cooperative communication. Multiple –Input and Multiple-Output (MIMO) mechanisms that can minimize the transmission power and increase coverage in the transmission are used. This allows multiple nodes to share antennas and other resources and therefore to save space and costs [28]. The routing protocols under this class are:

2.4.2.4.1. Relay selection based cooperative Routing(RBCR) protocol [143]. Energy consumption and channel quality are considered in the development of this protocol to enhance energy efficiency. Rayleigh fading is overcome by using the available cooperative diversity and selecting optimal paths. RBCR is well suited for high-quality channels [28].

2.4.2.4.2. Energy-balanced cooperative routing (EBCR) protocol. Unlike RBCR, EBCR [144] uses only one hop neighborhood. The best relaying sets are identified, and multiple relay method is followed. The delay performance is not different from that of ordinary single relay methods. Higher throughput is achieved with EBCR, but the protocol does not cater for noise or fading. Hence the bit error rate is high.

Multi-Parametric Mixed-Integer Linear Program (mp-MILP) Protocol [145].

To realize the optimal selection of node relays and resource allocation (e.g., power), with no noise or fading, a problem that demonstrates minimum energy cooperative routing is formulated as an mp-MILP. A simple implementation is achieved by solving the mp-MILP problem offline based on the multi-parametric theory. The decision of the next nodes is derived from the Euclidean distance between the nodes. Multiple neighboring relays apply, and each node's transmission power is tuned. Nodes indicating the least attainable transmission power are chosen. To overcome fading, a modulation scheme is applied. Networks that require high reliability are suitable applications for this protocol.

2.4.3. Routing protocols for mobile homogeneous wireless sensor networks

The networks can consist of a single mobile sink, a mobile sink and source, and multiple mobile sinks. A network using multiple mobile sinks demonstrates higher performance than one using a single mobile sink, but at a higher cost.

Routing protocols for networks consisting of one mobile sink are:

2.4.3.1. Termite hill [21, 30]. Inspired by the behavior of termites, this routing protocol demonstrates routing behavior which emanates from defined rules that are followed by data packets when using the principles of swarm intelligence. Each sensor node in Termite Hill acts as both a router and a source node. The hill or hills serve as sink nodes and a network node can also become a termite hill, depending on the network. Communication links between sensor nodes serve as pathways for packet transmission in the network. Pheromone is deposited along these communication links, and as packets traverse from the source to the sink, they follow the pheromone heading for the sink and leave pheromone along the path for its source. This demonstrates positive feedback. The packets are led to move towards the sink pheromone slope direction. Negative feedback reduces the amount of pheromone along the path by allowing exponential pheromone decay. Termite hill operates in multi-hop communication fashion to evenly distribute the energy consumed by the sensor nodes. Routes are discovered only when they have sought after. The protocol operates by generating a forward soldier to relay information to the sink when it does not have the relevant routing table entry. The forward soldier has broadcasted to its neighbors who in return search their local routing table for a suitable route required for the destination. On finding the suitable route, the node at the receiving end generates a backward soldier that is unicasted back to the originating source node through some reverse communication links. Failure to find a valid route to the destination means the sensor node sets a reverse link to the node that had forwarded the forward soldier. The node continues to broadcast the forward soldier packet. On receiving the forward soldier packet, the sink node generates a backward soldier packet. This packet is as well unicast back to the source node. Every router node then updates its routing table and sets up a forward pointer. The backward soldier packet is forwarded by use of a reverse pointer to the next hop. The cycle continues until the backward soldier arrives at the source node.

2.4.3.2. Update-based routing protocol (LURP)/adaptive LURP (ALURP) protocol. LURP [148], instead of allowing regular position updates of a mobile sink to the whole network, it confines the scope of these updates to a destination area, and minimizing the communication overhead. A circular destination area is defined by choosing the current position of a mobile sink as a virtual center, VC at a local distance R. These are broadcasted over the whole network. The mobile sink only broadcasts its location information to sensor nodes inside its destination area when it moves inside the area. Geographical forwarding is used to send data packets towards the VC outside the destination area. Topology-based routing applies when sending data packets inside the destination area. A new destination area is re-defined as soon as the sink leaves its current destination area. The new VC is flooded over the whole network. ALURP reinforces the restriction of the scope of the regular position updates of the mobile sink when it goes inside its destination area. In ALURP, the destination area is still a circular area with a center VC, but the update range is smaller than R and is defined by the distance from the VC to the current position of the mobile sink. The updated range is varied every time the mobile sink moves.

2.4.3.3. Data-driven routing protocol (DDRP) [149]. This simple protocol exploits the broadcast characteristic of wireless transmissions. It combines random walk routing with data-driven packet relaying to minimize the protocol overhead for discovering and maintaining routes in a mobile WSN. Each data packet offers an additional task of recording the hop distance between the source node and the target sink node. If another node overhears the transmission of this data packet, that node can learn a new route to the sink node which may be shorter or fresher than the previous route. In the case where a sensor node has no route information to a mobile sink, to transmit the data packet to the sink, a random walk is used until the sink is found or a sensor node with a fresh route to the mobile sink is discovered. DDRP has minimum control overhead and better route learning ability. Its performance can be easily improved as its route learning algorithm can work with other routing protocols [133].

2.4.3.4. Whirlpool routing protocol (WARP) [150]. It speculates routing by using gradient information after discovering that the mobile sink has moved from its original position. WARP initially forms a gradient-based forwarding structure at the mobile sink. As soon as the mobile sink moves, data packets are routed by speculation in a spiral trajectory around the previous location of the mobile sink.

2.4.3.5. λ – flooding [151]. This protocol offers a novel technique of collecting information from a network for mobile users. It partially updates a pre-built shortest path spanning tree every time the mobile sink changes its broadcaster node. This creates a limit on the worst case stretch ratio performance of end to end packet delivery [27]. Therefore, the performance of routing is controlled as opposed to the best performance, and the routing structure is updated by only carrying out a local modification. The λ-Flooding routing protocol can easily be implemented and is more scalable. It has been experimentally tested and its performance tested by simulation [27].

2.4.3.6. Predictive QoS routing (PredQoSR) protocol [152]. It improves the performance of the successful packet delivery ratio during sink mobility by combining information potential based routing with mobility prediction. In PredQoSR, a potential field is formed and information gradients are established in the sensor network. The probability that a random walk from a sensor node arrives at the mobile sink before reaching the network boundary is an interpretation of the information potential associated with that sensor node [27]. The potential field may be significantly altered for a movement that is not local leading to packet loss and even delays. A mobility graph is thus used to encode any knowledge concerning the chances of any mobility patterns in the network. The graph will then be used to foretell forthcoming forwarding nodes for the mobile node. Additional routing states can be efficiently stored, enabling maintenance of uninterrupted data streams in the communication protocol. This protocol improves routing performance and uses valuable mechanisms to optimize sensor networks [27].

The routing protocols for networks with mobile sink and source are:

2.4.3.7. Trace announcing routing scheme (TARS) [153]. TARS bring forth a tracking technology that is more enhanced than tracking assisted technologies that preceded it like Tracking-assisted Routing Scheme for Wireless Sensor Networks (TRENS). TRENS routing protocol was developed to avoid frequent re-routing that consumes energy. TRANS, on the other hand, is a simple approach that allows a short cut to reducing data redundancy in a network and improves routing algorithms efficiency as well as optimizing routes in a frequently changing network structure. TARS save energy by controlling radio channels of inactive nodes through the use of a time scheduling scheme. This scheme allows a few inactive grid heads to rest or sleep so that their radios may be turned off to minimize energy consumption. A Java-based simulator J-Sim was used to evaluate the performance of TARS. The protocol demonstrated less energy consumption and improved delivery of data as well as successfully handling routing in the network much better than TRENS and EADA.

