



Journal of Applied Sciences

ISSN 1812-5654

science
alert

ANSI*net*
an open access publisher
<http://ansinet.com>

Issues and Challenges of Energy-efficient Hybrid Routing Schemes: A Review

^{1,2}Ming Ann Ng, ¹Kok-Lim Alvin Yau and ³David Chieng

¹Department of Computer Science and Networked Systems, Sunway University,
Malaysia No. 5 Jalan Universiti, Bandar Sunway, 46150 Petaling Jaya, Selangor, Malaysia

²Wireless Software Architecture Development, MIMOS Berhad, Malaysia MIMOS Berhad,
Technology Park Malaysia, 57000 Kuala Lumpur, Malaysia

³Wireless Communications Cluster, MIMOS Berhad, Malaysia MIMOS Berhad,
Technology Park Malaysia, 57000 Kuala Lumpur, Malaysia

Abstract: The increasing focus on green communications is bringing a fresh attention towards the research works on energy-efficient hybrid routing schemes. The energy-efficient hybrid routing schemes are applied in various types of wireless multi-hop networks. This review discussed the characteristics and challenges associated with energy-efficient hybrid routing schemes.

Key words: Routing schemes, energy-efficiency, wireless multi-hop networks, wireless mesh protocol

INTRODUCTION

Various researches on energy-efficient hybrid routing schemes have been carried out to provide energy-efficient wireless communications in order to prolong the lifetime of battery-powered devices in wireless multi-hop networks, such as Wireless Mesh Networks (WMNs) (Wei *et al.*, 2007), wireless ad hoc networks (Alfawaer *et al.*, 2007), Mobile Ad hoc Networks (MANETs) (Viswacheda *et al.*, 2007), Wireless Sensor Networks (WSNs) (Thangammal *et al.*, 2012) and cognitive radio networks (Tingrui *et al.*, 2011). Routing enables a source to search and establish the best possible route(s) to the destination (Al-Rawi and Yau, 2012). Each link within a route represents different types of dynamic costs or rewards. For instance, the link cost is generally associated with energy consumption in energy-efficient routing schemes (Nurul Huda *et al.*, 2007; Shi *et al.*, 2010).

Although, hybrid routing has been investigated in the past (Cano and Kim, 2002; Helmy, 2005), this topic has gained fresh attention with the recently published IEEE 802.11s Wireless Mesh Networking standard by the 11s Task Group in September, 2011. A hybrid routing scheme, namely Hybrid Wireless Mesh Protocol (HWMP), has been proposed. CARMEN (Azcorra *et al.*, 2009) is another kind of wireless mesh network, which aims to provide high performance triple play services. High performance triple play services ensure that voice, video and data contents are received by the end users with the highest possible

quality. Studies have been made on CARMEN, such as cost analysis (Chieng *et al.*, 2010), monitoring and performance management (Loziak *et al.*, 2010), MAC layer analysis (Serrano *et al.*, 2009), self configuration design (Simsek *et al.*, 2009) and Architecture design (Banchs *et al.*, 2008).

Figure 1 shows an IEEE 802.11s-based WMN. Three types of nodes are mesh STATION (STA), mesh gateway and Mesh Access Point (MAP). The mesh STAs connect among themselves to form a mesh network. Based on its functions, a STA may serve as a MAP or a gateway. A MAP provides access to the clients; while a gateway provides connection to internet or other IEEE 802-based networks (e.g., IEEE 802.16) (Hiertz *et al.*, 2010). Packets from a client are sent to a mesh MAP, and they traverse through the mesh network in one or multiple hops to the mesh gateway (Lin *et al.*, 2010).

HWMP applies layer two (data-link layer) routing, which is based on MAC address, instead of applying layer three (network layer) routing, as seen in the conventional IEEE 802.11 standards. The upper layers see any destination node in a WMN as its direct neighbour; but in fact, the destination node may be multiple hops away. HWMP is a hybrid routing scheme comprised of proactive tree-based and reactive routing approaches. Using a proactive tree-based routing approach, a root node establishes and maintains routes connecting all nodes in the network. A drawback is that all packets must be forwarded to the root node, which then forwards them to their respective destinations. Thus, a source node must

