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Power Saving Protocols in Wireless Networks

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Abstract

Most mobile devices in wireless networks have limited energy storage capability. Similar limitations can apply to fixed devices found in sensor networks and in the longer haul relay stations in rural networks. Despite this, there appears to have been only a modest amount of research conducted on routing strategies which take into account energy. Current research on battery technologies shows that only small improvements in the battery capacity are expected in the near future. Thus, in order to make the wireless networks (especially rapidly deployed networks) available commercially, we need to reduce the energy consumption in wireless devices. There are two main approaches to the problem. The first approach is to reduce the energy consumption of electronic circuits in wireless devices. *The second approach is to manage nodes's sleep/wake-up cycles (MAC power-save protocols) to reduce idle energy consumption while minimizing impact on data transmission. The third approach is to design energy based routing techniques to reduce the energy consumption of wireless devices in networks. The focus of the survey paper is on techniques that use the second and the third approach. There are two common problems in energy consumption considerations: maximizing network lifetime and minimizing total energy consumption. The mathematical models for optimizing energy consumption are also discussed in the paper.*

Keywords
Ad hoc Networks, Energy Consumption, Wireless Sensor Networks, Network Routing and Network Protocol.

1. Introduction

Wireless networks have become very popular in the last few years. There are two types of wireless network (WN) that we focus on in our survey paper: wireless mesh networks (WMN) in which all nodes have equal roles, resources, and centralized and clustered networks in which there are central nodes and non-central nodes. The applications of these networks include:

- Military communication applications between soldiers and stations in a battlefield.
- Data acquisition in an unfriendly terrain that cannot be monitored by humans.
- Exploration of natural resources.
- Emergency services or disaster recovery applications.
- Commercial applications, for example, meetings and conventions, electronic classrooms etc, where people can share information quickly.

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Since the mobile networks and the rapidly deployed networks industry increase very fast and there are only small improvements in the battery capacity, the research needs to be done to reduce the energy consumption of wireless devices in the networks.

Heinzelman et al. have proposed many routing protocols for wireless sensor networks. They are Low-Energy Adaptive Clustering Hierarchy (LEACH), centralized LEACH (LEACH-C), Randomized sleep scheduling (RS), Distance based sleep scheduling, and Balanced–energy Sleep scheduling scheme (BS). Other research groups have proposed power save medium access protocol (MAC) protocols which are energy conserving access medium access control (EC-MAC), power aware multi-access protocol with signalling (PAMAS) and sensor MAC (S-MAC). These protocols are implemented in the new version of network simulator NS [64].S-MAC has been implemented on Mote hardware, and the source code is freely available to the research community. Simulations in NS show that these protocols obtain significant energy savings compared with a MAC protocol without sleeping.

In [59], the authors pointed out some weaknesses in LEACH model and proposed some improvements in their protocol called EEEAC.

Safwat, Mouftah et al. proposed a new approach to achieve energy conservation for wireless mobile ad hoc networks called Power-Aware Virtual Base Stations (PA-VBS) architecture. They also further developed a novel cluster-based infrastructure creation protocol, namely: Warning Energy Aware Clusterhead (WEAC).

Feeney et al. carried out a well-known experiment to measure the energy consumption of 2.4GHz DSSS Lucent IEEE 802.11 WaveLAN PC “Bronze” (2Mbps) and “Silver” (11Mbps) 802.11 wireless cards. Their results reveal important knowledge about the energy consumption of practical wireless interface.

Woesner et al. technical university Berlin, Germany summarised modifications in 802.11 for power saving using timing synchronization.

Jones E. and Sivalingam M. showed current improvements in the idle energy consumption of network wireless interface (NIC) in their survey of energy efficient network protocols.

Mathematical models and solutions are also discussed in the survey paper. In general, the optimising energy consumption model can be formulated as a linear programming problem. The problem can be solved by the simplex method or well-known heuristic methods such as Tabu Search (TS), Simulated Annealing (SA) and Concave Branch Elimination (CBE).

This survey paper reviews MAC protocol and routing protocol standards for WNs and addresses issues related to the energy consumption of devices in the WNs. From these backgrounds, this paper extends to the main topic, which is the modification of protocols into power save protocols.

2. Standard MAC protocols and power-save protocols

The medium access control (MAC) layer is responsible for data framing, efficient sharing of the channel and part of error control. In the initial MAC design for wireless products, all stations are always awake to hear the existence of other stations to receive data and to avoid collision. As the result, the electronic circuits of these stations are still active all the time even when there are no data transmissions. As the results, the energy consumption in idle mode is very high and there must be works to improve the power saving in MAC layers. Currently, the Blue tooth (BT) and the 802.11 are two most common MAC layers in commercial wireless products. These MAC layers define both the MAC layer and the Physical layer.

2.1 Standard MAC layer designs

2.1.1 Bluetooth networks

The Bluetooth (BT) technology is used for ad-hoc and sensor network interfaces. BT defines ways that each BT device can communicate with neighbouring devices in a multihop fashion. The BT network comprises many clusters (piconets). A node can be a master in one piconet and a slave in one or in multiple piconets. Devices configured multiple roles act as gateways to adjacent piconets. They connect piconets into multihop ad hoc networks called a scatternet [44, 66].

Bluetooth operates in the 2.4 GHz, unlicenced ISM band. It adopts frequency-hopping spread spectrum technology to reduce interference both among BT nodes and devices that operate in the same band such as 802.11b. The transmission range depends on the device class. Class 1 radios have a range of 100 meters and they are used primarily in industrial cases. Class 2 radios have a range of 10 meters and they are found in mobile devices. Class 3 radios have a range of 1 meter. BT technology is designed to have very low power consumption. This is reinforced by allowing radios to be powered down when they are inactive. Class 2 consumes 2.5 mW and it is the most commonly used. Class 1 consumes 100mW and Class 3 is 1mW. One example uses Bluetooth as the radio interface with the capacity 700Kbps, the power source operates at 2.7V and 30mA with the transmission range d is approximate 30m [14].

In Bluetooth network, when establishing a connection one node must assume the role of master of the communication while the other becomes its slave. The maximum number of slaves that can be actively communicating with the master is seven. If a master has more than seven slaves, some slaves have to be parked. In order to communicate with parked slave, a master has to un-parked it while parking another slave. All devices in a piconet share the same channel (a frequency hopping sequence) which is derived from the unique identifier and the clock of the master. Each individual come to and from a device uses TDD scheme in pairs of 625 microseconds.

2.1.2 IEEE802.11 ad hoc networks

Another common network interface layer for MANETs and sensor networks is the IEEE 802.11 technology. An IEEE 802.11 wireless local access network (WLAN) can operate in two modes: ad-hoc or infrastructure. The infrastructure mode is used to construct the so-called Wi-Fi hotspots to provide wireless access to the Internet. In ad-hoc mode, mobile station (MS) can directly communicate with each other. When operating in this mode, stations form an Independent Basic Service Set (IBSS). Any station that is within the transmission range of any other, after a synchronized phase, can start communicating.

The MAC layer provides two different types of access: a contention-free service provided by the Distributed Coordination Function (DCF) and a contention free service implemented by the Point Coordination Function (PCF). These access methods run on top of a variety of physical layers. There are three physical technologies which are employed: Infrared (IF), Frequency Hopping Spread Spectrum (FHSS), and Direct Sequence Spread Spectrum (DSSS). The DCF provides the basic access method of the 802.11 MAC protocol and is based on a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. The PCF is implemented on top of the DCF and is based on a polling scheme. It uses a Point Coordinator that cyclically polls stations, giving them the opportunity to transmit. In ad hoc mode, only DCF can be used [44].

In DCF, each MS uses a first in first out (FIFO) transmission queue. A station can senses whether the medium is busy or idle (there is no transmission). When a station transmits a frame, the station checks the state of the medium. If the medium is busy, it waits for a duration of DCF Inter-Frame Space (DIFS). If the medium is still idle during the DIFS interval, the station initiates the back off procedures. Backoff Counter (BC) is chosen as a random integer in the uniformly distributed interval [0, CW], where CW is the current contention window of this station. The initial value of CW is CW min. CWmin and CWmax values for FHSS are 16 and 1024, respectively. The Backoff Interval (BI) is the backoff time of this station, which is equal the BC multiplied by the SlotTime. If the medium is idle for SlotTime, the BC is decremented by 1. When BC is 0, the station transmits the frame. If during the backoff procedure, the medium becomes busy (another station finishes its backoff procedure and transmit a frame), the BC is suspended. As the result, this station will have to wait for the medium to become idle again, wait for extra DIFS duration before continuing the backoff procedure with the suspended BC value [55].

If the transmitted frame is received successfully, the receiving station waits for the duration of short inter-frame space (SIFS) and sends back an Acknowledgement (ACK) frame. The sending station, upon receiving this ACK frame, resets its CW to CW min, defers for DIFS and initiates a post backoff procedure, even if there is no frame waiting in the transmission queue. The post backoff procedure guarantees that there is at least one BI between transmissions of two successful frame transmissions. If the sending station does not receive the ACK frame after some time (either due to two or more stations finishes backoff process at the same time and the transmitted frames collide, the transmitted frame is lost or the ACK frame is lost), it assumes that the frame transmission is unsuccessful. It increases the CW to the new value of 2_(CW+1)-1, with upper limit of CWmax, waits for the medium to become idle again, waits for DIFS and performs backoff process with this new value of CW.

The two MAC layers are inefficient in the energy consumption because stations are awake all the time even when they are in standby mode. As a result, the idle energy consumption dominates the total energy consumption of a wireless device. As wireless products are usually small, mobile and have limited battery capacity, MAC protocols must be modified to be power-save protocols. These protocols can be applicable for infrastructure networks, ad hoc and sensor networks.

It is observed in many wireless products that the only way to reduce power consumption in radios is to shut them off and to propose a power efficient MAC layer protocol suitable for wireless products.

These protocols are discussed in the following sections.

2.2 Power save protocols

There are four main sources of energy waste that are idle listening, collision, overhearing and control overhead. A power save protocol puts a node's network interface into sleep state in order to save energy. A sleeping node cannot forward or receive traffic and its sleeping state may stop the data flow in networks. Power save protocols is designed to maximize energy saving while minimizing impact on throughput, latency and supporting good scalability collision avoidance.

There is substantial work in managing nodes's sleep/wake-up cycles to reduce idle energy consumption while minimizing impact on communication.

802.11 power save MAC layers

Woesner et al. [11] at technical university Berlin, Germany summarized modifications in 802.11 for power saving using timing synchronization. Within the standard, the general idea is for all stations in PS mode to switch off the radio part for some period. They have been synchronized to wake up at the same time when a window opens in which the sender announces buffered frames for the receiver. A station that receives such an announcement frame stays awake until the frame is delivered. This is easy to do in the PCF, where there is a central AP which is able to store the packets for stations in sleep mode and to synchronize all mobile stations. It is much more difficult for the DCF, where packet store and forward as well as timing synchronization have to be done in a distributed manner.

In PCF, the access point (AP) is responsible for generating beacons which contain a valid timestamp. Stations within the base station adjust their local timers to that timestamp. If the channel is in use after the beacon interval, the AP has to defer its beacon transmission until the channel is free again.

In DCF, due to the absence of AP, timers synchronize in a distributed way: Every station is responsible for generating a beacon. Each station has a timing synchronization function (TSF) timer that is a modulus 2^64 counting increments of microseconds. The sending station sets the beacon timestamp of its TSF timer at the time the beacon is transmitted. Upon reception of a beacon, the receiving station looks at the timestamp. If the beacon timestamp is later than the station's TSF timer, the TSF timer is set to the value of the received time stamp. In other words, all stations synchronize their TSF timer to the quickest TSF timer. The node that wins the competition will initiate an independent basic service set (IBSS) and establishes a synchronized beacon interval. At the beginning of each beacon interval, a common fixed length, ad hoc traffic indication message (ATIM) window is defined. All nodes in the IBSS wake up from the beginning of the beacon interval to the end of the ATIM window. Each node transmits an ATIM to every other node which has pending unicast traffic. Each node, that receives an ATIM, responds with an ATIM acknowledgement. At the end of the ATIM window, nodes that have not sent or received ATIM announcements go back to sleep. All other nodes remain awake until the end of the beacon interval to send and receive traffic.

Other power save Mac layers

There are other power save MAC layers that are proposed for infrastructures, ad hoc and sensor networks. They are EC-MAC, PAMAS, BECA, AFECA, RS, DS, Span, GAF and S-MAC.

EC-MAC is designed for infrastructure networks. In EC-MAC, base station uses frames to control the data transmission. At the beginning of each frame, the base station transmits the frame synchronization message, which contains synchronization information and the data transmission order for all stations. In the request/ update phase, the base station broadcasts a transmission order list, which defines the order that registered mobiles transmit their request/update information. New mobiles need to register with the base station in another phase called new user phase. After the request and update phase, the base station broadcasts a schedule message that contains virtual circuits that each particular mobile should transmit/receive data. While the EC-MAC protocol described above was designed primarily for infrastructure networks, the PAMAS (Power Aware Multi-Access) protocol [10] was designed as an energy efficiency MAC protocol for the ad hoc network.

The PAMAS protocol provides separate channels for control and data packets. In PAMAS, a mobile with a packet to transmit sends a RTS (request-to-send) message over the control channel and waits the CTS (clear-to-send) reply message from the receiving mobile. The mobile enters a back off state if no CTS arrive. However, if a CTS is received, then the mobile transmits the packet over the data channel.

The receiving mobile transmits a "busy tone" over the control channel alerting that the data channel is busy. Power conservation is achieved by requiring mobiles that are not able to receive and send packets to turn off the wireless interface. The idea is that a data transmission between two mobiles need not be overheard by all the neighbours of the transmitter. The use of a separate control channel allows for mobiles to determine when and for how long to power off. Each mobile determines the length of time that it should be powered off through the use of a probe protocol, the details of which are available in [10]. The results from simulation and analytical model show that between 10% and 70% power savings can be achieved for fully connected topologies.

Span is another power-save protocol in which some nodes become coordinators. Coordinators stay continually in the idle state, whereas non-coordinator nodes wake up periodically to exchange traffic with the coordinator nodes and participate in coordinator election. In other words, the coordinators act as backbone nodes for the network and buffer traffic for sleeping destinations.