Routing protocols for networks with multiple mobile sinks are:

2.4.3.8. MobiCluster [154]. This routing protocol addresses the challenge of the inability of mobile nodes to pass through some isolated 'sensor islands' in the network. Cluster heads in MobiCluster have to only communicate with sensor nodes that are positioned closer to the trajectory of a mobile sink, which are termed 'rendezvous' nodes. The five stages of operation of this protocol are clustering, rendezvous node selection, cluster head attachment to rendezvous nodes, data aggregation, and communication between rendezvous nodes and mobile sinks. The distance between a cluster head and the mobile sink is used to control the cluster size through a clustering algorithm optimally. This helps to balance the energy between the static sensor nodes. A longer distance leads to larger cluster size. To minimize the number of packets that may collide and energy consumption, rendezvous nodes are selected by use of an algorithm. Whenever there is a demand to replace either the rendezvous nodes or cluster heads due to low energy levels, the sensor nodes are replaced to extend the lifetime of the network.

2.4.3.9. W-L. (Wang - Li) [155]. This is an energy efficient distance aware routing protocol having multiple mobile sinks proposed by [155]. W-L tunes the transmission power concerning transmission range by uses a radio energy model. The probability of encountering interference lowers as the transmission power decreases. Mobile sinks wander around the periphery of a rectangle to collect data from pre-determined parking positions. Data can only be collected when they are stationary. The larger the number of the mobile sinks the longer the network lifetime.

2.4.3.10. Elastic routing (ER) protocol [156]. As a source node continues to report data to the destination node or sink, its reception of the updated data on the location of the sink is maintained by use of ER protocol. This helps to minimize the communication overhead of the source node. The source node receives the new position information of a sink node that has moved through a backward propagation along the data path. This is achieved through the periodic broadcasts of beacon messages sent by the mobile sink to its close neighboring nodes, announcing its current position. The source node can then be able to know the very recent location of the mobile sink. It communicates with through the delivery of continuous data packets along the data path in the forward direction.

2.4.3.11. Anchor based Vonoroi routing protocol (AVRP) protocol [157]. It reduces the protocol overhead by using both the Voronoi scoping and dynamic selection of a broadcaster node for each mobile sink. The protocol assumes that several mobile sinks uncontrollably wander around the sensor field. A broadcaster node with the highest link quality is selected from the neighbor nodes by the mobile sink. It then broadcasts its data to the entire network, forming a Voronoi scope for the sink it is associated with. Each sensor nodes creates for itself; a target sinks for data reporting by choosing a broadcaster node that is closest to it.

2.4.3.12. Multi-stage data routing protocol (MDRP) protocol [158]. As an improvement of AVRP, MDRP was proposed to reduce the huge amount of control overhead brought about by the maintenance of the data delivery structure that is efficient. It divides the Voronoi scope for each mobile sink into many layers depending on the gradient information of the sensor nodes [133]. The updates of sink movements diffusion scope are more likely to be reduced by this design as well as the rate at which the structure of data delivery is refreshed. When compared to DDRP, Trail, and AVRP through simulation, it shows higher packet delivery ratio and effective reduction of the protocol overhead [133].

2.4.3.13. Dream protocol [159]. The dream is a routing protocol designed based on distance effect and the rate of mobility. A great distance separation between two nodes makes the nodes appear to be moving slowly concerning each other. Similary, an update of location information in routing tables can be made as a function of the range between the sensor nodes with no compromise on the accuracy of routing. On the other hand, updates on the slower mobile nodes need to be less frequently made than on the highly mobile ones. Frequency optimization in sending updates to the network is realized at each node resulting in bandwidth minimization and less energy usage. Dream addresses the challenge of overhead by differentiating the nearer mobile nodes from the distant mobile nodes. Efficient data packet transmission is realized in this protocol because there always exists an end to end path. Its drawback is in wastage of the network bandwidth [57].

2.4.4. Routing protocols for static heterogeneous wireless sensor networks

Energy Heterogeneity: These are routing protocols whose heterogeneity is based on the sensor nodes energy.

2.4.4.1. An energy and coverage aware distributed clustering protocol (ECDC) protocol. ECDC [91] is a routing protocol that combines the utilization of sensor node energy for network lifetime enhancement with coverage preservation to ensure the quality of service in the network. Relevant coverage importance metrics are designed and incorporated in the clustering algorithm for various applications. The algorithm breaks down the network into cluster head, cluster member and plain node. Selection of a cluster head is based on the remaining energy and coverage of a sensor node, which results in even cluster sizes. Cluster heads and data forwarders are selected from reliable nodes with high levels of energy and coverage importance that is smaller. Data aggregation is performed by cluster heads from its members and returned to the nodes in the next hop on the created routing tree. The phase of data transmission should be made longer than the phase of setting up to minimize protocol overhead and extend the lifetime of the network.

2.4.4.2. An energy efficient multilevel heterogeneous routing (EEMHR) protocol. In EEMHR [92], to conserve energy, sensor nodes are divided into *m* level normal nodes and *m* level advanced nodes. *m* denotes the energy level. A higher value of m indicates a higher energy level. All sensor nodes are initially categorized into level-1 normal nodes and level-1 advanced nodes. The categorized nodes are further divided into level-2 normal nodes and level-2 advanced nodes respectively. The division carries on until eventually level-k-1 nodes are produced from level-k normal nodes and level-k advanced nodes. Nodes having the highest energy being level-k advanced nodes are thus selected as a cluster head. Energy hole forming is avoided in EEMHR by using weighted selection probabilities when choosing cluster heads. Experimental investigations of EEMHR was performed under five different lifetime definitions on three different network sizes with two different initial energy levels and based on the number of nodes alive. EEMHR is more stable and energy efficient compared to other heterogeneous routing protocols.

2.4.4.3. A lifetime extended multi-levels heterogeneous routing (LE-MHR) protocol [93]. LE-MHR is an improvement of EEMHR [136]. Instead of boosting the initial energy of a network by selecting k-levels of vertical energy heterogeneity as it is the case in EEMHR, LE-MHR chooses to improve network lifetime by selecting *m* levels of horizontal energy heterogeneity. The amount of initial energy for each level is different, so the total initial energy of the network is improved. The network lifetime in EEMHR is almost doubled in LE-MHR.

Cost, Sensing, and transmission range heterogeneity: Heterogeneity of the protocols are based on the different costs, sensing distance, and transmission distance.

2.4.4.4. Coverage sink location and routing problem (CSLRP) protocol [94]. CSLRP has been developed to address issues of sensor field coverage, data routing and sink identification or position. For M set of sensor node types with different sensor coverage cost, their sensing and transmission ranges are also different. A mixed integer linear program monitors the total routing energy dissipated on the arcs. A second linear program is responsible for reducing the total routing energy involved in the transmission from the sensor node to the sink. CSLRP is suitable for small sensor networks consisting of less than fifty sensor nodes.

2.4.5. Routing protocols for mobile heterogeneous wireless sensor networks

Energy Heterogeneity: These are routing protocols for mobile sensor networks, whose heterogeneity is based on the sensor nodes energy.

2.4.5.1. Hierarchical adaptive and reliable routing (HARP) protocol. Management of node mobility and efficient tolerance to link failures is found in HARP, where the organization of nodes is realized by directly building hierarchical trees. Improved reliability and network scalability are provided by supporting more than a single node. In HARP [86], nodes are divided into ordinary nodes and cluster nodes depending on the abilities of their remaining energy. The remaining energy of the nodes determines the selection of the cluster heads with the intention to form a hierarchical tree in both the intracluster and intercluster layers. A cluster head is elected as root from a hierarchical tree built from normal nodes by the intra-cluster layer, while the sink node as a root built by inter-cluster layer from cluster heads. MATLAB simulations were performed based on energy consumption, stable region and useful network lifetime to evaluate the performance of the routing protocol against that of LEACH and Stable Election Protocol (SEP). HARP performed much better than the two routing protocols, demonstrating stable and efficient characteristics of tree structures and clusters in the whole network process.