In the coordinator election, nodes exchange HELLO messages to discover their two-hop neighbourhood. A node is eligible to be a coordinator if it discovers that two neighbours cannot communicate directly or via other coordinators. Each marked node schedules a back off interval, during which it listens for announcements from other nodes. Nodes are effective at connecting new pairs of neighbours, and have higher energy resources announce themselves as coordinators. Nodes have lower energy volunteer can become coordinators if they are still needed to complete the connected dominating set. After spending some time as coordinator, a node withdraws as a coordinator, allowing other nodes to consider themselves as coordinators. Rotating the coordinator role in this way tends to balance nodes's energy resources [44, 67]. Packet level simulations using ns-2 shows that, compared to IEEE 802.11 power saving, Span provides about 50% energy saving in dense networks (12-78 nodes/transmit area), with only minimal impact on throughput and packet loss. Rotation of the coordinator role equalizes energy consumption and network lifetime increase 50-100% as discussed above.

Mac layer power-save for sensor networks

Sensors networks are different from other wireless networks in that all nodes cooperate for a single common task. At any particular time, one node may have dramatically more data to send than some other nodes. In order to save energy, sensor nodes need to be remaining inactive for a long time, but becoming active when a communication is detected.

There were two sleep-scheduling schemes, termed the Randomized Scheduling (RS) scheme and the Distance-based Scheduling (DS) scheme, which were proposed in the past. In the RS scheme, sensor nodes are randomly selected to go into the sleep state. In the DS scheme, the probability that a sensor node is selected to sleep depends on the distance it is located from the cluster head.

There are drawbacks of the RS and the DS schemes. Since the sleep probability is not related to the battery energy of nodes, the average energy consumptions of sensors with different distance to the cluster head might be different. In term of balancing the energy consumption of nodes, the DS scheme is better than the RS scheme since it selects sensor nodes to sleep based on their distances from the cluster head. As a result, the variation of energy consumptions of all sensor nodes is lowered. However, since the sleeping probability in the DS scheme is only linearly related to the distance to the cluster head, while the transmission energy consumption is at least quadratically related to distance, the coefficient of variation of sensor nodes' energy consumption is still significantly different.

In order to improve these schemes the Balanced-energy Sleep Scheduling is proposed. In the Balanced-energy Scheduling (BS) scheme, a sleeping probability p(x) is chosen in such a way that as many sensor nodes as possible consume the same amount of energy, on average. Let EBS(x) be the expected energy consumption of a node at a distance x from the cluster head. In order to balance the residual energy of nodes, the probability p(x) must be calculated so that EBS(x) does not depend on the value of x [52].

S-MAC protocol is a well-known power-save protocol designed for wireless sensor networks. There are many updated versions of S-MAC protocol. SMAC protocol is designed to reduce energy consumption from idle listening energy consumption, packet collision energy waste, packet overhearing energy waste and packet control overhead. In order to achieve this goal, S-MAC uses three techniques, which are periodic listen and sleep, collision and overhearing avoidance, and message passing. In order to synchronize the listening and sleeping, all timestamps are exchanged. The listen period is significantly longer than clock error or drift. If the listen duration is 0.5 s, then the duration is more than 10^5 times longer than typical clock drift rates. Compared with TDMA schemes, SMAC requires much looser synchronization among neighboring nodes. All nodes are free to choose their own listen/sleep schedules. Updating schedules is accomplished by sending a SYNC packet. The SYNC packet is very short, and includes the address of the sender and the time of its next sleep. The next-sleep time is mapped to the time that the sender finishes transmitting the SYNC packet, which is approximately when the receivers get the packet. Receivers will adjust their timers immediately after they receive the SYNC packet. A node goes to sleep when their timers fire. The listen interval is divided into two parts in which one is for receiving SYNC packets and the second one is for receiving RTS packet. If a sender wants to send a SYNC packet or data packet, it starts to sense when the receiver begins listening. It randomly selects a time slot to finish its carrier sense. If there is no transmission, it wins the medium and starts sending its SYNC packet or data at that time. S-MAC also applies message passing to reduce contention latency for sensor-network applications that require store-and forward data when transmission [32, 51].

The protocol has been already implemented in NS2. It is also developed at UCB using Rene Motes, as development platform. Details are given in section 4.5. The experimental results show that on average, an 802.11-like MAC consumes 2–6 times more energy than S-MAC for traffic load with messages sent every 1–10s.

The first version of SMAC protocol was designed in the year 2000 by Wei Ye [32, 51] and is ported into ns by Padma Haldar, June, 2002. The protocol has been updated from year 2000 to year 2006. The later version has been trying to solve three main sources of energy waste of idle listening, collision, overhearing. The new version is included in ns2.29, which is last modified on August, 2005. The research at RMIT University has shown significant improves in idle energy consumption of later versions of SMAC protocols in the sensor and air navigation project [73].

802.11	802.11 power save	PAMAS	SPAN	S-MAC
Power save mode is not the default one	30% saving with 10% reduce in throughput	10-70% reduction in the amount of energy	50% energy saving (12-78 nodes/transmit area) Lifetime of networks increases 50-100%	75% saving with messages sent from 1 to 10s

Table 1: Power save MAC protocols comparison

Network layer power save protocols

In network power save protocols, there are three techniques. The first and simplest approach is a synchronized power-save mechanism. Nodes periodically wake up to listen to announcements of pending traffic. The second approach is based on network topology in which a covering set of nodes provide connectivity equivalent to that of full network and the remaining nodes can spend most of their time in the sleep state. In the third approach, if any two nodes need to communicate, they try a bounded number of attempts to establish connectivity and start to transmit real data. Other nodes are in sleep mode.

The basic energy conservation algorithm (BECA) is one of network power save protocols. A node alternate between the sleep state and the listening state in the absence of traffic. Once a node transmits or receives traffic, it transitions to the active state. Nodes in the active state return to the sleep state only after they have been not received data for some time. Because nodes make decisions independently, in order to guarantees quality of data transmission there must be a careful relationship between the timing interval of the listening interval, the time-out and the listening interval. Intermediate nodes need to be awake during the time of the discovery process [35, 44].

Once the route has been established, only the nodes that forward traffic will remain active. The other will return to the low-energy-consumption sleep-listen cycle. Once traffic along the route ceases, the nodes on the route also time out and returns to the sleep-listen cycle. The adaptive fidelity energy conservation algorithms (AFECA) is an extension of BECA in which nodes adapt their sleep interval depending on the estimated network density. The proportion of nodes that nodes must be awake to achieve the connectivity needed to forward traffic depending on the number of nodes on network. The performance of BECA/AFECA has been studied using ns-2 simulation packet level simulation, with the AODV protocol. The average saving was on 35% to 45% across a range of traffic loads with a minimum sleep interval of 10 seconds.

Geographical adaptive fidelity (GAF) is a power-save protocol based on position information. Each node transitions independently among three states: sleep, discovery and active. Nodes periodically wake up from the sleep state and transition to the discovery state. In the discovery state, a node listens for other nodes's announcements and sends its own grid position ID and residual energy status to neighbours. If the node hears no "higher ranking" announcement, it transitions to the active state, otherwise it transitions back to the sleep state. Nodes in the active state are responsible as coordinators like in Span protocol. After spending some time in the active state, nodes transitions back to the discovery state, allowing the active role to be rotated among the nodes in the networks [42, 44]. Simulation in ns-2 packet shows that in general, AODV and AODV/GAF have similar data delivery ratios and transfer delays, whereas the mean energy consumption per node is reduced by 40-50% with GAP.

Another power save location based routing protocol is Energy-conserving grid routing protocol ECGRID. In the protocol, each mobile host has a positioning device called Global Positioning System (GPS) receiver to determine its current position. Each host uses its unique ID as the paging sequence. One mobile host in each grid will be elected as the gateway and remains in active mode. Other non-gateway hosts can sleep to conserve battery energy. The gateway host must maintain a host table that stores the host ID and status of all other hosts in the same grid. The power consumption in transmit mode, receive mode, idle mode and sleep mode is 1400, 1000, 830 and 130mW.The power cost for GPS is 33mW. Simulation shows that ECGRID cannot prolong the lifetime of entire networks but maintain good packet delivery ratio [42]. Details about GPS are given in the global positioning system section.

AODV Routing protocol	BECA/AFECA	GAF	ECGRIG
No sleeping mode	35%-45% of Energy saving with a minimum sleep interval of 10 seconds compared with AODV protocol	40-50% reduction in the mean energy consumption per node compared with AODV protocol	Similar energy saving to GAF but better quality of service

Table 2: Power save network protocols comparison

Global positioning system (GPS)

The global positioning systems (GPS) are global radio navigation systems that provide communications between satellites and ground stations. Ground stations are spread to monitor the status of satellites. The satellites provide continuous dimensional position information and velocity information to GPS receivers. Each GPS receiver contains a clock. In order to measure the receiver's three-dimensional location, the time of arrival (TOA) measurements are made to four satellites. After the receiver clock is synchronized with the satellite clocks, only three measurements are required [42].

Synchronization in mobile networks with the support of GPSs can be achieved by use of the absolute time information up to 100 ns resolution [4], [13]. In a synchronous network, each node wakes up regularly to "listen" for change and goes back to the sleep mode to conserve power. Given any number of randomly deployed nodes over an area, the authors in [13] shows that a simple local optimization scheme can be obtained to guarantee global minimum energy solution and strong connectivity for stationary networks. In the simulation, each mobile is assumed to have a portable set with transmission, reception, and processing capabilities. In addition, each has a low-power global positioning system (GPS) receiver on board, which provides position information within at least 5 m of accuracy [4]. The authors also argue that the recent low-power implementation of a GPS receiver [5] makes its presence a viable option in minimum energy network design and the topology is found via a local search, this protocol can be applied to a mobile ad hoc network. Their simulation results show that average power consumption per node is significantly low.

3. Current routing protocols standards

As wireless networks are being developed, routing protocols need to be developed or modified from wired networks to wireless networks to support wireless communications. For examples, Microsoft ® is developing their mesh networks based on dynamic source routing (DSR) and many other companies are using ad hoc on-demand distance vector (AODV) routing for their products.

In general, routing in WNs can be divided into flat-based routing, hierarchical-based routing, and location-based routing depending on the network design. In flat-based routing, all nodes have the same roles and functionalities. In hierarchical- based routing, nodes play different roles and have different capacities. Therefore, this type of network is often divided into clusters. In location-based routing, the positions of nodes are exploited to route data in the network. Flat-based routing can be further divided into two types, reactive and proactive. The hybrid protocols are also proposed for research as some time a network needs to switch between the two routing protocols depending on the network performance.

As flat protocols are applied in more commercial cases, the Internet Engineering Task Force's (IETF) working group has been working on flat routing protocols for MANET. After years of consideration, this working group is focusing on a few of these protocols. Two of these, AODV and OLSR, are now experimental "Request for Comments" (RFC). AODV is expected to be commercialized in the near future. Although these routing protocols were initially designed for MANET, they can be applied for WMNs and general WNs. The operations of reactive and proactive routing protocols and examples of these protocols are described below.

3.1 Reactive Routing Protocols

Reactive protocols are on demand routing protocols. The source initially does not know about any route. When a route to a destination is requested, the source broadcasts a route request packet (RREQ) to the network. If intermediate nodes have information about the destination, or the RREQ reaches the destination, these nodes send a route reply packet (RREP) back to the source.

Dynamic source routing (DSR) is an example of this protocol. In the DSR protocol [38], intermediate nodes add their identifiers (IDs) to the RREQ packet and forward the packet to other nodes. The other nodes check IDs of nodes in the packet to avoid retransmission. If intermediate nodes have information about the destination, these nodes send a RREP with the entire path information. Once the RREP is received by the source, the sender knows about the entire path to the destination. The source includes the entire information about the destination in the header of every data packet to route the data to the destination. If a link breaks, the intermediate node reports an error back to the source, and the source then needs to make decisions. The source initiates a new RREQ or use another path if there are multiple paths in its cache.

AODV [37] is another example of the protocol. In the AODV protocol, a source initiates a route discovery by flooding a RREQ packet when it needs to transmit data to a destination. The node receiving the RREQ stores the route to the originator of the RREQ before it forwards the RREQ to other nodes. The destination node or an intermediate node with recent information about the path replies by unicasting a RREP along the reverse path to the originator. As RREP travels back to the originator, any node receiving the RREP will add or update the route to the destination generating RREP. The major difference between AODV and DSR is that the information about a destination is stored in the routing table in each node on a path. This information is not added into data packets. As there may be many paths from an originator to a destination, AODV maintains the most up to date information in the routing table of nodes. Every node on the network has its own sequence number. When a node sends a RREQ, it increases its sequence number by one and includes the number in the RREQ. Before the destination issues a RREP, it updates its sequence number to the maximum of its current sequence number and the one indicated in the RREQ. Each routing element in a routing table also has a field called the route life time. If there are many paths to the same destination, the node will keep the one with the longest life time. After a route expires, this route is removed from the routing table. Any node in the network sends 'Hello' messages frequently to check connectivity with their immediate neighbours.

3.2 Proactive Routing Protocols

Proactive protocols are table driven routing protocols. There are periodic exchanges of control message among the nodes in the network to maintain consistent and up-to-date information about the status of the network in the routing tables of these nodes. Each node uses the information to calculate the routes to every other node in the network. The main feature of this type of protocol is that routing information is readily available before any route requests are made.

OLSR is the most popular proactive protocol. Nodes are kept in touch by Hello messages and the information about link-state is disseminated and updated by topology control messages. All nodes calculate the optimal path to every other node on the network based on the link state messages that are ready in the routing table before the data transfer requests are made.

However, there are optimizations in OLSR compared with normal link state protocol like open shortest path first (OSPF). In OSPF every node disseminates their Control messages to every other node on the network. In OLSR only nodes selected as such multipoint relays (MPRs) are responsible for forwarding control traffic into the entire network. Also, the link state information disseminated through the network may only contain the information about a node's MPR sets. This means that only MPR nodes declare link-state information for their MPR selectors thus the volume of information exchanged is also further reduced. This is illustrated in Fig. 1 where only MPR nodes (grey nodes) are participating in broadcasting the link state information [36].

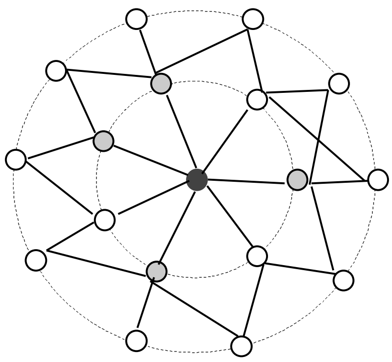


Fig. 1: Example of possible MPR set (grey nodes)

3.3 Simulation tools

In our survey paper, there are two simulations tools that are considered. Ns-2 is a discrete-event simulator that provides substantial support for simulation of MAC and routing and multicast protocols over wired, wireless (local and satellite), and wireless multihop ad hoc networks.