2.4.5.2. A routing algorithm for heterogeneous mobile network (RAHMoN) protocol [96]. Here all sensor nodes are divided into static and mobile, and the energy of the static nodes is low when compared to that of the mobile nodes. Cluster heads or sink nodes are made from mobile nodes having different mobility models. They are responsible for configuring the network, identifying and selecting cluster heads and delivering data to the sink node. In consideration of transmitted data packets and overhead messages, RAHMoN indicates high energy efficiency [28]. Energy, Transmission Range, and Data Rate Heterogeneity: In this mobile wireless sensor networks heterogeneity is based on sensor node energy, transmission distance, and data rate.

2.4.5.3. A clustered heterogeneous sensor network (HSN) protocol. Depending on energy levels of the nodes in the network, three classes of nodes are found in HSN [97]. These are HIGH energy level (H-nodes), Low energy level (L- NODES) and the sink node with infinite energy. Longer communication distances and higher rates of data are realized H-nodes. HSN has a fixed cluster head that transmits data in a single hop. Optimization of the sink’s motion trajectory between cluster heads is achieved by utilizing particle swarm optimization, qualifying it for application in large scale WSNs.

2.5. Analytical comparison of routing protocols in WSNs

In Table 3 through Table 10, we show the main characteristics of the different routing protocols. The classification is for both Homogenous and Heterogeneous routing protocols. The tables show all the classifications of the reviewed routing protocols. We further described each routing protocols based on energy efficiency, network structure, location awareness, route selection, data aggregation. Furthermore, we pointed out the way each protocol addresses or responds to events as either query based or on-demand, as well as the environment where the protocols were simulated and compared.

2.5.1. Analysis and comparison of homogeneous data-centric communication protocols

Most, if not all of the routing protocols in this class are query based, which makes them less favorable for real-time applications like monitoring and surveillance. Their route selection is mostly reactive, indicating that even though they save energy and avoid data redundancy and congestion at the destination, they can also contribute to delays in delivery of data at the destination. GBR and ACQUIRE demonstrate a

Table 3
Homogeneous data-centric communication protocols.

Routing Algorithms	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
F&G [37, 38]	Data-centric	↑	↑	Reactive	↓	→	NS-2
SPIN [39]	〃	↑	↑	Proactive	↓	↓	NS-2
DD [40, 41]	〃	↑	↑	Reactive	↓	↓	NS-2
GBR [1]	〃	↑	↑	Hybrid	↓	→	Not stated
EAR [42]	〃	↓	↑	Reactive	↑	↑	OPNET
RR [1, 43, 44]	〃	↑	↑	Reactive	↓	↓	LecsSim
CADR [45]	〃	↑	↑	Reactive	↓	↓	Math. Model
ACQUIRE [46]	〃	↑	↑	Hybrid	↓	→	Math. Model
COUGAR [47]	〃	↑	↑	Reactive	↓	↓	Not stated
EAD [48]	〃	↑	↑	Reactive	↓	→	NS-2
Mcfa [49]	〃	↓	↑	Reactive	↓	↓	Not stated

Where “↓” represents No or Low, “↑” represents yes or Very high and “→” represents High or Medium.

routing selection characteristic that is hybrid and can be well suited for many applications that demand continuous flow of information or information that can be collected when needed. EAR, as an energy aware routing protocol shows that it can deliver more packets to the sink as opposed to the energy dissipated by the nodes, hence demonstrating high throughput. However, since it is reactive route selection, it may also not be well suited for monitoring and surveillance applications.

2.5.2. Analysis and comparison of homogeneous hierarchical communication protocols

Table 4 shows hierarchical routing protocols, in which APTEEN demonstrates better usage of energy in the network. APTEEN having the characteristics of both proactive and reactive route selection, it is suitable for both real-time applications and those that are event based. It, however, is not applicable to query-based applications and may contribute control overheads since it is not location aware (see Table 5).

2.5.3. Analysis and comparison of homogeneous location based communication protocols

Many routing protocols in the location-based category are location aware and query based. This means that fewer control packets will be added to the data that is transmitted and that most of them are suitable for applications that are based on events. Most of the protocols are also reactive in their routing selection, making them appropriate for on-demand applications. EAGRP and LUCA demonstrate better use of energy in the network, which translates to high throughput. Unlike EAGRP that is reactive, LUCA with hybrid routing selection characteristic will be more suited for event-based applications and real-time applications. However, the simulation environment in LUCA was not stated. This makes very difficult to compare its performance with that of other routing protocols.

2.5.4. Analysis and comparison of homogeneous NF & QoS -aware communication protocols in WSNs

The route selection in network flow and QoS aware routing protocols is mostly hybrid as shown in Table 6. This makes the routing protocols to be implemented in various applications as opposed to one. The only protocol that is reactive in this class is AODV, which shows that it saves energy by setting up routes only when needed. It is also suitable for query-based applications, but since it is not location aware and lacks data

Table 4
Homogeneous hierarchical communication protocols in WSNs.

Communication Protocols	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
LEACH [50]/LEACH-C/LEACH-MF/MODLEACH [51]	Hierarchical	↑	↓	Proactive	↓	→	MATLAB
PEGASIS [52]	〃	↑	↓	Hybrid	↓	→	Not stated
SOP [53]	〃	↓	↓	Proactive	↓	↓	Not stated
TEEN [1, 54, 55]	〃	↑	↓	Reactive	↓	→	NS-2
APTEEN [55]	〃	↑	↓	Hybrid	↓	↑	NS-2
HEED [56]	〃	↑	↓	Hybrid	↓	→	Not stated
EAR-CSN [57]	〃	↑	↓	Hybrid	↑	→	Math-model
BCEE [58]	〃	↑	↓	Hybrid	↓	→	MATLAB
CEBRCA [59]	〃	↑	↑	Proactive	↓	→	MATLAB
HERO [60, 61]	〃	↑	↑	Reactive	↓		COOJA
ECPF [62]	〃	↑	↑	Reactive	↓	→	MATLAB
FSC [63]	〃	↑	↑	Proactive	↓	↓	MATLAB
NEECP [64]	〃	↑	↓	Proactive	↓	→	NS-2

Table 5
Homogeneous location based communication protocols in WSNs.

Communication Protocols	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
GAF [65]	Location Based	↓	↓	Hybrid	↑	↓	Testbed
GEAR [66]	〃	↓	↓	Reactive	↑	→	NS-2
MECN [67]	〃	↓	↓	Reactive	↑	↓	OPNET
SMECN [67]	〃	↓	↓	Reactive	↑	↓	NS-2
TBF [68]	〃	↑	↑	Reactive	↓	→	NS-2
EAGRP [69]	〃	↑	↓	Reactive	↑	→	NS-2
Span [70, 71]	〃	↑	↓	Reactive	↑	↓	Not stated
BVGF [72]	〃	↓	↓	Reactive	↑	↓	Not stated
GeRaF [73]	〃	↓	↑	Reactive	↓	↓	Not stated
LUCA [74, 75]	〃	↑	↓	Hybrid	↑	→	Not stated

Table 6
Homogeneous NF & QoS -aware communication protocols IN WSNs.