Among all the existing networks simulators, ns-2 is most popular tool which is used for wireless simulation. The drawback of ns-2 is the execution time of the simulation, mainly due to the sequential implementation of the discrete-event simulator [64].

OMNeT++ is a freely distributed, object-oriented, modular, discrete-event simulator written in C++. OMNeT++ support for parallel execution and portable parallel discrete event simulation is an ongoing research activity [74], [75].

4. Background on Energy Consumption in Wireless Networks

4.1 Batteries

Batteries are the most common power source for mobiles and portable wireless devices. The most important parameters of a battery are primary (disposable) or secondary (rechargeable), nominal voltage and nominal charge capacity.

The materials of battery's electrodes determine these parameters. Table 3 lists theoretical properties of several rechargeable battery families:

Chemistry	Theoretical Voltage, (V)	Theoretical charge capacity, (C/kg)	Theoretical Energy capacity, (Wh/kg)

Li-ion	3.9	100	390
NiCd	1.3	180	240
NiMH	1.3	210	270

Table 3: Theoretical properties of common rechargeable battery chemistries [61, p711]

In the table, the charge capacity is specified in Ah where 1 Ah =3600 C. The energy capacity of a battery is the nominal voltage multiplied by the nominal charge capacity and its unit is Watt-hours (Wh). Li-ion batteries are currently the most common choice for mobile devices because of their superior energy capacity.

Table 4 shows some practical battery packs and their performance with the UHF transceivers products from ICOM Company. The BP-231 provides 8.51 Wh which is 8 hours of operating time for The BP-232 provides longer operation of 15 hours [70].

Battery packs	Type and capacity	Operating time*	Output power
BP-230	Li-Ion 7.4V/ 800mAh	6 hours	4W
BP-231	Li-Ion 7.4V/1150mAh	8 hours	4W
BP-232	Li-Ion 7.4V/2000mAh	15 hours	4W

Table 4: Typical Lithium-Ion battery

4.2 Battery management

All mobiles include measure and display residual power. These circuits are part of the battery management. There are improvements in the resolution of analog to digital converters which improve the measurement of these circuits. The RREQ and RREP formats need to be modified so that a suitably discredited version of residual energy can be inserted into the reserved field of these formats which are described in RFC 3561 [37].

4.3 Wireless Interfaces

There are two main power consumption sources: transmission power and processing power inside a wireless device. The transmission power is a large portion of the total energy consumption of wireless devices since this power needs to be large enough (especially in the long transmission range) to transmit data successfully.

At a normal wireless interface, the radio state is always either in sending, receiving or idle mode. If the radio interface gets a packet from an upper layer, it is in sending mode. If the noise level at the interface is higher than the radio sensitivity, or the signal power level of any frame coming is higher than the radio sensitivity, the radio is in receiving mode. Otherwise, it is in idle mode.

The signal power received P_r is related to the transmitted power P_t by [1]:

$$P_r = \frac{\alpha}{d^{\gamma}} P_t \quad (1)$$

where α depends on the gain of the transmitting and receiving antennas G_t and G_r, the frequency of the microwave, the heights of the transmitting and receiving antennas above the ground H_t and H_r, and the loss factor of the transmitting environments. d is the distance between two stations. The formula is applied for cellular mobile systems which are often known as 40 dB/dec rule. The general formula to calculate the signal power received P_r in a real mobile radio environments. _ is usually between 2 and 5 depending on the actual conditions. _ =2 is applied for free space direct transmission from a transmitter to a receiver. Of course, _ cannot be smaller than 2. With a specific transmission system, the transmission power depends only on the distance between two stations. The formula (1) can be used to calculate the transmission power between two mobile stations, or from a base station to a mobile station and vice versa. Also _ depends on the field propagation. The range of near field propagation is calculated by:

$$d_F = \frac{4\pi h_t h_r}{\lambda} \quad (2)$$

$$\lambda = \frac{u_p}{f} \quad (3)$$

where u_p and λ are the microwave velocity and microwave wavelength.

The signal received within the near field ($d < d_F$) uses the free space loss formula and the signal received outside the near field ($d > d_F$) can use the mobile radio path loss formula. Details about mobile radio propagation of large-scale path loss model and small-scale fading and multi-path model are given in [34].

4.4 Transmission Power and Noise Power.

In wireless transmission, the power transmission and the noise must be considered to transmit data successfully. For a long transmission range system, the transmission power is a main part of the power consumption in wireless devices. During the time from the start of receiving the first bit to the final bit, the S/N of the receiving frame may change because there may be other frames coming and their signals add noise to the noise of the S/N ratio of the current receiving frame. If at any time, the S/N value received at a node n_j is smaller than the S/N threshold $\_{j}$, the frame receiving is corrupted and it is impossible to decode the signal. This threshold value $\_{j}$ is closely related to the bit error rate (BER) of the received signal. For successful transmissions from node n_i to node n_j, the transmission power P_i at node n_i must satisfy the following equation (4):

$$\frac{P_i G_{i,j}}{\sum_{k \neq i} P_k G_{k,j} + \eta_j} \geq \psi_j \quad (4)$$

where P_i is the transmission power of node n_i . $G_{i,j}$ is the path loss between node n_i and node n_j and η_j is the total noise at node n_j.

To the best of our knowledge, there are shot noise, dark current noise, thermal noise, equipment noise and man-made noise.

It is interesting to look at the signal and the noise of a few practical wireless networks. In cellular frequency band, the thermal noise at a room temperature (27 deg) and a bandwidth B of 30kHz is –129dBm. Assume that the received front-end noise is 9 dB, the noise level is –120dBm. In addition, there are two man-made noises, the ignition noise and the emission noise. The ignition noise generated by the vehicles and the noise generated by 800-MHz emissions with a bandwidth of 30kHz is from –75dBm to –124dBm. The 800 MHz emission noise can be measured in the 869 MHz to 894 MHz regions while the mobile receiver is operating on a car battery in a city. It was found that in some areas the noise level is 2 to 3 dB higher than –120dBm at the cell sites and 3 to 4 dB higher than –120dBm at the mobile stations. If the mobile radio signal received by a receiving antenna is amplified by an amplifier then there is internal noise of the amplifier [1].

_In [13], authors show an example with the carrier frequency of 1GHz, and the transmission bandwidth of 10kHz. The antenna used is omnidirectional antennas with 0dB gain, -160 dBm/Hz thermal noise, 10 dB noise figure in the receiver and a predetection signal to noise of 10dB. As a result, the thermal noise is –70dBm and the signal threshold at the receiver is about –60dBm or 10^{-9} W. If the noise is after the demodulator then the signal threshold of the receiver is about

$$\frac{10^{-9} \times 10^{4}}{10^{9}} = 10^{-14} W$$

In [23], authors show examples of receiving systems for geostationary satellite transmissions at 2 GHz. Receiver have a noise figure of 2.8dB and bandwidth of 200kHz. The noise power input to the receiver is:

$$1.38\times10^{-23}\times262\times200\times10^{3} = 0.91\times10^{-15}W$$

In the second example, the receiving system has a bandwidth of 1 MHz, which consists of an antenna pre-amplifier with a noise temperature of 124 K and a gain of 20dB followed by an amplifier with a noise figure of 12 dB and a gain of 80dB. Antenna noise temperature is 59K.

$$T_{sys} = \frac{124+4.35\times10^{3}(12dB)}{100} = 167.5K$$

Noise power at receiver input is:

$$(167.5+59)\times(1.38\times10^{-23})\times10^{6} = 3.13\times10^{-15}W$$

If the receiving antenna feeder cable has a loss of 1.5dB then:

$$T_{sys} = 119+124/0.708+4.35\times10^{3}/0.708/100 = 355K$$

Noise power at receiver input is:

$$(355+59)\times(1.38\times10^{-23})\times10^{6} = 5.71\times10^{-15}W$$

If the preamplifier is placed at the antenna end of the feeder cable then

$$T_{sys} = 124+119/100+4.35\times10^{3}/0.708/100 = 186K$$

Noise power at receiver input is:

$$(186+59)\times(1.38\times10^{-23})\times10^{6} = 3.38\times10^{-15}W$$

In the above examples, it is assumed that there is only one wireless system deployed at one time. In reality, there might be many wireless systems available at the same time. Therefore, the interference between wireless systems needs to be considered.

In [61], the Federal Communications Commission in US has used specified received signal strength for the coverage boundary, which is –93 dBm for a dipole or monopole matching on a 50Ω load at 850 MHz. For cellular coverage, -100dBm is proved to be sufficient for cellular coverage. Because the cell site transmit frequency f_{Tc} lies in the 870 MHz to 890 MHz band and f_{TV} lies in the 780 MHz to 800 MHz, f_{Tc} will interfere with the TV receiver.

Let us look at two interesting cases of power interference between mobile receiver and TV receiver:

Case 1: When the mobile is located near a TV receiver.

The cellular telephone mobile unit has a receiver sensitivity of about -100 dBm, the TV receiver signal is -63 dBm. Therefore, the difference in signal levels between the TV receiver and the mobile receiver is about 37dB. As a result, the non-interference from a transmitting cellular mobile to a TV is about 14ft.

Case 2: When the cell site transmitter is located near a TV receiver.

The cell site antennas are located on high towers found that generally; the required distance could be less than 200m.

Case 3: Interference to portable mobile units (in cars)

At the cellular cell boundary, the mobile unit received a signal at –100 dBm. If the cell site has a 10W transmitter and a 6dB gain antenna, then the transmitting site has an ERP of 46dBm. The path loss to mobile and portable unit is assumed about 133 dB. Also, the reception signal at the thirtieth floor in Tokyo is 13 dB higher than that at street level.

A normal portable unit has a 600mW (28dBm) transmitter, and the mobile unit has a 3W (35 dBm) transmitter. As a result, the signal received is –105 dBm for the portable unit and –111 dBm for the mobile unit. The difference in received levels is 6dB. This near end to far end ratio interference can be eliminated by the frequency channel and power control of the portable unit.

It is noted that it is very hard to measure the $(S/N)_{in}$ since wideband meters usually measure down to about –70 dBm. In order to measure the ratio, it is amplified by amplifier and the ratio $(S/N)_{out}$ is measured with wideband meters. After that, the $(S/N)_{in}$ is calculated when the amplifier gain is known [23]. However, our recent measurement shows a record of -140 dBm by Agilent Spectrum Analyser E4405B equipment even without amplifier. A pocket power meter can measure up to -60 dBm [23, 60 and 63].

4.5 Energy Measurements and Energy Models in current commercial products

Energy aware routing techniques for wireless networks require practical study of energy consumption behaviours of actual wireless devices. The variety of devices, operating modes, energy management techniques and usage scenarios make it hard to make statements about energy consumption in wireless devices. In only a few commercial 802.11b cards, the total energy consumption can vary from 4 (J/MB) to nearly 18 (J/MB) [65].

In order to make WNs available commercially, we need to reduce the energy consumption in wireless network interfaces (NI) because a NI consumes a large portion of the total amount of energy of wireless devices.

Stemm et al. [6] reported that currently the network interfaces (NIs) consumed from 350mW to 1300mW when idle, and the PDAs consumed about 700mW to 1200mW when idle. The authors showed detailed measurements of the energy consumption of several NIs in their sleep, idle, packet sending and packet receiving modes. In their experiments, there were two PDAs: the Apple Newton Messagepas 100, and the Sony Magic Link (PIC 1000). There were four NIs: AT&T's Wavelan PCMCIA card operating at 915 MHz and 2.4 GHz, Metricom's Ricochet Wireless Modem, and IBM's Infrared Wireless LAN card.

The authors found that energy consumption in receiving mode and idle mode is increased proportionally with a packet size in both 915 MHz Wavelan and Metricom. The increase is more significant in sending mode with the packet size. The results are shown in the Fig. 3 and Fig. 4. Also the energy in receiving mode is only a bit higher than in idle mode. For a 500 bytes packet, it is about 3mW.second for 915 MHz Wavelan and 45mW.second for Metricom when they are in idle mode. The numbers are 4mW.second (2J/MB) and 100mW.second (50J/MB) for Wavelan and Metricom cards respectively when these cards are in sending mode. These values for Metricom are higher than those of Wavelan because Metricom has a transmission range of 1 km while Wavelan has a transmission range of 40 m. The authors also found that sending mode consumes significantly higher energy compared with idle mode only if the device is sending a large amount of information.

Feeney et al. [19] tried to reveal energy consumption behaviours of actual wireless devices. These authors argued that the knowledge of current draw while transmitting and receiving is not enough to calculate per packet energy consumption. The reason is that other factors, like the energy consumption in idle mode, the energy consumption in switching between different modes and the internal energy management, may not be considered. This case happened with the measurement method in [9]. The authors in [9] tried to compare the total energy used while sending or receiving with the energy in idle mode. The difference provided the total energy cost of processing traffic but little packet-oriented information detail. In order to model per packet energy consumption, [19] used a simple linear formula (5) to model the energy consumption when hosts send, receive or discard packets.

$$Energy = m * size + b \qquad (5)$$

where $size$ is the packet size, m and b are linear coefficients for different operations. In order to validate the model, [19] used two popular wireless cards: 2.4GHz DSSS Lucent IEEE 802.11 WaveLAN PC "Bronze" (2Mbps) and "Silver" (11Mbps) cards. Their simple experiments use a common electronic knowledge:

The authors in [19] also presented some oscilloscope traces of their measurements. In the experiments, a frame is 300 bytes (228(data) +8(UDP) +20(IP) + 24(PLCP header) + 20(MAC frame header). The PLCP header is transmitted at 1Mbps. The total time for transmitting and receiving the frame at 2Mbps is about 1.3ms which is seen from Fig. 2 and Fig. 3. The energy consumption in receive mode is only slightly higher than that of idle mode.

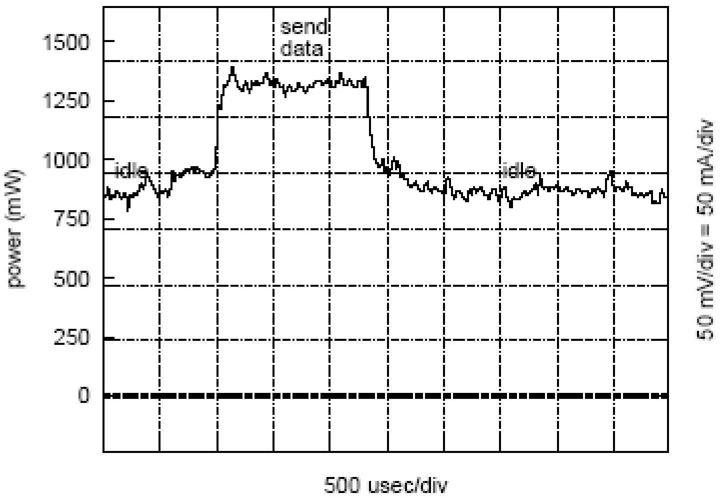


Fig. 2: Sending 256 bytes UDP/IP traffic [19]

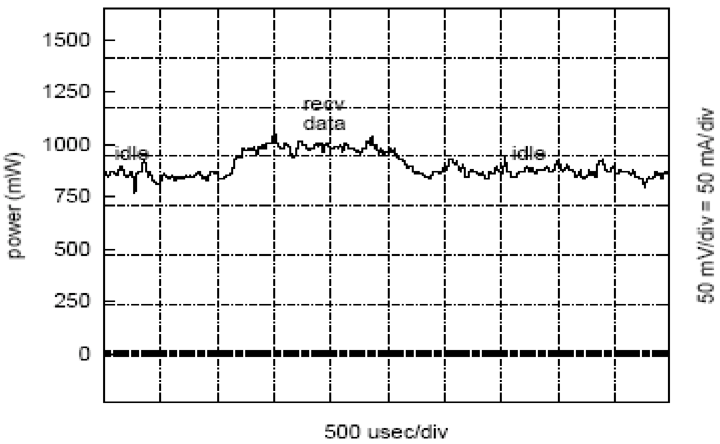


Fig. 3: Receiving 256 bytes UDP/IP traffic [19]

As a consequence of operating in ad hoc mode, a network interface overhears all traffic sent by nearby hosts. Therefore, it is important to consider the energy consumed by an interface when it discards traffic after determining that this interface is not the intended destination. This case is a common case for traffic in ad hoc networks. Fig. 4 shows the case of discarding the same frame in Fig. 2 and Fig.3 of a host in the range of both source and destination. After receiving the MAC header and determining that the frame is not for a host, the host enters a reduced energy mode. The energy consumption for processing MAC header is equal to that of receiving mode, but the energy consumption for discarding data is lower than that of idle mode. The amount of energy that can be saved, when discarding traffic, is dependent on the amount of time that data transmission takes, as well as the amount of time and energy needed to return to the idle mode.

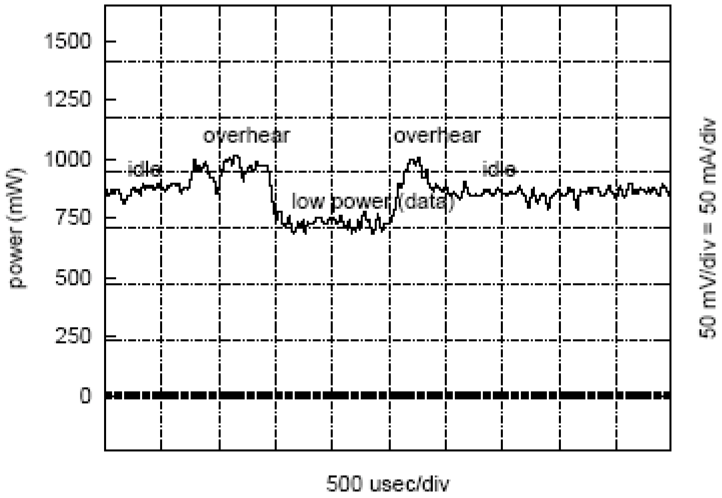


Fig. 4: Discarding 256 bytes UDP/IP traffic [19]

There are recent improvements in the idle energy consumption [42], [8] and [21]:

Wirless, IEEE 802.11,WaveLan Card	Transmit mode	Receive mode	Idle mode	Sleep mode
Lucent 11Mb/sec	284mA/4.74V	190mA/4.74V	156mA/4.74V	10mA/4.74V
Cabletron Roamabout 802.11 DS High Rate network, 2 Mb/sec	1400mW	1000mW	830mW	130mW
Proxim RangeLAN 2.4 GHz (1.6Mbps)	1.5W	0.75W		0.01W
Lucent's 15 dBm 2.4 GHz 2 Mbps Wavelan PCMCIA card	1.82W	1.80W		0.18W
24.5 dBm 915 MHz 2 Mbps PCMCIA card	3W	1.48W		0.18W

Table 5: Energy consumption for different wireless cards

An early implementation of S-MAC uses Atmel AT90LS8535 microcontroller and the TR1000 radio transceiver from RF Monolithics, Inc. The radio uses the OOK (on–off keyed) modulation, and provides a bandwidth of 10 kb/s. It has three operational modes: receiving, transmitting, and sleep, consuming 13.5 mW, 24.75 mW, and 15 uW, respectively. There is no power difference between listening and receiving.

The later version is implemented on Mica motes that are equipped with the Atmel Atmega128L microcontroller of 128kB of flash and 4 kB of data memory. It also has RFM TR3000 radio transceiver and a matched whip antenna [32], [51].

In summary, the energy consumption of wireless devices and wireless interfaces is high and it is hard to deploy such devices in a big MANET or WMN network under the battery constraints of these devices. One solution is to reduce the energy consumption of electronic circuits by modifying communications protocols. This solution can be done by MAC layer power saving protocols and network layer power saving protocols, which are presented previously in section 2. The other solution is to design energy based routing techniques to reduce the energy consumption of wireless devices in networks. This is presented in the next sections.

5 Factors Affecting Energy Based Routings in Wireless Networks

Besides the parameters applicable to wired networks, such as bandwidth and node capacity, an energy based routing in WNs is subject to several restrictions, such as the limited energy supply of client nodes and much more frequent changes in the position of nodes due to the nature of wireless networks and the mobility of client nodes. Energy based routing protocols need to carry out data communication while considering the lifetime of clients. The lifetime of a client is the time until the client runs out of energy. While working to reduce the energy consumption of nodes in a network, the protocols still need to guarantee the quality of services (QoS) in packet delay, packet throughput and packet loss [46].

The design of energy based routing protocols in WNs is influenced by many challenging issues. An energy efficient routing protocol design needs to address the following issues:

- Performance metrics: Many existing routing protocols use minimum hop-count as a performance metric to select a routing path. This technique is not efficient in many cases. If any link on the path has insufficient resources, the connection path will be broken. Besides, the distance between any two nodes in the minimum hop count path is often longer than that of the path in other routing techniques. The power transmission increases proportionally with a power factor from 2 to 4 with distance. The calculation is derived from a commonly used decay model in [46] to calculate the power loss, which follows an inverse _-th law (7). From the formula (7), if we double the distance we have to increase the transmission power by 2^{α} times. Also, one of the objectives of WNs is to share the network resources among many users. When a part of a WN experiences congestion or lack of resources, new traffic flows should not be routed through that part. Multiple metrics such as current node energy or energy cost need to be considered for balancing network resources.

  (6)

  where 2≤α≤4, c is a constant depending on specific communication system. P_{TX} and P_{RX} are transmission power and received power respectively. d is the distance between the transmitter and the receiver.

- Resource-constrained nodes: Nodes in a WN are typically battery powered and limited in storage and processing capabilities. Moreover, they may be situated in areas where it is not possible to re-charge quickly and thus have limited lifetimes. Battery energy is finite and represents one of the greatest constraints in designing routing algorithms for mobile devices. Current research on battery technologies shows that only small improvements in the battery capacity are expected in the near future. Under these conditions, it is vital to have routing protocols which use less power, preferably with no impact on the upper application layer. The protocols also need to operate with limited processing and memory resources.

- Recovering from node and link failures: Wireless networks need the ability to recover rapidly from network events because these events happen very frequently. "Some client nodes may fail or be blocked due to lack of power, physical damage, or environmental interference" [46,p8]. Link metrics on the network are also unreliable due to the transmission environment, and the effects of mobility. When node failures and link failures happen, the networks may require active adjustment of transmission powers and transmission rates on the existing links to reduce energy consumption, or the rerouting of packets through regions of the network where more energy is available. Also transmission nodes may need to find new paths in their transmission ranges to transfer data. Sometimes, energy recharge for nodes is required. In other words, a node should have many options in a fault-tolerant wireless network [46].

- Scalability: "Setting up a routing path in a very large wireless network may take a long time, and the end-to-end delay can become large [53, p465]". In order to setup the path, broadcast and hello message are periodically sent across the network. Furthermore, in the wireless network even when the path is established, the node status on the path may change very quickly. Besides, the number of client nodes deployed in a network may be in the order of hundreds or thousands, or more. Routing protocols should be scalable enough to respond to events under these conditions. After an event occurs, involved parties must know how to react quickly to update information.

- Quality of services (QoS): QoS means routing paths that can satisfy performance requirements under given resource constraints. A routing protocol should work together with QoS signals to establish and guarantee paths through the network that meet end-to-end QoS requirements. While considering energy as a QoS factor, these protocols also need to satisfy other QoSs such as delay, delay jitter bounds and bandwidth demand. The main difficulty for QoS routing protocols in energy constrained WNs is that traditional approaches for a fixed network is no longer valid because of limited power resources and paths broken by mobility.

- Data sending method**:** Data sending in WNs is application-dependent and also depends on the time criticality of the data. The application layer decides the frequency and the duration of each data transmission. Also the transport layer may require the destination to send acknowledgements before it sends other data. This acknowledgement consumes more energy. In addition, sending data at a bigger packet size can save energy since the number of transitions between sleep mode energy and wake up energy can be reduced. These factors affect the energy consumption. Also, depending on time criticality or the accuracy of the information, sometimes, there must be tradeoffs in the energy consumption.

Another very important issue that can have significant impact on the energy consumption of nodes in a network is the mobility behaviour of nodes. It is very important that we use a mobility model that accurately represents the movement of mobile nodes (MNs), because the position of the client nodes determines the frequency that the nodes send or receive data since the nodes become intermediate nodes for other data transmissions. These data transmission activities drain energy resources of the nodes.

There are two major techniques used to model mobility behaviors i.e. trace and synthetic models. Traces are mobility patterns that can be obtained from measurements in the real life. Traces provide accurate information because there are many participants in the collection of the data for a quite long period of time. However, this technique is quite expensive and may take a long time. "Moreover, it is not applicable for new network environments (e.g. ad hoc networks) as traces have not yet been created in advance. In this type of situation it is necessary to use synthetic models. Synthetic models attempt to realistically represent the behaviors of MNs without the use of traces" [28, p2]. In many scenarios, random models are far from reality and they can be adopted in order to emphasize worst-case scenario results.

There are five most common mobility models in the synthetic method:

- Random walk mobility model
- Restricted random walk mobility model
- Random waypoint mobility model
- Random direction mobility model
- Normal markovian mobility model

The random walk model is one of the most commonly used in ad hoc simulation because it is quite realistic. In the random walk model, the speed is uniformly distributed between a determined minimum speed and maximum speed. The direction is also uniformly distributed between 0 and 2π. Each node moves a fixed distance. After that, they choose a random speed and a random direction again.

The restricted random walk model is similar to the above. The only difference is that after a node finishes a movement, it chooses a speed uniformly between s-k and s+k, where s is the last speed, k is a changing factor. It also chooses a direction angle uniformly between _-π/4 and _+ π/4 of which _ is the last angle.

The random waypoint model is difference from the first two is that the host selects a random destination first. It moves to the destination with a speed between minimum speed and maximum speed. The node stays stationary for a pause time and selects a random destination again. However, the model tends to produce high node density in the centre of the map which is sometimes not correct.

The random direction mobility model tries to avoid high node density on the centre of a map by combining the random waypoint and the random walk models. A node chooses a speed and a direction distributed uniformly and goes on until it reaches a map border. After a pause, the node chooses a new destination and speed.

Depending on the mobility model and its parameters, they produce different node densities on the networks. As the topology of network changes, the data transmission patterns on the network also changes and the energy consumption of each client on the network also varies. In general, research should be done to evaluate the mobility model that most closely matches the expected real-world scenario. This can be done by anticipating the moving and stopping behaviors of client nodes. After that, one or a combination of the above models is used. The more accurate the mobility model is used, the more efficient the energy based routing protocol is designed.

Fig. 5 below shows a simulation scenario MANET with 50 nodes on the area of (500m, 500m). The transmission range is 100 m. The scenario may be applicable for a group of people in a camping area or in a campus. Every node moves with the random walk model with the average of the velocity is around 1m/s. The model is used to test the current AODV routing protocol in the network in term of its energy consumption, packet loss ratio and packet delay of every node in the network [54].

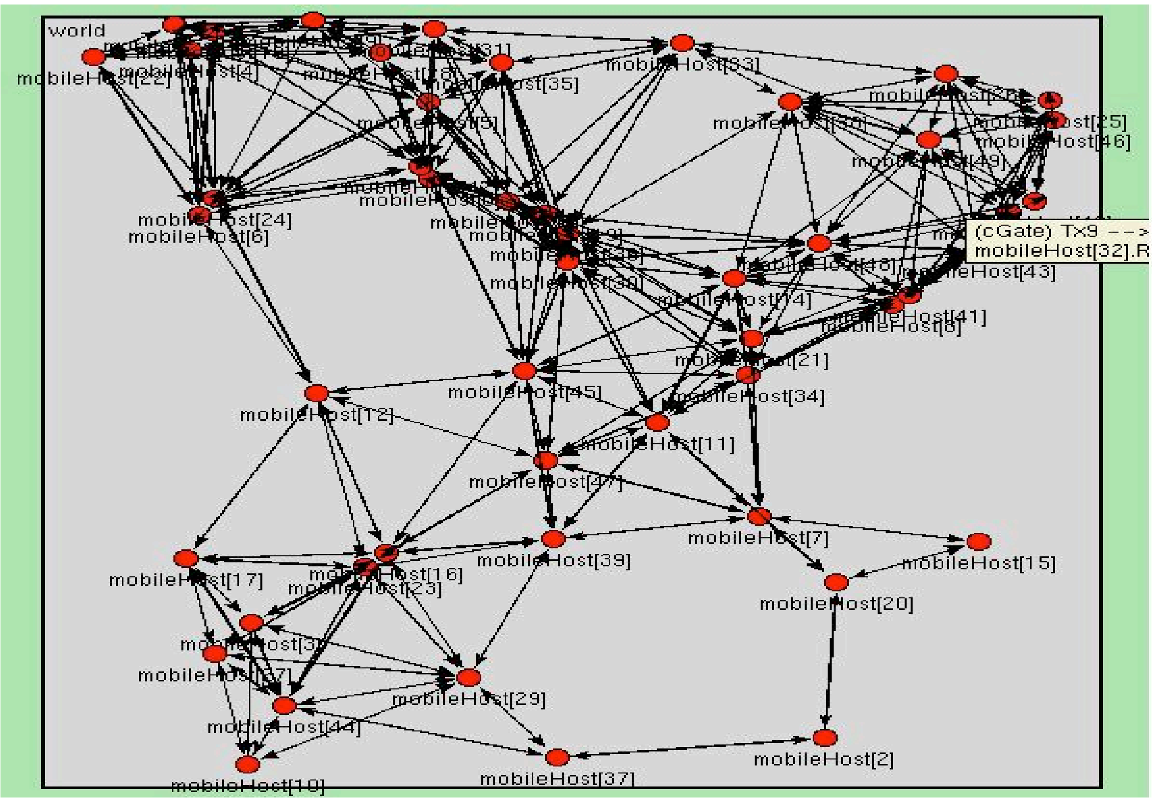


Fig. 5 A simulation scenario for AODV with Random Walk Model

In summary, routing techniques need to address the above issues to be applicable in wireless networks. The next sections review current energy based routing techniques.