Communication Protocols	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
MLDG [76]	*NF & QoS*	↑	↓	Proactive	↑	→	Not stated
SAR [77]	〃	↑	↑	Hybrid	↓	↓	Parsec
MLER [78]	〃	↓	↓	Hybrid	↓	→	C-Lang
SPEED [79]	〃	↓	↑	Hybrid	↓	↓	GloMoSim
EAQSR [1]	〃	↓	↑	Hybrid	↑	→	Math. Model
MCBR [80]	〃	↓	↓	Hybrid	↓	→	RMASE
AODV [81]	〃	↓	↑	Reactive	↓	↓	Parsec
Smart Routing with Learning-based QoS aware meta-strategies [82]	〃	↑	↓	Hybrid	↓	↓	RMASE

aggregation, it adds more control overheads to the transmitted data and delivers fewer data packets to the destination as opposed to energy dissipated by sensor nodes; hence it has low efficiency in energy. MLER and EAQSR demonstrate better energy efficiency as they set-up routes in a hybrid manner.

2.5.5. *Analysis and comparison of static homogeneous routing protocols in WSNs: nature inspired routing protocols*

Static homogeneous routing protocols include nature-inspired, cross-layer, opportunistic and cooperative routing protocols. Nature inspired routing protocols can also fall under data-centric, hierarchical, location-based and network flow and QoS aware category of routing protocols. The design of these protocols was inspired by the natural behavior of some organisms which demonstrated attractive properties of self-organization and administration without any common coordination. Many protocols are found in the nature-inspired routing protocols category. Most of them are energy efficient like CRP, IEEABR, Beesensor-C, EAQR, BIOSARP, and others. These protocols, except Beesensor-C, though energy efficient are likely to increase control overheads by using control packets to update paths that may not be needed when establishing routes because they are proactive. They are also not well suited for query-based applications, are not location aware and lack data aggregation, which may impact their energy efficiency. BIOSARP, although it has data aggregation cannot be easily compared to other routing protocols because its simulation environment has not been stated. We also find in this category, routing protocols that combine both the reactive and proactive nature of setting up routes and demonstrate a medium or moderate use of energy such as SC, MSRP, ACLR, ACOLBR, and AntSenseNet. Although they are suitable for applications that are both event-based and real-time, they cannot be applied for query-based applications. ACOLBR and AntSenseNet have data aggregation enabling them to reduce the amount of data delivered to the destination, hence avoiding data redundancy and congestion. Generally, most routing protocols in this class lack location awareness and are not query based, but also most of them show a moderate to high level of energy efficiency (see Tables 7, 8, 9, 10 and 11).

2.5.6. *Analysis and comparison of Static Homogeneous Communication Protocols in WSNs: cross-layer, opportunistic and cooperative routing protocols*

Almost all routing protocols in these classifications have data aggregation but lack location awareness and querying. Cross-layer routing protocols use different parameters of the network layer jointly to obtain improved network performance and enhance network lifetime. JRPA and CLOD can control congestion at the destination node because as hybrid route selecting routing protocols, they possess qualities of both reactive and proactive route selection and also have data aggregation. CLOD, however, is not suitable for large scale sensor networks due to the reduction of complexities in processing data. Opportunistic routing in its goal to reduce unwanted retransmission of data and unreliable link failures in the network uses many forwarders, utilizing the broadcasting nature of wireless sensor networks to improve energy efficiency. This is confirmed by the medium to high network throughput shown by most opportunistic routing protocols like EEOR, E^2R, and K-S. EEOR uses a forwarder list to reduce the cost of energy but is suitable for unicast applications only. However, since E^2R routing protocol is not query-based and can also be used in a mobile environment, it is applicable to large scale wireless sensor networks. Due to their concept of space diversity in Cooperative routing protocols, many nodes shares resources by creating an ideal Multiple-Input-Multiple-Output (MIMO) system, that possess data aggregation and improve the capacity and quality of transmission. *Mp-MILP* demonstrates moderate to high energy efficiency due to the high reliability of the wireless sensor network contributed by the data aggregation and hybrid nature of the routing selection.

2.5.7. *Analysis and comparison of mobile homogeneous communication protocols in WSNs*

Many routing protocols in this class have data aggregation and they are query based and location-aware. This is because the sink node(s) is mobile and hence the network is more scalable and flexible. Termite Hill, TARS, MobiCluster, and W-L routing protocols show improved energy efficiency (successful delivery of data at the sink node with the amount of energy consumed in the network). This confirms the energy consumption balance that mobile sinks bring to wireless sensor networks. The simulation environment for other routing protocols that performed well under this classification was not specifically stated, leaving Termite Hill to be the only one analyzed by a specific simulation environment, hence making it easier to compare it with other routing protocols.

2.5.8. *Analysis and comparison of static heterogeneous communication protocols in WSNs*

Most of the protocols in this classification have data aggregation as most of them are cluster based. Since ECDC, EEMHR, and LE-EMHR are based on energy heterogeneity, they demonstrate a high level of energy efficiency. This is because they use single hop intra-clustering and multi-hop inter-clustering routing. The energy efficiency for CSLRP is slightly lower because its heterogeneity is based on cost detection and propagation range which makes it complex and can only apply to smaller network sizes.

2.5.9. *Analysis and comparison of mobile heterogeneous communication protocols in WSNs*

Protocols in this classification are more energy efficient to avoid energy holes and balancing energy consumption among nodes in the network. HARP achieves this energy efficiency by using multi-hop data communication and is well suited for reliable wireless sensor networks. RAHMoN, also based on energy heterogeneity uses multi-hop data communication and has a mobile sink and cluster heads as mobile elements. HSN with a mobile sink uses single-hop communication and is suitable for large scale networks.

2.6. *Experimental comparison of nature inspired and conventional routing protocols*

2.6.1. *Experimental parameters*

For the simulation experiment, we adopted a well-known simulation

Table 7
Static homogeneous communication protocols in WSNs.

Communication Protocols	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
PSO [89, 90]	Nature inspired	↑	↓	Proactive	↓	↓	Not stated
PEADD [91]	〃	↑	↑	Reactive	↓	↓	NS-2
CRP [92]	〃	↓	↓	Proactive	↓	↑	NS-2
SC [93]	〃	↓	↓	Hybrid	↓	→	RMASE
SDG [94]	〃	↑	↓	Proactive	↓	↑	NS-2
EBAB [95]	〃	↑	↓	Proactive	↓	→	Not stated
ACO [96, 97]	〃	↑	↓	Proactive	↓	↑	MATLAB
ACO-C [98]							
ACALEACH [99]	〃	↑	↓	Proactive	↓	↑	MATLAB
MACS [100]	〃	↓	↓	Proactive	↓	→	NS-2
AntChain [101]	〃	↑	↑	Reactive	↑	→	NS-2
PZSWiD [102]	〃	↑	↑	Reactive	↓	↑	NS-2
ACMRA [103]	〃	↓	↓	Reactive	↓	→	Not stated
ACMT [113]	〃	↓	↓	Reactive	↓	↓	Not stated
ACLR [104]	〃	↓	↓	Hybrid	↑	→	OPNET
MSRP [105]	〃	↓	↓	Hybrid	↓	→	OMNET ++
Communication Protocols	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
JARA [106]	Nature inspired	↓	↓	Hybrid	↓	↓	Not Stated
ACOLBR [107]	〃	↑	↓	Hybrid	↓	→	NS-2
EEABR [108]	〃	↓	↓	Proactive	↓	↑	NS-2
IEEABR [109]	〃	↓	↓	Proactive	↓	↑	RMASE
FF [110]	〃	↓	↓	Hybrid	↓	↓	RMASE
FP [110]	〃	↓	↓	Hybrid	↓	↓	RMASE
E-D ANTS [111]	〃	↓	↓	Proactive	↓	→	OPNET
AR and IAR [112]	〃	↓	↓	Proactive	↓	→	Java
Beesensor [13]	〃	↓	↓	Reactive	↓	↑	RMASE
Beesensor-C [113]	〃	↓	↓	Reactive	↓	↑	RMASE
iACO [114]	〃	↓	↓	Proactive	↓	→	Castalia
ACO-QoSR [115]	〃	↓	↓	Reactive	↓	→	NS-2
MO-IAR [116]	〃	↓	↓	Proactive	↓	→	Java
Ant-aggregation [117]	〃	↑	↓	Proactive	↓	→	MATLAB
ASAR [118]	〃	↓	↓	Proactive	↓	→	NS-2
BABR [11]	〃	↓	↓	Proactive	↓	↓	RMASE
AC0-EAMRA [92]	Nature inspired	↓	↓	Proactive	↓	→	Not stated
EAQR [120]	〃	↓	↓	Proactive	↓	↑	NS-2
IACR [121]	〃	↑	↑	Proactive	↓	→	OMNET ++
QDV [122]	〃	↓	↓	Reactive	↓	→	GloMoSim
AntSenseNet [123]	〃	↑	↓	Hybrid	↓	→	NS-2
BIOSARP [124]	〃	↑	↓	Proactive	↓	↑	Not stated
Bat Algorithm [15]	〃	↑	↓	Proactive	↓	→	MATLAB
Communication Protocols	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
JRPA [125]	Cross-layer	↑	↓	Hybrid	↓	→	Not stated
LMCRTA [136]	〃	↑	↓	Proactive	↓	→	〃
CLOD [126]	〃	↑	↓	Hybrid	↓	→	〃
ExOR [127]	Opportunistic	↑	↓	Proactive	↓	↓	〃
MORE [128]	〃	↑	↓	〃	↓	↓	〃
EEOR [129]	〃	↑	↑	Multipath	↓	→	〃
E^2R [130]	〃	↑	↓	〃	↓	→	〃
K-S [131]	〃	↑	↓	Single path/Multipath	↓	→	〃
RBCR [132]	Cooperative	↑	↓	Hybrid	↓	↓	〃
EBCR [133]	〃	↑	↓	〃	↓	↓	〃
mp-MILP [134]	〃	↑	↓	〃	↓	→	〃

environment known as RMASE, which stands for Routing Modeling Application Simulation Environment [106], which is an application that is built on top of (Prowler); referred to as Probabilistic Wireless Network Simulator [107, 167]. The simulator was built to run under the Matlab environment, which in turns provides a fast and easy way to prototype applications also of having nice visualization for experiments run under it for the case of comparison.

2.6.2. Performance metrics

Among the several results obtained during the simulation process, we have reported on few but important metrics to fully describe the performance of the routing protocols such as:

1. Latency
2. Success rate
3. Energy consumption and
4. Energy efficiency, which is:

$$Energy\ efficiency = \left(\frac{Success\ rate*Total\ packet\ sent\ to\ the\ sink}{Total\ energy\ consumed}\right)$$

2.6.3. Simulation results

We run simulation for different routing protocols. We have compared eleven (11) routing protocols using different metrics for ease of reporting. Therefore, for evaluation purpose, we compared Termite-hill, Beesensor, BABR, AODV, EEABR, MCBR-AST, SC, MCBR-RTSR, FF, MCBR-CFR and FP using the metrics defined in sub-section 2.6.2. The results are shown in Table 12 through 22, and Fig. 31 through Fig. 34. For the cases of results presented in Fig. 31 through Fig. 34, we considered two cases: Case 1 for sink mobility with static sensor nodes in the network, and case 2, for static sink node and mobile sensor nodes in the network.

Table 8

Mobile homogeneous communication protocols in WSNs.

Communication Protocols	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
Termite Hill [4, 135, 136]	One mobile sink	↓	↓	Reactive	↑	↑	RMASE
LURP/ALURP [137]	〃	↓	↓	Geographic routing (global) + Topology based routing (local)	↑	→	Not stated
DDRP [138]	〃	↓	↓	Reactive	↓	→	〃
WARP [139]	〃	↓	↓	Shortest path routing + speculative routing	↓	→	〃
λ-Flooding [140]	〃	↓	↓	Approximate shortest path routing	↓	→	〃
PredQoSR [141]	〃	↓	↓	Information potential based routing + mobility prediction	↓	→	〃
TARS [142]	Mobile sink and source	↑	↓	Reactive	↑	↑	〃
MobiCluster [143]	Multiple mobile sinks	↑	↓	Proactive	↑	↑	〃
W-L [144]	〃	↓	↓	Proactive	↑	↑	〃
ER [145]	〃	↓	↓	Geographic routing	↑	→	〃
AVRP [146]	〃	↓	↓	Shortest path routing	↓	→	〃
MDRP [147]	〃	↓	↓	Shortest path routing	↓	→	〃
Dream [148], [149]	〃	↓	↓	Proactive	↑	→	〃

Table 9

Static heterogeneous communication protocols in WSNs.

Communication Protocols	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
ECDC [83]	Energy Heterogeneity	↑	↓	Proactive	↓	→	Not stated
EEMHR [92]	〃	↑	↓	〃	↓	→	〃
LE-MHR [84]	〃	↑	↓	〃	↓	→	〃
CSLRP [85]	Cost, Detection and Propagation range heterogeneity.	↑	↓	〃	↓	↓	〃

Table 10

Mobile heterogeneous communication protocols in WSNs.

Communication Protocols	Category	D - A	QB	Route Selection	L - A	Energy Efficiency	Simulation Environment
HARP [86]	Energy Heterogeneity	↓	↓	Proactive	↑	→	Not stated
RAHMoN [87]	〃	↓	↓	〃	↑	→	〃
HSN [88]	Energy, Propagation range and data rate heterogeneity	↓	↓	〃	↑	→	〃

2.6.3.1. Case 1: sink mobility with static sensor nodes. From Figs. 13 and 14, we assumed that the network has one end node (sink), which is a mobile node having the sink node to move around the network along the border of the area of interest in the network (monitored area). In terms of Throughput (number of packets or events that were successfully delivered per unit time), it is observed that both protocols have a maximum success rate at the initial level (at the speed of 10 m/s) as shown in Fig. 31. The success rate slightly dropped when the speed increases to 20 m/s. It then remains almost constant after the 20 m/s. This shows that, even if the speed of the sink increases beyond 20 m/s for 100 nodes in the network, the success rate was seen not to be greatly affected. In Fig. 32, which is a mobility scenario with an increase in node speed, it is observed that the energy efficiency of the network increases as well. The energy efficiency of the network for the two (2) routing protocols tends to increase rapidly for both protocols with an increase in speed of the sink node. The network also experiences low energy consumption of the nodes, which directly influence the energy efficiency of the entire network. This is to say that, with data collection node (sink node) mobility in the network, that is the sink node moving around the area of interest (monitored area), which shorten the number of hops of the event or data in the network, reduced the energy consumption of the network's nodes participating in the routing process in the network.

Table 11

Simulation parameters.

Parameters	Values
Routing Protocols	Termite-hill, AODV, MCBR, EEABR, SC, FF, FP, Beesensor, and BABR.
X_dist, Y_dist	1, 1
Number of Nodes	9, and 100
Source type, center type, radius, rate, Random rate	Static and mobile, random, 1, 4, 0
Destination type, center type, radius, rate, random rate	Static and mobile, random, 1, 0.5, 0
Maximum Hops	Infinity
Data Traffic	Constant Bit Rate (CBR)
Data rate	250 Kbps
Simulation Time	360 Sec.
Energy Consumption	Waspmote-802.15.4

2.6.3.2. Case 2: static sink with mobile sensor nodes. Fig. 33 presents the packet success rate ratio concerning a different number of nodes having a fixed speed of 10 m/s (mobile sensor nodes). From the simulation result, it is evident that nature inspired species-based routing protocol (termite-hill) attained a high percentage success rate as compared to conventional based routing protocol (AODV). Though both protocols have high packet delivery ratio. With reason been that, they both use recovery strategies during communication phase and are both reactive in the sense that, they are on-demand protocols, and only forward packets when there is a need to forward.