6. Mathematical Models for Optimizing Energy Consumption

Definition of Variables:

A general wireless network can be modelled as a directed graph $G(N, A)$. N is the set of all nodes and A is the set of all directed links $i, j \in N$. S_i is the set of all nodes that can be directly reached by node i in its transmit range. There are two common problems in energy consumption considerations: maximizing network lifetime and minimizing total energy consumption. Let E_i to be the initial battery energy E_i stored at of node i. Let e_{ij}^t be the energy consumed at node i to transmit a data unit on link (i, j), and let e_{ij}^r be the energy consumed by the receiver j to receive the data unit. Let us consider the complex scenario in which there are multiple commodities in the network. These commodities have different energy costs to reach from any node i to any node j in this network. A commodity is defined by a set of source nodes and destination nodes. For each commodity $c \in C$, there exists a set of origin nodes $O^{(c)}$ where information is generated at node i with rate $Q^{(c)}$, i.e,

$$O^{(c)} = \left\{ i \mid Q^{(c)} > 0, i \in N \right\} \quad (7)$$

and a set of destination nodes $D^{(c)}$ among which any node can be reached in order for the transfer of commodity c. Let q_{ij}^c be the transmission rate of commodity c from node i to node j. $Q_i^{(c)}$ is the information-generation rates at the set of origin nodes $O^{(c)}$ and the set of destination nodes $D^{(c)}$ for each commodity c.

Maximize network lifetime problem:

The maximizing network lifetime can be written as the following mathematical problem:

$$\begin{aligned}
&\text{Maximize T} \\
&Tq_{ij}^{(c)} \geq 0, \forall i \in N, \forall j \in S_i, \forall c \in C, \\
&\sum_{j \in S_i} e_{ij}^t \sum_{c \in C} Tq_{ij}^{(c)} + \sum_{j: i \in S_j} e_{ji}^r \sum_{c \in C} Tq_{ji}^{(c)} \leq E_i, \forall i \in N \qquad (8) \\
&\sum_{j: i \in S_j} Tq_{ji}^{(c)} + TQ_i^{(c)} = \sum_{j \in S_i} Tq_{ij}^{(c)}, \forall i \in N - D^{(c)}, \forall c \in C
\end{aligned}$$

where $T\ Q_i^{(c)}$ is the amount of traffic generated by node i until time T. Variable T is an independent variable in the linear programming problem [45].

Minimizing total energy consumption problem:

The minimizing total energy consumption can be written as the minimizing commodities cost on network problem. This problem is the common mathematical problem for network.

$$\begin{aligned}
&Minimizing : E_{tot} \\
&q_{ij}^{(c)} \geq 0 \forall i \in N, \forall j \in S_i, \forall c \in C_i \qquad (9) \\
&\sum_{j: i \in S_j} q_{ji}^{(c)} + Q_i^{(c)} = \sum_{j \in S_j} q_{ij}^{(c)}, \forall i \in N - D^{(c)}, \forall c \in C
\end{aligned}$$

Both problems can be formulated as a linear programming (LP) problem. Details are given in [2]. These LP problems can be solved by any linear programming software package. These packages normally implement the simplex method but some newer methods are also available. Many well-known heuristic methods have been proposed for solving the LP problems practically: Tabu Search (TS), Simulated Annealing (SA) and Concave Branch Elimination (CBE) etc. There are tradeoffs in the processing time and the optimizing effectiveness of these algorithms. However, a simpler heuristic solution is preferred since the route discovery process and the routing decision need to be made 'on the fly' i.e. very fast. LP algorithms and the above heuristic methods are too complex to be run online inside a mobile device. Also, the faster the processing unit, the more energy the unit consumes. Therefore, a simpler heuristic solution is preferred since the computation to reduce the energy consumption must itself be energy efficient.

7. Energy Based Routing Techniques

7.1 Energy Based Routing Techniques for Wireless Mesh Networks

In wireless mesh networks, all nodes have equal roles, resources.

Mathematical models of any optimization problems are very useful because they provide bounds for practical solutions and show how good the solutions are. It is very hard to get the mathematical solutions in wireless mesh networks since mobile devices have very limited hardware capabilities. However, mathematical solutions can be applicable for centralized networks where base stations have very high resources and computing capacities. This is discussed more in centralized networks section.

7.1.1 Routing Techniques using Energy as Routing Metrics

In [18, 25], a minimum total power routing (MTPR) was proposed. In this protocol, the route with minimum total power consumption is selected from the set S containing all possible paths. The transmission power and the transceiver power (the power used when receiving data) are used as a link cost metric.

$$C_{i,j} = \mathrm{P}(\mathrm{n}_i, n_j) + \mathrm{P}_{\mathrm{tranceiver}}(n_j) \qquad (10)$$

where $P(n_i, n_j)$ is the transmission power between node n_i and node n_j that needs to satisfy the equation (4). $\mathrm{P}_{\mathrm{tranceiver}}(n_j)$ is the transceiver power at node n_j.

The total transmission power for route l , P_l can be derived from

$$P_l = \sum_{i=0}^{D-1} P(n_{i,} n_{i+1}) \text{ for all node } n_i \text{ in the route} \qquad (11)$$

where n_0 and n_D are the source and destination nodes, respectively. The desired route k can be obtained from:

$$P_k = \frac{\min}{l \in A} P_l \qquad (12)$$

where A is the set containing all possible routes.

Minimum battery cost routing (MBCR) [18] was another way to approach. In this protocol, the inverse of node batteries is used as metrics. The path metric is the total of the inverse of battery level of nodes. The path with smallest metric is preferred and selected from the route set. Let c_i^t be the battery capacity of node n_i at the time t. The battery cost function of node n_i: $f_i(c_i^t)$ is

$$f_i(c_i^t) = \frac{1}{c_i^t} \qquad (13)$$

The battery cost for route l consisting of D nodes is

$$R_l = \sum_{i=0}^{D-1} f_i(c_i^t) \quad (14)$$

The desired route k can be obtained from:

$$R_k = \frac{\min}{l \in A} R_l \qquad (15)$$

where A is the set containing all possible routes. However, since only the summation of values of battery costs is considered, a route containing nodes with little remaining battery power may still be selected. For example, if we have a route with 3 nodes and in the route, node 3 has a very low battery. If node 1 and node 2 have a very high battery, the total sum is still a small number and the route is still preferred route.

In order to improve the previous routing, min-max battery cost routing (MMBCR) was developed [18, 25]. In this protocol, node with the smaller remaining battery power will be avoided in selected paths to balance energy across networks. The battery cost for route l is redefined as:

$$R_l = \frac{\max}{i \in route\_l} f_i(c_i^t) \quad (16)$$

The desired route k can be obtained from:

$$R_k = \frac{\min}{l \in A} R_l \qquad (17)$$

But the disadvantage of the algorithm, like MBCR, is they do not try to minimize the energy consumption as the power consumption is not included in metrics. In order to achieve both saving energy and maximizing network lifetime**,** a protocol conditional max-min battery capacity routing (CMMBCR) was proposed [18]. In the protocol, when all nodes on a path have energy above a value called threshold value then MTPR is used. When the energy of any nodes is no longer higher than the threshold value, routing protocol is switched to MMBCR. Let R_j^c be the battery capacity for route j at time t:

$$R_j^c = \frac{\min}{i \in route\_j} c_i^t \qquad (18)$$

Let A be the set containing all possible routes between any two nodes at time t satisfying the following equation:

$$R_j^c \geq \gamma, \text{for any route } j \in A \qquad (19)$$

where γ is a predefined energy capacity threshold.

If (19) is satisfied, MTPR routing protocol is used. Otherwise, MMBCR is used.

Chang et al. [45] proposed a more complex formula to calculate link cost energy. In their approach, the path cost energy is the sum of the link costs on the path.

$$\cos t_{ij} = (e_{ij}^t)^{x1} \underline{E}_i^{-x2} E_i^{x3} + (e_{ij}^r)^{x1} \underline{E}_j^{-x2} E_j^{x3} \qquad (20)$$

where x_1,x_2 and x_3 are nonnegative weighting factors. $\underline{E}_i$ and $\underline{E}_j$ are residual energy of node i and j respectively. E_i and E_j are the initial energy of node i and j. e_{ij}^t and e_{ij}^r are the cost to send and receive a bit on link (i,j).

After each _ packets are sent, the residual energy of each node is updated again. The Bellman-Ford algorithm is used to calculate the shortest path cost from a source to a destination. The above formula includes energy cost for sending and receiving packet, residual energy and initial energy. This can be considered as a combination of routing metrics discussed in the previous techniques. The authors tried to run extensive simulations as combinations of F($x1, x2, x3$) to find a near optimal solution for energy consumption in their proposed network. An optimal solution can be obtained by solving linear programming problems which are described in the mathematical models for optimizing energy consumption section. If $x_1 = x_2 = x_3 = 0$ then the routing is the minimum hop path. If $x_1 = 1$ and $x_2 = x_3 = 0$ the routing is MTPR, and if $x_2 = 1$ and $x_1 = x_3 = 0$ the routing is MBCR. In an example of 20 nodes randomly distributed in a square of 50 m by 50 m, with the transmission range of each node limited by 25 m, one hundred randomly generated networks was experimented. In these networks, nodes 1 through nodes 5 are the origin nodes and nodes 16 through nodes 20 are the corresponding destination nodes, respectively. Simulations in the paper showed that the network life time in F(1,10,10) obtains nearly five times longer than that of MTPR on the worst case. On average, the network lifetime in F(1,10,10) is about 78 % longer than that of MTPR. Also, F(1,10,10) is always over 95% of the optimal solution.

In [47], energy consumption in multihop wireless sensor networks was studied. Wireless sensor networks are different from ad hoc networks in that there are larger number of nodes, usually thousands and the data rate is small. Also, broadcast communication is more common than point to point communication. As the nodes in this type of network are battery-powered, it is important to maximize the operation time of each node under energy constraints. In the paper, the energy consumption model of each node is illustrated in Fig. 6. In the model, e_{te} is the energy per bit needed by transmitter electronics, e_{re} is the energy per bit for receiver electronics to process the bit, and e_{ta} is the energy needed to successfully transmit one bit over one meter. The startup energies E_{st} and E_{sr} are the energy consumption for switching between idle and sending modes as well as between idle and receiving modes. The model is shown in Fig. 6.

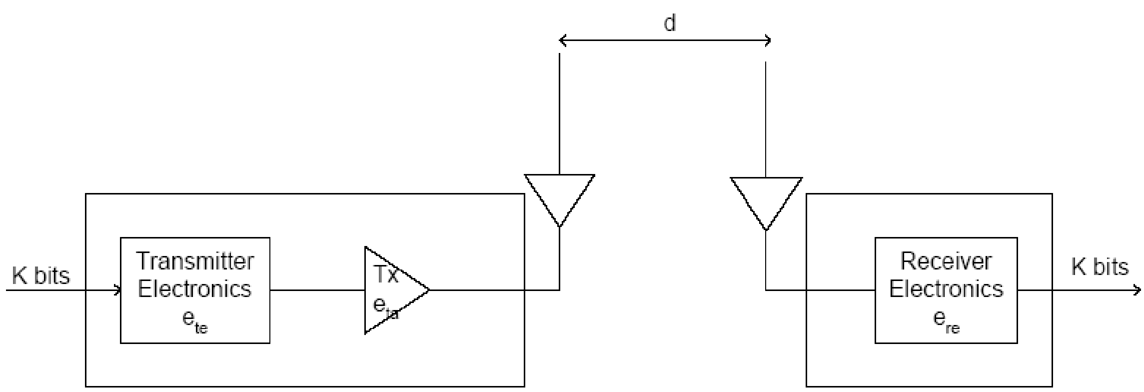


Fig. 6 Radio energy consumption model

7.1.2 Energy Based Routing Techniques based on Traditional Routing Protocols

7.1.2.1 Adding Energy Information into Control Packets

The routing techniques summarized in 7.1.1 do not report how the energy information is disseminated over a network. This makes these techniques less convincing.

Recently, work has been carried out to include the energy cost in control packets in MANETs. One approach for the method can be the usage of energy metrics in a protocol which is similar to the OSPF protocol. Each node runs the Dijkstra algorithm to find energy optimal routes. However, routing protocol overheads from these energy metrics result in scalability issues. Moreover, the routing protocols, like OSPF, are not fast enough to update the mobility information of mobile nodes.

In order to address the problem, a localized power-aware routing protocol (LPAR) has been introduced [48]. In this protocol, the connectivity of networks is maintained by a traditional reactive or proactive routing protocol. Each node periodically sends “hello” messages at its full transmission power. These "hello" messages contain the identifier of the sender and the minimum power to transmit a unit of data from the sender to each of its neighbours. Fig. 7 explains the ideas of communicating between nodes. Node 3 sends the information about itself and the power needed to transmit a unit of data from node 3 to node 5 (3, 5). Node 2 sends the information about itself and the power needed (2, 5) and (2, 6). From this information, node 1 builds a subgraph G(1,2,3,4,5,6) and runs the Dijkstra shortest path algorithm to compute the minimum-power path from itself to every node in the subgraph. The result is a localized optimization for the subgraph G(1,2,3,4,5,6). Node 1 puts the computation into its power table and exchanges the information with other subgraphs, like G(7,8,9), on the whole network. The total power used can be optimised with these collective localized optimisations at intermediate nodes in the subgraphs. The protocol only works on top of a traditional routing protocol, and thus it can provide energy efficiency but does not increase the number of routing overheads.