Fig. 34 presents the effect of increased speed of sensor nodes on percentage success rate in a network. From the results, it is observed that the percentage success rate of the routing protocols decreases when the node's mobility is increased. However, nature-inspired species-based protocol (termite-hill) provide better percentage success rate when compared to conventional based routing protocol (AODV). It is evident from the result that Termite-hill with better recovery strategy provides the highest delivery ratio.

In Table 23, we have shown the summary of comparison of results of

Table 12
Simulation results based comparison for IEEABR protocol.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ-Rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	3.12	358.12	88.8890	200.64	24.11	36	1594.90
20	3.227	364.39	90.7890	370.24	51.05	76	1863.65
30	3.17	373.22	93.1030	525.44	79.10	116	2055.41
40	3.20	369.82	92.3080	691.52	105.31	156	2082.38
50	3.17	369.87	92.3470	859.36	131.86	196	2106.22
60	3.15	369.88	92.3730	1011.04	159.23	236	2156.20
70	3.19	369.9	92.3910	1180.64	186.16	276	2159.84
80	3.18	369.91	92.4050	1348.48	212.71	316	2165.40
90	3.16	369.93	92.4160	1500.16	240.09	356	2193.11
100	3.15	369.94	92.4240	1666.24	266.24	396	2196.56

Table 13
Simulation results based comparison for EEABR protocol.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ-Rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	3.80	125.19	30.5560	118.72	11.80	36	926.56
20	3.27	212.98	52.6320	274.24	43.89	76	1458.59
30	3.19	236.25	58.6210	423.52	74.93	116	1605.60
40	3.17	250.13	62.1790	573.28	106.13	156	1692.00
50	3.15	260.34	64.7960	730.56	138.80	196	1738.39
60	3.14	263.69	65.6780	881.28	170.16	236	1758.81
70	3.14	267.48	66.6670	1036.80	202.50	276	1774.70
80	3.14	270.37	67.4050	1192.32	234.84	316	1786.43
90	3.14	272.58	67.9780	1343.36	266.26	356	1801.47
100	3.13	275.34	68.6870	1494.88	297.82	396	1819.55

Table 14
Simulation results based comparison for flooded forward ant routing protocol.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ-Rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	10.30	101.78	25.0000	343.20	14.64	36	262.24
20	6.83	233.48	57.8950	643.20	38.16	76	684.08
30	6.12	270.44	67.2410	849.60	64.88	116	918.07
40	5.64	288.12	71.7950	1029.60	92.18	156	1087.80
50	5.51	308.94	77.0410	1188.00	120.15	196	1271.05
60	5.62	314.23	78.3900	1413.60	147.50	236	1308.72
70	5.48	323.77	80.7970	1567.20	176.33	276	1422.92
80	5.47	325.96	81.3290	1766.40	204.53	316	1454.93
90	5.46	330.81	82.5840	1929.60	232.83	356	1523.63
100	5.42	332.85	83.0810	2085.60	261.33	396	1577.49

Table 15
Simulation results based comparison for flooded piggybacked ant routing protocol.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ-Rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	3.57	401.24	100.0000	530.24	17.04	36	678.94
20	3.42	400.59	100.0000	1096.96	36.63	76	692.82
30	3.38	400.4	100.0000	1663.52	56.17	116	697.32
40	3.40	400.3	100.0000	2230.40	75.72	156	699.43
50	3.35	400.23	100.0000	2796.32	95.28	196	700.92
60	3.34	400.19	100.0000	3362.40	114.86	236	701.88
70	3.36	400.17	100.0000	3928.00	134.41	276	702.65
80	3.35	400.14	100.0000	4495.04	154.03	316	703.00
90	3.33	400.12	100.0000	5061.92	173.58	356	703.29
100	3.33	400.12	100.0000	5630.24	193.20	396	703.34

Table 16
Simulation results based comparison for beesensor routing protocol.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ-Rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	9.30	357.23	88.89.00	81.28	17.53	36	3937.06
20	5.87	374.50	93.00.00	146.88	37.58	76	4812.09
30	7.55	368.19	93.10.30	300.16	55.35	116	3598.06
40	9.27	372.19	92.94.90	539.84	71.54	156	2685.99
50	11.03	371.72	93.36.70	822.72	86.11	196	2224.32
60	10.91	374.83	93.64.40	1008.32	104.01	236	2191.76
70	12.47	352.21	88.40.60	1283.20	118.56	276	1901.50
80	12.56	359.69	89.87.30	1534.40	136.13	316	1850.88
90	12.64	364.15	91.01.10	1750.40	152.67	356	1851.00
100	12.29	363.79	90.90.90	1896.96	170.42	396	1897.77

Table 17

Simulation results based comparison for babr protocol.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ-rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	15.33	56.45	13.8890	268.80	13.86	36	186.01
20	12.01	164.13	40.7890	626.40	46.36	76	494.89
30	8.97	235.38	58.6210	844.80	81.30	116	804.93
40	8.22	267.66	66.6670	1070.40	116.64	156	971.60
50	7.87	282.29	70.4080	1272.00	153.83	196	1084.90
60	7.60	293.79	73.3050	1483.20	193.28	236	1166.40
70	7.39	301.95	75.3620	1694.40	231.29	276	1227.57
80	7.24	303.08	75.6330	1879.20	268.82	316	1271.82
90	7.16	309.37	77.2470	2076.00	306.46	356	1324.66
100	7.04	316.52	79.0400	2265.60	343.90	396	1381.53

Table 18

Simulation results based comparison for AODV routing RPOTOCOL.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ-rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	3.52	169.41	41.67	272.05	50.33	36	1176.27
20	3.24	180.32	44.74	537.49	105.58	76	1315.00
30	3.25	175.47	41.38	837.65	167.99	116	1289.32
40	3.27	175.01	43.59	1133.33	229.51	156	1279.42
50	3.31	167.50	41.33	1442.45	293.75	196	1268.67
60	3.31	159.71	39.83	1738.13	355.25	236	1271.48
70	3.31	159.76	39.86	2037.17	417.46	276	1197.74
80	3.31	154.71	38.61	2382.13	489.18	316	1192.20
90	3.31	151.23	37.64	2699.09	555.07	356	1200.40
100	3.28	152.65	38.01	2946.61	606.57	396	1221.74

Table 19

Simulation results based comparison for adaptive spanning tree routing protocol.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ-rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	3.07	369.58	91.67	247.20	35.47	36	1294.51
20	3.08	369.84	92.11	468.00	73.70	76	1510.26
30	3.10	376.82	93.97	667.20	113.19	116	1618.70
40	3.09	380.18	94.87	856.80	152.57	156	1692.35
50	3.08	382.18	95.41	1046.40	191.96	196	1748.85
60	3.08	378.43	94.49	1228.80	229.88	236	1798.50
70	3.07	380.11	94.93	1418.40	269.28	276	1720.25
80	3.08	380.09	94.94	1605.60	308.20	316	1768.80
90	3.08	382.33	95.51	1797.60	348.10	356	1802.40
100	3.08	380.07	94.95	1980.00	386.04	396	1818.18

Table 20

Simulation results based comparison for real-time search communication protocol.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ- Rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	3.05	385.90	94.44	237.60	34.07	36	1346.82
20	3.06	377.47	93.42	432.00	72.64	76	1636.11
30	3.06	381.83	94.83	633.60	112.59	116	1704.54
40	3.06	383.92	95.51	842.80	152.19	156	1720.46
50	3.06	381.06	94.90	1041.60	190.99	196	1756.91
60	3.06	384.30	95.76	1243.20	230.97	236	1777.67
70	3.07	380.74	94.93	1454.40	269.76	276	1677.67
80	3.07	379.39	94.62	1663.20	309.31	316	1707.54
90	3.07	380.59	94.94	1874.40	348.78	356	1728.55
100	3.07	382.55	95.46	2078.40	389.29	396	1732.10

Table 21

Simulation results based comparison for constrained flooding routing protocol.