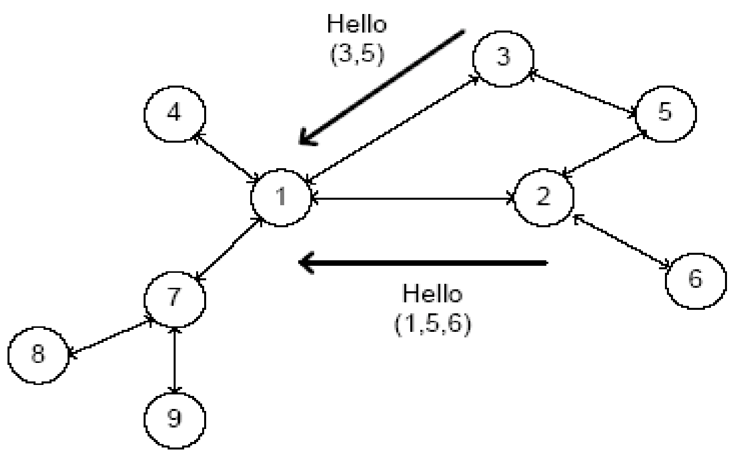
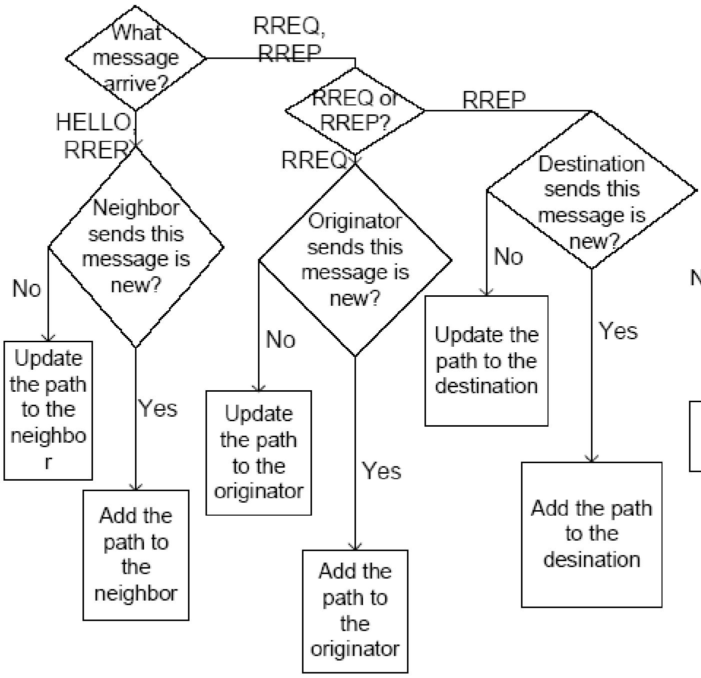


Fig. 7 Example of exchanging "hello" messages

Similarly, reactive protocols can be modified to be energy awareness protocols. In the original protocols, RREQ control messages are used in the route discovery process and RREP control messages are used in the route acknowledgement process. HELLO and RERR messages are additional control messages. HELLO messages maintain the network connectivity and RERR messages notify network disconnections to every node of the network. The route discovery procedure and the route maintenance procedure are modified to compute and maintain energy-efficient routes [26, 43]. These modified techniques vary depending on how control messages are broadcast over a network. However, the general idea of these protocols can be described by the operation of the balanced energy consumption (BE) algorithm below [56].

BE operation has two phases: handling control packets and updating routes in a routing table. It considers two parameters of a routing path: the minimum residual energy of all nodes of the path (X) and the number of hop counts of the path(Y). The operation of BE is described in the flow charts below:



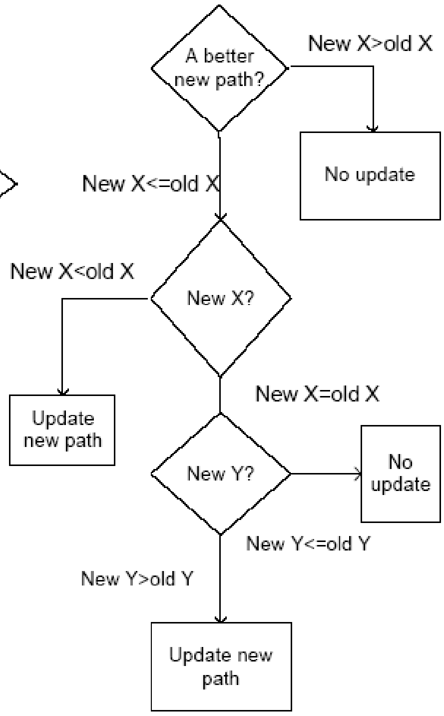


Fig. 8: Handling control messages **Fig. 9: Updating routes in the routing table**

In this section, we have assumed that devices have a fixed transmission power, and thus the energy needed to send a unit data between any two nodes is constant for any distance in the transmission range. However, some wireless devices are able to adjust their transmission power. If the transmission power dominates the total energy consumption of wireless devices, the power adjustment can save a significant amount of energy. This is often true with wireless devices of a long transmission range. Let us describe a few wireless systems with different transmission ranges.

Aironet 350 series card [69, 26] is one of IEEE802.11b wireless interface card. It offers 6 levels of transmit power control. The available power levels are 100 mW (20 dBm), 50 mW (17 dBm), 30 mW (15 dBm), 20 mW (13 dBm), 5 mW (7 dBm) and 1 mW (0 dBm). The tables below show the transmission range, capacity and receiver sensitivity performance.

Transmission range(m)	Capacity (Mbps)
40	11Mbps
107	1 Mbps
244 (out door)	11 Mbps
610 (out door)	1Mbps

Table 6: Transmission range versus capacity

Receiver sensitivity (dBm)	Capacity (Mbps)
-94	1
-91	2
-89	5.5
-85	11

Table 7: Receiver sensitivity versus capacity

The transmission power levels presented above are small (from 1 mW to 100mW) compared with the power consumption in electronic circuits and amplifiers. Therefore, the transmission powers cannot become link cost metrics to make routing decisions since we need to consider the total power consumption of these devices.

The authors in [22] show two examples about power transmission for geostationary satellite transmissions at 14 GHz. For uplink transmission:

$$P_R = \frac{P_T \times G_T}{L_{FS}} \times G_R = 20 + 53.1 - 207{,}4 + 38.2 = -96.1dBW = 250pW$$

For downlink transmission at 12 GHz:

$$P_R = \frac{P_T \times G_T}{L_{FS}} \times G_R = 10 + 38.2 - 206.1 + 51.8 = -106.1dBW = 25pW$$

Where P_T, G_T, L_{FS}, G_R and P_R are transmission power, transmission antenna gain, free space loss, receiver antenna gain and receiver power respectively.

In current cellular mobile phone systems, the mobile phone receiver sensitivity is about -110 dBm (10^{-14}W). The loss factor in cities is about 0.005. From formula (2) with α=4 for multi paths reflection transmission, if one mobile phone or one coreless phone wants to talk directly to another mobile phone over 1 km, the phone needs to transmit 1W out of its antenna, assuming the height of a transmitter and a receiver is 1 m [1], [62].

Typical UHF transceivers of cordless phones are used in many commercial applications and emergency services applications. Each phone can talk directly to another coreless phone in the transmission range from 1km to 5 km. Each transceiver transmits at the power cost of 4W with the current drain of 1.7A [70].

In order to transmit such a high power, portable wireless devices and mobile phones have to be designed so that the power flow out of antenna is maximized. This is done by matching output impedance with manufactured transmission lines. The impedance of general RF and microwave is 50 _ and the impedance of free space is 377 _.

These transmission powers in later examples definitely dominate the total energy consumption of the mobile phone. Therefore, the power adjustment capability can be employed in energy based routing techniques to optimize the energy consumption in wireless devices. These techniques are presented in the next section.

7.1.2.2 Adjusting the Transmission Power of Nodes

Adaptive power control

There are many studies in literature to work out the best transmission power because this can change the network topology and thus determine the best performance of network in terms of throughput, delay and energy consumption. The reduction of the transmission range will lead to the reduction of the energy consumption for delivering traffic on the network, because the radio frequency (RF) transmission power is estimated to be half of the total energy consumption of network interface cards (NIC) [50]. For long transmission range wireless systems over 1km, the RF transmission power even dominates the total energy consumption as the example in the previous section.

There are many practical works in controlling power transmission. In CDMA systems, each node maintains for each destination a weighted history of the received signal strength indication is larger than this threshold, the transmission power is reduced (subject to the constraints of the control loop). If the MAC layer times out waiting for a response, it records this threshold signal strength and retransmits using a higher transmit power. (In the example above, nodes a and b, experiencing loss due to interference, would increase their transmission power until their control traffic properly suppressed interference transmissions from node A [44]. There are another specified power control examples of mobile units in the United States.

There are three power classes. Each mobile station has eight full power levels (0 to 7) with power level 0 being the highest. The full power control range of class 1, level 0 is 28dB. The power of each level reduces 4 dB [1].

Power class	P, power level=0
Class 1	6dBW (4W)
Class 2	2dBW (1.6W)
Class 3	-2dBW (0.6 W)

Table 8: Power specification for mobile stations

Existing reactive protocols send or broadcast packets at the maximum fixed power. There are drawbacks to this approach. First, networks waste bandwidth due to the packet broadcast storm. Secondly, packets are lost due to contention and collision. A new protocol cross-layer power aware protocol for mobile ad hoc called CONSET was proposed in [43]. In CONSET, the MAC layer changes the routing tables by adjusting the power to send RREQ packets. In general, a smaller transmission range is preferred because the distance between any two hops is small. The small distance consumes less energy per path according to formula (1). However, the transmission range can not be too small to guarantee the network connectivity. If the transmission range is too small, there are fewer options of paths to deliver data. When a link is broken, all data sent are lost. In summary, in this technique, each node needs to dynamically compute its transmission power to make efficient energy paths but also maintain network connectivity.

Similarly, the trade-offs in selecting transmission powers were discussed in more detail in [50]. In this study, the authors reported that the ratio of the energy consumption by the transmission power over the total energy consumption of wireless devices is expected to increase in the near future as the energy consumption for data processing is reducing now. As the result, low power for transmission saves a significant amount of energy for wireless communications. Furthermore, this reduces unnecessary energy consumption of neighbours that are not involved in the transmission. If neighbours receive unnecessary packets, they waste their energy to discard these packets. However, reducing transmission power can reduce the number of active links and so partition and disconnect the network. In order to avoid the degradation of the network, the network layer needs to interact with the MAC layer to dynamically control transmission powers to save the energy consumption but also to maintain network connections.

There are other advantages in adjusting the transmission power. The transmission power adjustment can be used to balance the energy consumption of nodes on networks. This is done by employing the radio channel capacity to control the transmission power. Each data transfer is partitioned into two segments. The first one uses the regular connection path on the network. The second one uses the direct transmission between a source and a destination. The duration of each segment is calculated based on the energy capacity of nodes on the network, thus the total energy consumption is balanced across the network [40].

7.2 Energy Based Routing Techniques for Centralized and Clustered networks

So far, we have discussed mesh networks, where every node has equal role and capacity. When the number of nodes increases to the order of hundreds, thousands or more, there is a long delay in setting up paths between nodes and a waste of bandwidth due to the large number of packet overheads. This is often true with wireless sensor networks and wireless sensor ad hoc networks Al-Karaki et al. [53] argued that clustering based protocols are more suitable for a scalable network. In clustered networks, nodes are grouped into clusters, where a centre node collects, processes and forwards data to every node in the cluster.

The clustering network problem involves combinatorial optimization problem, which may not be solved by mathematical approach because of computational complexity. As for example, consider the topological configuration problem, if n denotes the number of nodes, the maximum number of links is given by n(n-1)/2. Thus, the number of possible topological configurations that can be constructed is $2^{n(n-1)/2}$. For n=10, there are 2^{45} possible configurations. A powerful computer which would be capable of generating 1000 configurations per second would spend about 1,116 years to explore the entire search space of candidate topological configurations. Therefore, many heuristics methods have been proposed for the design of clustering networks: TS, SA, CBE and Cut Saturation (CS). In fact, TS and SA have been widely used to design clustering networks. An example of the routing protocol using SA is presented in this section.

Fig. 10 shows the average power consumption versus different Intel® StrongARM™ CPU processor's speeds.

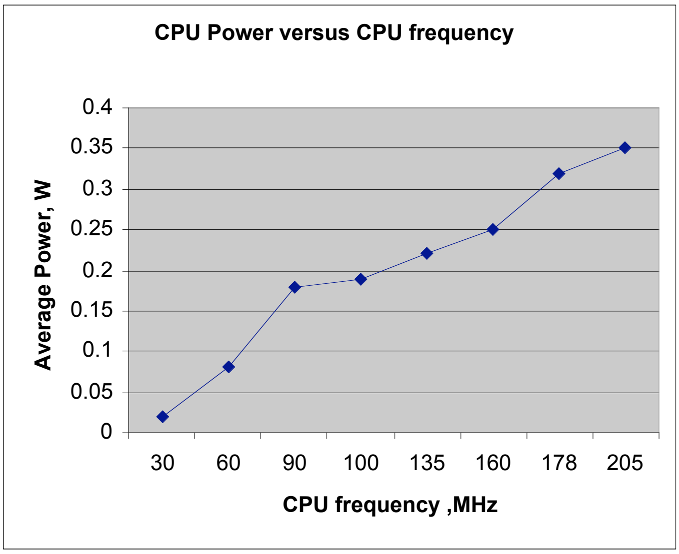


Fig. 10 Measured system power versus CPU frequency at 3 V power supply [61, p719]

Muruganathan et al. [57] mentioned that clustering networks helps to reduce the amount of control information that is needed to be broadcast to all nodes on these networks. However, conventional clustering techniques have not addressed the network lifetime issues as they assume that centre nodes are fixed and have a very high energy capacity.

In order to improve network lifetime, Heinzelman et al. [14] proposed a Low-Energy Adaptive Clustering Hierarchy (LEACH). In this technique, the operation of the protocol is divided into rounds. Each round consists of setup and transmission phase. In the setup phase, the network is divided into clusters and nodes negotiate to nominate cluster heads (CHs) for the round. During the setup phase, in the whole network, a predetermined fraction of nodes, p, elect themselves as CHs as follows. A node chooses a random number, r, between 0 and 1.