Simul. Time (s)	Delay (/100)	Throughput (/100)	Succ-rate (%)	Energy Dissipation (/100)	STD. DEV (/100)	No. Packets	EE (/100)
10	21.86	368.16	91.67	729.60	6.95	36	438.60
20	21.87	385.77	96.05	1548.00	8.62	76	456.59
30	21.85	383.74	95.69	2316.00	11.47	116	466.32
40	21.77	383.22	95.51	3079.20	16.16	156	470.90
50	21.69	379.93	94.90	3825.60	21.30	196	478.35
60	21.49	380.18	94.92	4581.60	26.59	236	482.36
70	21.51	381.31	95.29	5361.60	31.45	276	455.09
80	21.52	381.43	95.25	6141.60	36.40	316	462.42
90	21.56	382.36	95.51	6936.00	40.31	356	467.13
100	21.42	381.02	95.20	7696.80	44.87	396	467.73

Table 22
Simulation results based comparison for communication algorithms based on different metrics.

Communication Algorithms	Delay (ms)	Succ- Rate (%)	Energy Dissipation (J) (/100)	EE (/100)	STD. DEV (/100)	Lifecycle/Year
MCBR-CFR [80]	21.42	95.2000	7696.80	467.73	44.87	26099.93
SC [93]	3.13	68.6870	1494.88	1819.55	297.82	0.7270
AODV [82]	32.81	38.0100	2946.61	1221.74	606.57	0.7141
FP [110]	3.33	100.0000	5630.24	703.34	193.20	0.7173
MCBR-RTSR [80]	3.07	95.4600	2078.40	1732.10	389.29	0.72273
BABR [11]	7.04	79.0400	2265.60	1381.53	343.90	0.7234
Beesensor [13]	12.29	90.9090	1896.96	1897.77	170.42	0.7293
MCBR-AST [80]	3.08	94.9500	1980.00	1818.18	386.04	0.7231
EEABR [108]	3.15	92.4240	1666.24	2196.56	266.24	0.7274
FF [110]	5.42	83.0810	2085.60	1577.49	261.33	0.7262

Tables 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, and 22. It is the average of sets of 10 simulations performed on each protocol reported in this paper. However, from the results presented as gotten from the simulation environment (Prowler), EEABR outperforms all the protocols tested in the environment with similar conditions and metrics. The EEABR also happen to have the highest energy-efficiency, with SC protocol nodes having lesser energy consumption, though having low performance regarding energy efficiency which is due to low packet delivery. However, one can regard Beesensor as having much longer lifetime as shown in Table 23. For some applications that cannot tolerate the loss of information like security applications, one can adopt FP, though the high packet success rate is a trade-off of energy consumption by the participating nodes in the network adopting FP protocol.

3. Conclusions

3.1. Conclusions and future work directions

This paper has reviewed and compared communication protocols in wireless sensor networks with the intention to provide a background and insight into current trends in WSNs. Critical factors to be considered during the design of wireless sensor networks and routing protocols have been exhaustively investigated. The sensor nodes energy challenge in these networks has been identified and is the area of focus that this study intends to address. Existing routing protocols for wireless sensor networks have been reviewed and classified into homogeneous and heterogeneous networks, which are further divided into static homogeneous and mobile homogeneous networks as well as static heterogeneous and mobile heterogeneous networks. Categories of routing protocols that fall under homogeneous networks are location-based, data-centric, network flow and QoS aware and hierarchical routing protocols. Static homogeneous networks are further categorized into cross-layer, nature-inspired, cooperative and opportunistic routing protocols, while mobile homogeneous are classified into one mobile sink, mobile sink and source, and multiple mobile sinks. Static heterogeneous networks, on the other hand, are categorized into energy heterogeneity and cost, detection and propagation range heterogeneity, while heterogeneous mobile networks are classified into energy heterogeneity, energy, propagation range, and data rate heterogeneity. Mathematical models on energy, sensing, and the network environment are presented and analyzed to give thorough background knowledge on the wireless sensor network. Analytical comparisons for the routing protocols are presented, and eleven selected routing protocols are simulated on RMASE Prowler simulation environment. Their performance is compared, and results are as shown in Tables 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, and 22 and Figs. 31, 32, 33, and 34. Simulation results for all tested protocols indicate that Termite Hill outperformed all other routing protocols tested under the same conditions and metrics. A summary of both the analytical comparisons and the simulation results is provided. This study has thus exhaustively presented useful insight into communication protocols in a wireless sensor network.

3.2. Future work direction

New futuristic applications for WSNs are envisioned with the emergence of new routing protocols that deal with energy efficiency, storage, and memory issues. Authors in [172] consider some open challenges for application towards Big Sensor Data Systems as an application for Smart Cities, such as the Internet of People (IoP), context-aware semantic sensor networks and sensor cloud infrastructure. We broaden the discussion towards a generalized WSNs application and also emphasize on wireless energy transfer and efficient localization and mobility in WSNs. The use of wireless energy transfer is on the adoption of mechanisms such as piezoelectric principles, laser beam, radio waves, inductive coupling, and microwaves. We highlight further four potential future directions which we hope will strengthen research in the new area of applications of

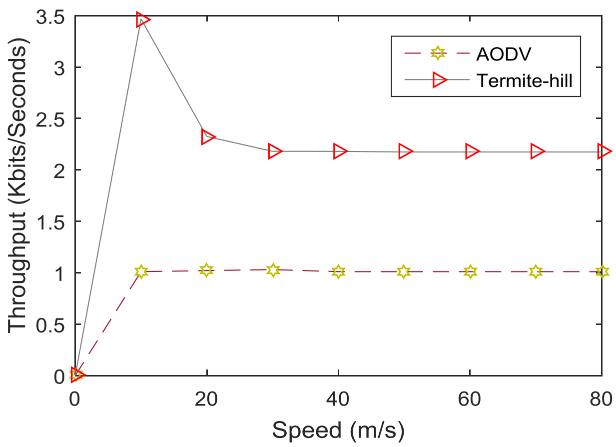


Fig. 31. Effect of varying speed on Throughput in Nature Inspired Species and Conventional based routing protocols.

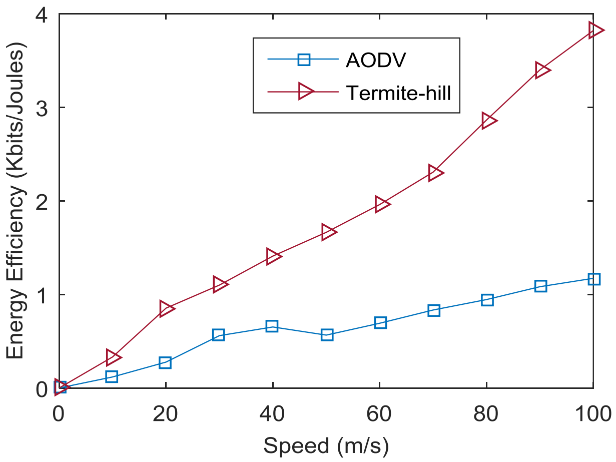


Fig. 32. Effect of varying speed on Energy Efficiency in Nature Inspired Species and Conventional based routing protocols.