If ($r < T(n)$) **then**

the node becomes a CH for the current round

else

the node is a non-CH node

where T(n) is a threshold value given by:

$$T(n) = \frac{p}{1 - p(r \bmod (1/p))}, n \in G, \quad (21)$$

where G is the set of nodes that are involved in the CH election. The formula incorporates the desired percentage to become a CH p, the set of nodes that have not been selected as a CH in the last (1/p) rounds.

In more details, let us expand the formula:

If $C_i(t)$ is the indicator function determining whether or not node has been a cluster head in the most recent r mod (N/k) rounds (i.e., $C_i(t)=0$ if node has been a cluster head and one otherwise), then each node should choose to become a cluster head at round with probability

$$P_i(t) = \frac{k}{N - k \times (r \bmod \frac{N}{k})} : C_i(t) = 1 \quad (22)$$

$$P_i(t) = 0 : C_i(t) = 0$$

The selected CHs for the round advertise themselves as the new CHs to the rest of the nodes in the network. All the non-CH nodes decide on the cluster to which they want to belong after they receive the advertisements. This decision is based on the signal strength of the advertisements. The non-CH nodes then inform the selected CH that they will be a member of the cluster. After receiving all feedbacks, each CH knows the number of nodes in its cluster. It creates a time-division multiple access (TDMA) schedule and assigns each member a time slot when the member can transmit data. The schedule is broadcast to all the members in the cluster. In the transmission phase of LEACH, the elected CH collects all data from nodes in its cluster and forwards data to a base station (BS). The authors found that only 5% of the nodes need to act as CHs. At the end of each round, a new set of nodes become CHs for the next round. It has been shown that LEACH saves energy consumption and improves network lifetime.

The radio model for low-energy radios of LEACH protocol includes the energy dissipation in the transmit and receive mode. In LEACH model, the radio dissipates Elec=50nJ/bit to run the transmitter and receiver circuitry and εamp=100pJ/bit/m^2 for the transmitter amplifier to achieve an acceptable E_b/N_o. If we use Bluetooth as the radio interface with the capacity 700Kbps, the power source operates at 2.7V and 30mA or 115 nJ/bit. As a result, the distance d is approximate 30m [14]. The example is modelled in Fig. 6 as well.

In the above approach, if the random number (say, generated between 0&1) is less than the threshold, then the node becomes a clusterhead. But in long run, there may be cases that the clusterheads are formed densely within a small zone, or there may be the cases that within a zone, there are almost no clusterheads. So the sensor nodes within that particular zone require considerable energy to communicate with the clusterheads. Again random selection mechanism can lead to a short-term variation in number of clusterheads. If too few clusterheads are present then intra-cluster communication over distances may waste significant energy. Another important point that should be noted in the formation of clusterheads is that LEACH considers the number of times the node has been a clusterhead so far and not the residual energy. A clusterhead formed at a large distance from the base station requires more energy to communicate with the base station compared to a clusterhead formed closer to the base station. As the result, in the first case the energy required by the cluster head in the second case can communicate twice with the base station using the same energy. So in any energy efficient routing protocol, what is most important is the residual energy of each node (and hence the lifetime of the node) rather than number of times the node has been a clusterhead.

In order to verify LEACH routing formulas and the above discussion, we use a well known random numbers generator written by I.W. Saunders [72]. There are 100 nodes in the network of 100m_100m.It is interested in looking at the nodes position distributions and the number of cluster heads in different rounds. For k=5, we run 15 different tests using the same random machine and we found that there is one run that there is only one cluster head but there is one run that the number of cluster head is equal 8. For k=8, the number of cluster heads vary from 4 to 11. When the number of runs increases, the average number of cluster heads converges but since the transmission energy consumption is at least quadratically related to distance, some nodes might run out of energy immediately. As a result, we discuss that k should be higher than 8 and in some scenarios; only 5% of the nodes need to act as CHs is not enough.

In order to address the above issues in LEACH, the enhanced-efficient adaptive clustering protocol for distributed sensor networks is proposed (EEEAC). The clusterhead can be formed based on the residual energy of each node. Residual energy is calculated for every node after each round of transmission. Every node transmits a code containing the information about its residual energy to its neighbour along with the node-identification. In this distributed sensor network environment, the nodes are assumed to be mobile, and so, the position of the nodes is changing from time to time. The base station is fixed and located far from the sensors and it is assumed to have infinite power. The cluster head can be formed based on the residual energy of each node. Residual energy is calculated for every node after each round after each round of transmission. A node, receiving the two strings and the code containing the residual energy of all other nodes, compares its residual energy with the residual energy of all other nodes in the same sub-area. If its residual energy is more than that of the residual energy of all other nodes under same sub-area, then the node is cluster head for that round within this sub-area. If its residual energy is less than that of residual energies of some of other nodes, then it can detect the node having the maximum residual energy and elect it as clusterhead.

The method of communication between the nodes and the clusterhead is same as that if the LEACH. In order to reduce the interference with nearby cluster, each cluster communicates using different CDMA. A unique code is assigned to each sub-area. Once the nodes identify their sub-area, they are assigned a particular code for that sub-area and use that code to communicate.

The result shows that after 3800 rounds no nodes are alive for LEACH but almost all the nodes are alive in EEEAC [59].

LEACH was further modified to a new centralized version called LEACH-C [29]. Unlike LEACH, LEACH-C utilizes the BS for creating clusters. During setup phase, the BS receives information about the location and the energy level of each node in the network. Using this information, the BS decides the number of CHs and configures the network into clusters. In order to do this, the BS computes the average energy of nodes in the network, and nodes that have energy storage below this average cannot become CHs for the round. From the remaining possible CH nodes, the BS finds clusters using the SA algorithm to find the k optimal CHs. The CH selection problem is an NP-hard problem [2]. The solution attempts to minimize the total energy required for non cluster head nodes in sending data to the corresponding CHs. When the clusters are found, the BS broadcasts a message that contains the cluster head ID for each node in each cluster. If a node's ID matches this ID, the node becomes a cluster head. Otherwise, the node determines its TDMA slot for data transmission from the broadcast message and is in the sleep mode until the time to transmit data. The transmission phase of LEACH-C is identical to that of LEACH. In more details, BS keeps tracks current CH node coordinates, nodes that are possible CHs for current round, cluster numbers. In addition, BS knows local CH for every node in the network, and possible new CH node number. In each round, BS recalculates the average energy per node. Only nodes with energy above the average are eligible to be cluster-head nodes during this round. From the eligible nodes, BS runs a simulated annealing algorithm to determine the set of nodes that minimize the sum of squared distances between the non-cluster-head nodes and the cluster-head nodes. Using SA algorithm, BS first finds the initial list of CH nodes with the initial cost of set C. BS iterates a predefined number of times. In each iteration, BS finds a new set C' that is a set of nodes that are random perturbations of the (X,Y) coordinates of the nodes in C. If C' < C, C' becomes new optimum. The final optimum will be the current CHs for the current round [71]. When the base station wants to send a message to the sensor nodes, it inserts packet header information and passes the message to the link layer. When the base station receives a packet form the link layer, it sends up the packet to the application layer.

The authors used the network simulator ns2 [64] to compare LEACH-C to LEACH and the minimum total energy routing protocol (MTE) which is similar to the MTPR above. In the simulation, a 100-node network was used. Each simulation was run for 1000 simulated seconds. The number of clusters was varied between 1 and 11. The simulation shows that the optimum number of clusters is 5 for the 100-node network. As the result, k is set to 5. The simulation also shows that LEACH-C delivers about 40% more data per unit energy than LEACH and LEACH distributes an order of magnitude more data per unit energy than MTE. Also static clustering does not perform well when the nodes in the networks have limited energy. The results are shown in Fig. 11. The authors in this paper explained reasons for the improvement of LEACH-C. The base station has a global knowledge of a network so it can select better clusters for optimizing the energy consumption. Also, the number of cluster heads in each round equals a predetermined optimal value, whereas the number of cluster heads in LEACH varies from round to round due to the lack of global information about the position of nodes.

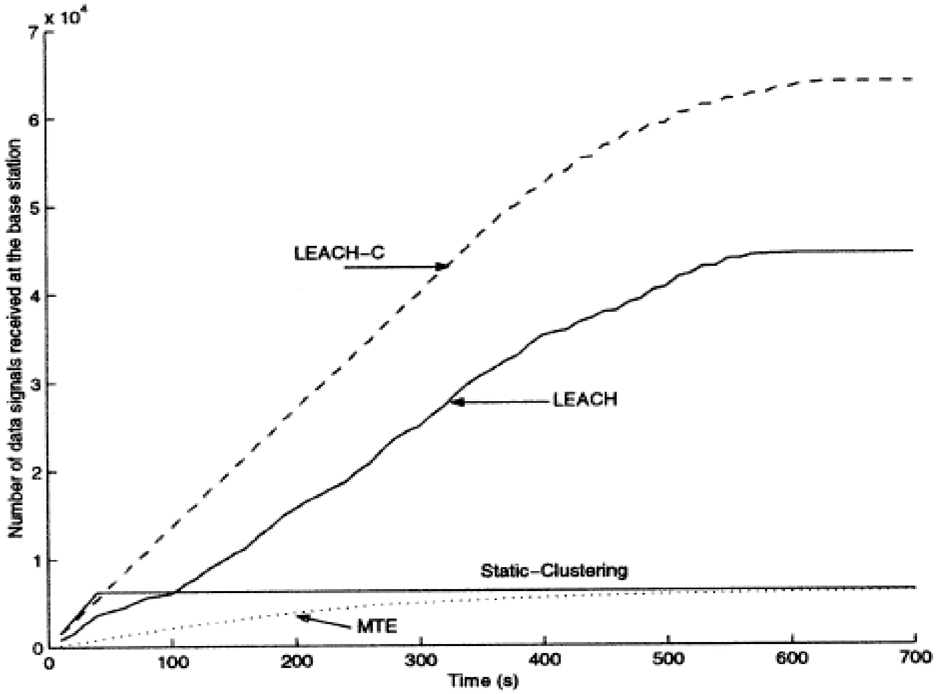


Fig. 11 Comparison between LEACH-C, LEACH, MTE and static clustering [29, p667]

Another enhancement over the LEACH protocol was proposed called Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [30]. The basic idea in this protocol is to reduce the energy consumption of nodes to transmit data to the BS. In order to do this, nodes need only transmit data to their closest neighbours, and these neighbours take turns in communicating with the BS. When the round of all nodes communicating with the BS ends, a new round starts, and so on. In order to locate the closest neighbour, each node uses the signal strength to measure the distance to all neighbouring nodes and adjusts the signal strength so that only the closest one can hear. Therefore, a path to the BS consists of those nodes that are closest to each other. In order to compare the performance of PEGASIS with LEACH, several random 100-node networks were simulated for both protocols in both scenarios: 50m_50m and 100m_100m. The BS is located at (25,150) in the 50m_50m field and (50,300) in the 100m_100m field. The lifetime of a network can be defined as the time until 1%, 20%, 50% or 100% of nodes run out of energy. Simulation results showed that the lifetime in PEGASIS performs better than that of LEACH by about 100% to 300% depending on the lifetime definition. This performance is shown in Fig. 12.

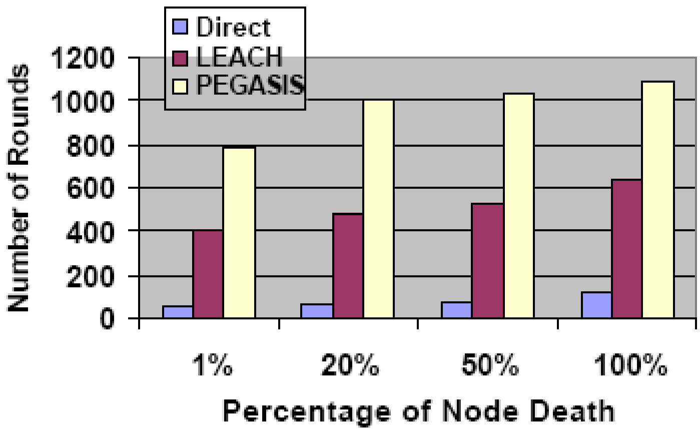


Fig. 12 Comparison between PEGASIS and LEACH [30, p5]

Muruganathan et al. [57] proposed another further improvement from the above centralized routing protocols called Base Station Controlled Dynamic Clustering Protocol (BCDCP). In this technique, a very high energy BS is employed to setup routing paths and clusters, and to nominate randomized and alternate CHs. During a setup phase, the BS receives information about the current energy level from all the nodes in the network. From this information, the BS chooses a set of nodes **S** which have their energy level above the average energy level of all nodes in the network. CHs for a round are chosen from the set **S**. From **S**, the BS identifies N_{CH} cluster heads and groups the other nodes into N_{CH} clusters so that the overall energy consumption to transmit data from every node to the BS is minimized. An iterative cluster splitting algorithm is used in the clustering process by the following steps:

1) From **S**, choose two nodes, s_1 and s_2 that have the maximum separation distance
2) Group the remaining nodes with either s_1 or s_2 , whichever is closest
3) Balance the two groups so that each group has approximately the same number of nodes
4) Split **S** into $\mathbf{S_1}$ and $\mathbf{S_2}$, and repeat step 1 with $\mathbf{S_1}$ and $\mathbf{S_2}$ until the number of clusters is N_{CH}

The central idea in this protocol is the formation of balanced clusters where each cluster head serves an equal number of nodes. This idea helps to balance the traffic load of cluster heads. In addition, the BCDCP optimizes the CH-to-CH multihop routing scheme to transfer the data to the BS. In order to do this optimization, the routing path between a CH to the BS is selected using the minimum spanning tree approach that minimizes the energy consumption for the CH to forward data to the BS. The optimization further improves the system lifetime and the energy consumption. 50 different 100m_100m network topologies with 500 nodes and the base station located at least 75 m away from the nearest node are simulated. Simulations in [57] showed that on average, BCDCP reduces the total energy consumption 40% and 30% over LEACH and LEACH-C, respectively. This is because all the CHs in LEACH and LEACH-C transmit data directly to the BS that is in a long distance from the CHs. Furthermore, on average, BCDCP improves the system lifetime by 100%, 30% and 5% over LEACH, LEACH-C and PEGASIS respectively.

Safwat et al. [42] proposed other cluster-based routing architecture called virtual based stations (VBS). In the protocol, the wireless mobile ad hoc networks rely on the wireless mobile infrastructure created by the protocol to provide connections between any pair of wireless stations. Therefore, only core nodes participate in the routing process. However, these nodes unfairly lose their remaining battery. In [20], he proposed a new approach to achieve energy conservation by developing a novel infrastructure formation scheme for wireless mobile ad hoc networks called Power-Aware Virtual Base Stations (PA-VBS) architecture. The protocol can be summarised by two main points. Some of the mobile terminals (MTs) are elected to be in charge of all the MTs in their neighbourhood, based on their current residual battery capacity. These MTs become PA-VBSs. If a PA-VBS moves or stops acknowledging its presence via its periodic hello messages for a period of time, a new one is elected. Let MAX-POWER be the minimum required battery capacity for a MT exists in one day without having to be re-charged, provided it does not become a VBS during the whole one-day period. Let NPV_i be the instantaneous battery capacity of MT i, divided by MAX-POWER. The implementation details of PA-VBS protocol can be described by the following steps:

1) An MT is chosen by one or more MTs to be their VBS based on some predetermined battery thresholds
2) MTs announce their NPVs in their periodic hello messages
3) An MT sends a merge-request message to another MT if the NPV of the latter is higher than or equal to that of the former, and is higher than a predetermined energy threshold, namely THRESHOLD_1 ,the latter becomes PA-VBS
4) The receiver of the merge-request responds with an accept-merge message
5) The PA-VBS set its myVBS variable to 0
6) When the MT receives the accept-merge, it increments its sequence number by 1 and sets its myVBS variable to the ID number of its new PA-VBS
7) If an MT hears from another MT whose NPV is larger than that of its VBS, it does not send a merge-request message to the MT as long as its VBS's NPV is above THRESHOLD_1
8) When the NPV of the PA-VBS reduces below the second energy threshold, namely THRESHOLD_2, the PA_VBS enters its service-denial mode of operation.

PA-VBS allows mobile hosts to use their energy capacity fairly. It does not drain all the battery of the cluster heads since PA-VBS nodes can be in the service-denial mode. In other word, a fair clustering is obtained.

In order to improve the protocol further for a dynamic wireless mobile infrastructure, a warning energy aware clusterhead (WEAC) is proposed [41]. In the WEAC protocol, a mobile node is elected from a set of nominees to act as a temporary base station for a period of time within its zone. Like PA-VBS, some of the MTs are elected to be in charge of all the MTs within their transmission ranges or a subset of them. Every MT acknowledges its location via hello packets (beacon packets). MTs are classified as follows:

a) Clusterhead: as it is named, the leader of the clusterhead
b) Zone_MT: an MT supervised by a clusterhead
c) Free_MT: an MT that is not a clusterhead nor zone_MT
d) Gateway or Border Mobile Terminal: MT that lies between more than one clusterhead or a Free_MT, it can be a clusterhead or a zone_MT or a free_MT

Every MT has a myCH variable. If a MT is a clusterhead, then the myCH variable will be set to 0. Otherwise, it will be set to -1 indicating that it is a clusterhead of itself or free node.

Clusterheads are elected from a set of nominees based on their BPL based on the following policy. A zone-MTs, accumulate information about network from their neighbour and broadcast their neighbour_list to their neighbour in their hello packets. An MT sends a merge-request message to another MT if the latter has a higher BPL and it should be higher than THRESHOLD_1. The receiver of the merge-request message responds with accept-merge message and set myCH variable to zero. When an MT receives the accept-merge message it sets its myCH variable to the ID number of its clusterhead. The BPL is characterized into four categories

1) MT BPL≥THRESHOLD_1: An MT is eligible to be clusterhead and willing to accept other MTs to be under its supervision if these MTs have a lower BPL. If myCH=0, no merge request will be sent by MTs.
2) THRESHOLD_1<MT BPL≥THRESHOLD_2: An MT will ignore any merge request messages that are sent to it by other MTs. If the MT is serving as a clusterhead, it will remain a clusterhead, but it will add no more nodes under its supervision, however; as in the first point, If myCH=0 no merge request will be sent by MTs
3) THRESHOLD_2=MT BPL≥THRESHOLD_3: If an MT is serving as a clusterhead, it set its warningThreshold flag to true, informing its zone_MTs to look for another clusterhead. But they can remain with it till its BPL down to THRESHOLD_3
4) MT BPL=THRESHOLD_3: An MT ignores any merge request messages and will

send I Am no longer your CH message to all the nodes under its supervision, if it was serving other nodes.

A clusterhead collects complete information about all other clusterhead and their lists of MTs and broadcasts this information in its periodic hello messages.

Simulation for the protocols were set up for wireless mobile ad hoc networks on the area of 7000_7000 unit. The transmission range of each mobile node is 250 units. Every node moves randomly in any direction with a velocity of each mobile node is uniformly distributed between 0 and 5 units/second. THRESHOLD_1 is set to 75%, THRESHOLD_2 is set to 45%, and THRESHOLD_3 to 25% of the maximum power of the battery. Each simulation is run for 6 simulated hours, and the network is sampled every 2 seconds. Compared with VA-VPS, WEAC has better performance in terms of load balancing, energy saving, and packet delivery time. There fore, WEAC is promising protocol for a QoS management.

In summary, to reduce energy consumption of devices, most energy-conserving protocols are designed to operate in a centralized-node or base station environment. With much higher resources, base station can control traffic and allow clients to be in a low power sleep mode most of the time and optimize the total energy consumption for the whole network.

7.3 Hybrid networks and Energy Consideration

A hybrid network is the combination of a wireless mesh network and a centralized and clustered network. There are more and more demands for hybrid networks, in which MANETs connect to the global Internet by routers. Hybrid networks are also solutions to the limitation of the energy capacity of mobile nodes.

Lamont et al. [39] argued that research needs to be done to connect MANETs to the Internet infrastructure to fill the gap in the area where Wireless Local-Area Networks (WLANs) coverage is not reachable. Currently, WLANs are limited in connecting to the Internet. Only hosts that are one hop away from routers can connect to the Internet. The desire is to use MANETs in a way that nodes which are multiple hosts away from routers are able to connect to the Internet. Also, since Internet Protocol (IP) has been a dominant protocol that supports Internet, MANETs are more competitive in markets if they can connect to the IP networks.

Let us consider the energy consumption of a practical ad hoc mobile network of the Lucent IEEE 802.11 Wavelan PC 2 Mbps cards with the transmission range of 250m. Fig. 12 shows the energy consumption associated with the delivery of a message of 1Kb to the destination node according to the number of hops necessary to reach the web station. The energy is the sum of the energy consumed on all the nodes involved in the communications [61].

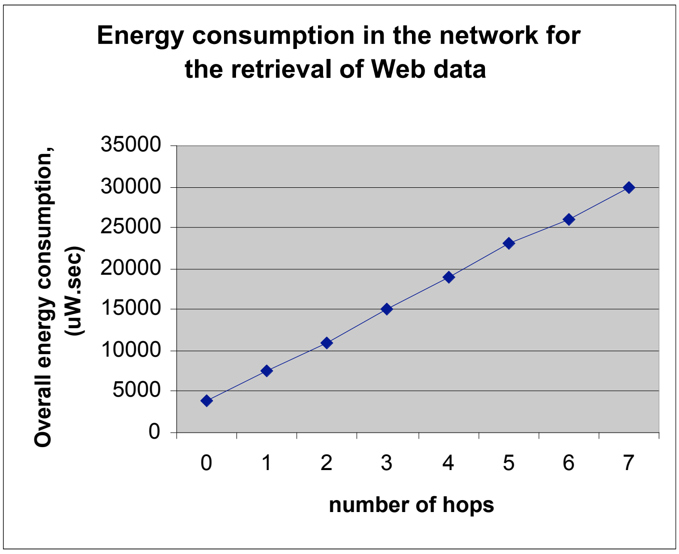


Fig. 13 Energy consumption in the network for the retrieval of Web data [61, p800]

Similarly, Wang et al. [58] anticipated that there are many scenarios of small MANETs connected to the global Internet by routers. The authors proposed a mechanism for IP version 6 (IPv6) mobile nodes to form a self-organizing, self addressing MANET tree structure which is rooted with an Internet gateway. Each MANET is formed by mobile devices in a small geographic area, such as a meeting room, a building or a train. The mobile IPv6 handover scheme will support mobile host moving from one MANET to another.

Lamont et al. [31] presented a novel approach to integrate WLANs and MANETs to IPv6 based Internet. A mobile host can belong to a WLAN or a MANET. The mobile host may connect to a WLAN and move to an area outside the WLAN. This host needs to switch into ad hoc mode and connects to a MANET. Handoffs between MANETs and WLANs are supported with an automatic mode-detection and mode-switching capacity.

Energy based routing techniques for hybrid networks can take advantages of previous proposed energy based routing techniques for both wireless mesh networks, and centralized and clustered networks.

In the case of mesh networks, mobile hosts can be connected together in a wide coverage area. However, energy consumption is a major issue when the number of connections between nodes on MANETs increases. In centralized and clustered networks, central nodes or base stations can control traffic and allow other mobile hosts to be in low power consumption mode. However, in these networks, all mobile hosts must be in the coverage area of the base stations.

In hybrid networks, mobile hosts can use energy based routing techniques for mesh networks when they have a high energy capacity. However, when their energy capacity reduces below a value called threshold value, these mobile hosts need to switch to a centralized and clustered mode. In the mode, mobile hosts can be in a low power sleep mode most of the time when they do not transmit their own data. Furthermore, when these mobile hosts have data to transmit, they can employ the nearest router to forward their data. As the results, the lifetime of hybrid networks are significantly improved compared with the lifetime of full mesh networks, but the coverage area can be extended bigger than that of the centralized and clustered networks.

8. Conclusions

The literature survey has introduced the current energy issues of wireless devices, the energy measurement results and energy models of commercial wireless devices. The information shows that the energy consumption of wireless devices is high and the consumption is a major issue when the number of connections between nodes on MANETs increases and the transmission range is extended to a long distance. There are two main approaches to the problem. The first approach is to design power-save protocols to reduce idle energy consumption while minimizing impact on data transmission. The second approach is to design energy based routing techniques to reduce the energy consumption of wireless devices in networks. In energy based routing techniques, there are two main approaches. The first one is for wireless mesh networks where nodes have equal roles and resources. The second one is for centralized and clustered networks.

The first approach is subdivided into three techniques. The first technique uses parameters related to energy as routing metrics to calculate routes in a routing table. The advantage of this method is that it is very simple and the routing decision can be made 'on the fly' i.e. very fast. However, the weakness of this method is that authors have not shown how the energy information is disseminated over nodes in networks. This makes the technique less realistic. The second technique employs control messages to carry the energy information to every node on the network. This technique is more realistic in telecommunication networks. It is also quite simple and the routing decision can be made online. The drawback of this technique is that the optimal solution is not obtained. The last technique optimizes the best power transmission range of each node on network to reduce the energy consumption. This technique can obtain the optimal solution. However, complex algorithms in the method are quite slow to run online. Also, a complex hardware circuit increases energy consumption. Furthermore, since the transmission power is different between nodes, connection links in the network are unidirectional. This asymmetry reduces the packet delivery percentage of the network.

The second approach employs two methods. The first method creates central nodes and clusters by electing central nodes depending on the energy resources of nodes on networks. The second method is to use a base station. The base station collects necessary information in a network and decides the number of clusters and which nodes are centre nodes. This decision is made to optimize the energy consumption of all nodes in the network. The two methods promise to improve energy consumption significantly since client devices can be in a low power sleep mode while they are not involved in communications. However, there have been discussions about the cost of building base stations and the speed at which algorithms run to create centre nodes and clusters.

While designing energy based routing protocols, other issues need to be considered because they are indispensable in designing routing protocols in general. They include resource-constrained nodes, node and link failures, scalabilities, quality of services and data sending methods. Another very important issue that can have significant impact on the energy consumption of node is the mobility behavior of the nodes. An energy based routing technique is only successful when a mobility model accurately represents the mobility of mobile hosts in the real world.

In summary, the existing problems in current energy based routing techniques are the practicality of power save protocols as well as the cost building base stations. Solutions are needed to make these routing techniques simpler, more practical and faster to run ‘on the fly’.

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List of Abbreviations

AODV	Ad Hoc On-Demand Distance Vector
AP	Access Point
BCDCP	Base Station Controlled Dynamic Clustering Protocol
BER	Bit Error Rate
BS	Base Station
CA	Collision Avoidance
CBE	Concave Branch Elimination
CS	Cut Saturation
CSMA	Carrier Sense Multiple Access
CH	Cluster Head
CMMBCR	Conditional Max-Min Battery Capacity Routing
CONSET	Connectivity Set
DCF	Distributed Coordination Function
DSR	Dynamic Source Routing
GSM	Global Service Mobile
IEEE	Institute of Electrical and Electronics Engineers

IETF	Internet Engineering Task Force
IP	Internet Protocol
LAN	Local Access Network
LEACH	Low-Energy Adaptive Clustering Hierarchy
LEACH-C	Centralized Low-Energy Adaptive Clustering Hierarchy
LOS	Line of Sight
LP	Linear Programming
MAC	Medium Access Control
MANET	Mobile Ad Hoc Network
MBCR	Minimum Battery Cost Routing
MMBCR	Min-Max Battery Cost Routing
MN	Mobile Node
MPR	Multipoint Relay
MS	Mobile Station
MT	Mobile Terminal
MTE	Minimum Total Energy
MTPR	Minimum Total Power Routing
NI	Network Interface
NIC	Network Interface Card
NLOS	Non Line of Sight
OLSR	Optimized Link State Routing
OSPF	Open Shortest Path First
PAVBS	Power Aware Virtual Base Station
PDA	Personal Digital Assistant
PEGASIS	Power-Efficient Gathering In Sensor Information Systems
PLCP	Physical Layer Convergence Procedure
QoS	Quality of Service
RERR	Route Error
RF	Radio Frequency
RFC	Request For Comment
RREP	Route Reply
RREQ	Route Request
SA	Simulated Annealing
SHDHL	Symmetric High-Bitrate Digital Subscriber Loop
TCP	Transmission Control Protocol
TDMA	Time-Division Multiple Access
TS	Tabu Search
UDP	User Datagram Protocol
WAN	Wide Access Network
WLAN	Wireless Local Access Network
WMN	Wireless Mesh Network
WN	Wireless Network