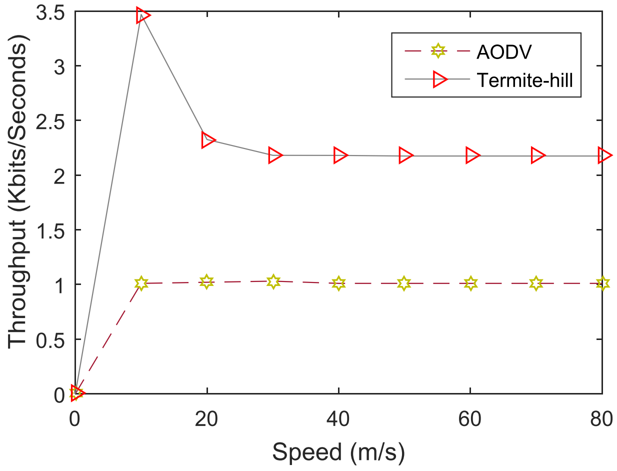


Fig. 33. Effect of increased number of nodes in a network on percentage success rate with fixed speed of 10 m/s.

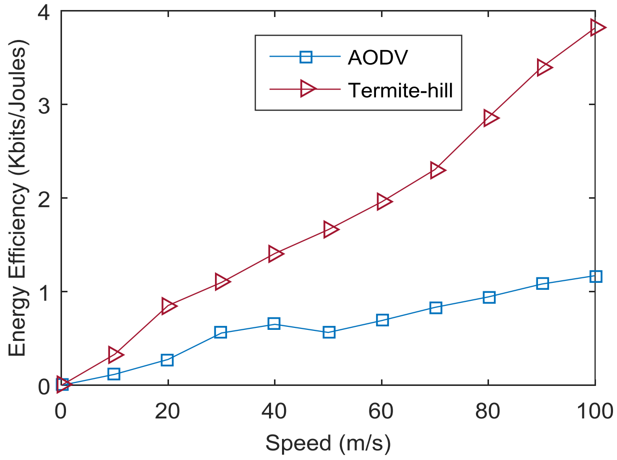


Fig. 34. Effect of increased speed of sensor nodes on percentage success rate in a network.

WSNs.

3.2.1. *Efficient localization and mobility in wireless sensor networks*

There have been efforts to improve localization in WSNs. Interferometric ranging-based localization can be considered in this area which takes error propagation into account in signal propagation. The approach tends to give precise measurements, but results reported by authors in [171] shows that error propagation can be a problem to worry about in interferometric ranging. As such, to localize large networks using this method of interferometric ranging from a small set of anchors, there is a need to develop new algorithms that will effectively limit the error propagation in WSNs. Another most important aspect of localization is the introduction of a robust algorithm for the mobile sensor network. The mobile sensor network can be in the form of the mobile sink and static sensor nodes or mobile sensor nodes and static sink. However, both the sensor nodes and sink can be mobile in the network, which each of the mobility scenarios comes with its advantages and disadvantages. Recently, researchers have been focusing on research in the use of mobility in sensor networks to assist in the initial deployment of nodes. The mobile sensor nodes can be useful in the sense that, they can move to locations that meet sensing requirement, hence guaranteeing proper sensing and coverage. Mobile nodes can also replace the dead nodes which might be because of exhaustion of their battery. It is therefore envisaged that new adaptive schemes have to be developed that will consider network dynamics, taking into consideration nodes leaving and joining clusters of sensor nodes in a network. However, more research is needed in the area to develop effective algorithms that will meet the need of different applications ranging from a query based, reactive and proactive mode of information dissemination.

3.2.2. *Wireless energy transfer*

Wireless energy transfer adopting the method of magnetic coupling is not new and have been simulated and found as a promising solution for power hungry microelectronics like the sensor nodes. Authors in [173] have proposed a promising approach which is based on cellular structure. The structure partitions the two-dimensional plane of a sensor network. It does the partitioning into adjacent hexagonal cells. They went on to pursue a formal optimization approach which considers a joint optimization of flow routing, traveling path and charging time. Their approach

Table 23
A new model for comparing routing protocols IN WSNS.

Protocol Characteristics		Routing Protocols									
		EEABR Protocol	SC Protocol	FF Protocol	FP Protocol	Beesensor Protocol	BABR Protocol	AODV Protocol	MCBR-AST Protocol	MCBR-RTSR Protocol	Termite-hill Protocol
Analytical	Classification	Nature inspired	Nature inspired	Nature inspired	Nature inspired	Nature inspired	Nature inspired	Network flow and QoS aware	Nature inspired	Nature inspired	Nature inspired
	Data Aggregation	↓	↓	↓	↓	↓	↓	↓	↑	↓	↓
	Query Based	↓	↓	↓	↓	↓	↓	↑	↓	↓	↓
	Route Selection	Proactive	Hybrid	Hybrid	Hybrid	Reactive	Proactive	Reactive	Proactive	Proactive	Reactive
	Location Awareness	↓	↓	↓	↓	↓	↓	↓	↓	↓	↑
	Energy Efficiency	↑	→	↓	↓	↑	↓	↓	↑	→	↑
	Simulation Environment	NS-2	Prowler-Rmase	Prowler-Rmase	Prowler-Rmase	Prowler-Rmase	Prowler-Rmase	Prowler-Rmase	Prowler-Rmase	Prowler-Rmase	Prowler-Rmase
Performance	Latency (ms)	320	310	540	330	1230	700	330	310	310	1206
	Throughput (/100)	369.9	275.3	332.9	400.1	363.8	316.5	152.7	380.0	382.6	807.78
	Succ-Rate	0.9242	0.6868	0.8308	1.0000	0.9090	0.7904	0.6139	0.9500	0.9550	0.9820
	Energy Dissipation (mJ)	16662	14950	20856	56302	18969	22656	29466	19800	20784	12968
	EE (/100)	2196.6	1820.0	1577.5	703.3	1897.8	1381.5	1593.5	1818.2	1732.1	2398.7
	STD. DEV (/100)	266.2	297.8	261.3	193.2	170.4	343.9	185.5	386.0	389.3	107.9

tends to probably develop an optimal solution for a certain degree of acceptable value. Currently, a popular method of wireless energy transfer is the use of magnetic induction approach. Also, authors in [36] have recently proposed a pulse power magnetic induction. Their approach also helps to deal with issues related to path loss reduction and improvements on the signal-to-noise ratio in a wireless underground sensor network. Their approach was also a promising approach to the increase in transmission range in the underground environment. This is to say that; pulse magnetic induction is a promising approach in wireless energy transfer. Other areas in the terrestrial environment using electromagnetic waves can be investigated.

3.2.3. *Security in wireless sensor networks*

Another important direction is security issues research in sensor networks. Due to the communication media, environment and nodes vulnerability in WSN, the WSN are more susceptible to security breaches known as attacks [174] to [175]. Security attacks can be active, which adversary tries to modify, fabricate the nodes and data content, which in turn leave traces in the network and hence can be detected or passive. However, these attackers, adversary eavesdrops the communications in the network, and based on these communications, active attacks can be launched. The other attacks in WSN are Node based attacks which deal with the maneuvering of nodes, with which the nodes tend to compromise their behavior and do node replication. Another attack is Message and network-based attacks, which deals with a replay of messages and attacks during routing and time synchronization. These attacks can be overcome by encryption, authentication, trust setup, key establishment, group management, security routing.

3.2.4. *Internet of People in wireless sensor networks*

Authors in [176] proposed Internet of People (IoP) an idea that promotes usage of smartphones gaining knowledge of a human being in its possession. This idea aims to make a strong link between the Internet of Things (IoT) and human beings. This will empower human beings to cooperatively act as human sensors as well as smart data processors for tasks that may be complicated. Mobile crowdsourcing is one technique that utilizes mobile phones to assign human beings to process data. Human processors can thus be assigned in wireless sensor networks in cases of disaster management to gather data from different affected locations to gather real-time data of different forms and report back to relevant points that will respond accordingly or appropriately in real time to solve real-life problems. Automated systems can also use IoP as a quality assurance measure, where human processors can be used to set performance standards from a random selection of automated categorization systems to confirm proper adherence to the system specifications. IoP can thus be exhaustively harnessed for various applications in wireless sensor networks.

Declarations

Author contribution statement

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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