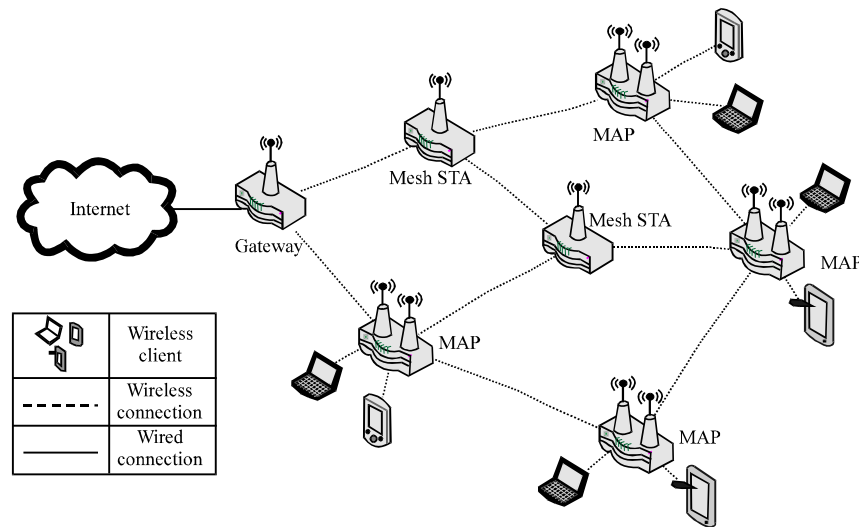


Fig. 1: A WMN based on the IEEE 802.11s standard

send its packets to the root node, which may be multiple hops away, in order to send packets to its neighbour node. Using a reactive routing approach, a source node can establish new route to destination node directly without passing through the root node, and this addresses the aforementioned drawback.

Despite of the elegant routing design, this aspect of energy efficiency has not been implemented in HWMP. This is important as WMNs are suitable to be deployed in rural areas where there is lack of basic infrastructure (Kwong *et al.*, 2011; Ting *et al.*, 2011). Due to the similarity in characteristics and challenges faced by WSNs, especially in terms of multi-hop transmissions and energy awareness, we include WSNs in our review beside WMNs and MANETs. To the best of our knowledge, this is the first comprehensive review on the aspect of energy-efficient for Hybrid Routing Schemes in Wireless Multi-hop Networks.

CHARACTERISTICS OF ROUTING APPROACHES

Traditional characteristics (e.g., tree and flat) are briefly presented. Figure 2 shows the taxonomy of the characteristics. Generally speaking, there are three types of characteristics, namely, network structure, routing approaches and energy-efficient decision factors.

There are four kinds of network structure, as follows:

- **R1.1: Tree structure:** A root node constantly broadcasts routing packets to the entire network in order to connect all nodes in a tree-like structure (Figueiredo *et al.*, 2007)
- **R1.2: Hierarchical/clustered structure:** The entire network is divided into lusters. Each cluster has a

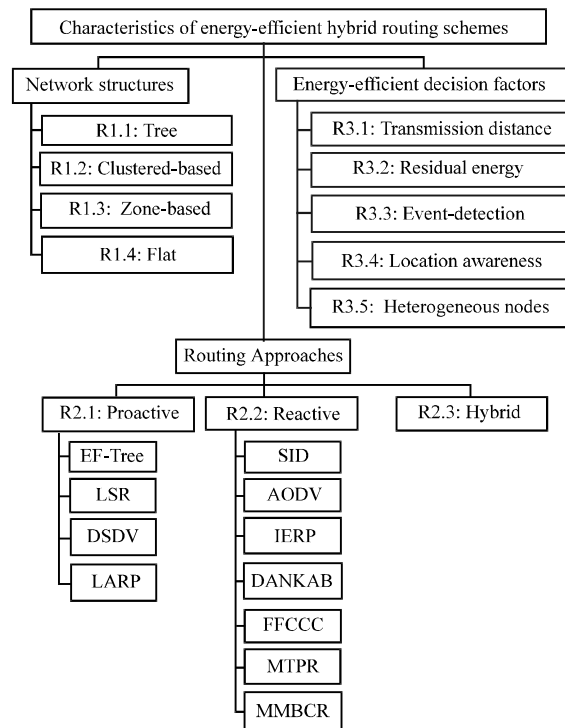


Fig. 2: Taxonomy of energy-efficient hybrid routing scheme characteristics

clusterhead that forwards its member nodes' packets to base station. There are two levels of routings: intra-cluster routing connects member nodes to their respective clusterheads; while inter-cluster routing connects clusterheads to base stations in single or multiple hops (Zhu *et al.*, 2008)

- **R1.3: Zone-based structure:** Each node forms its own routing zone comprised of nodes within a certain number of hops away. Border nodes, which are located at the border of a zone, establish routes between zones (Wang *et al.*, 2008)
- **R1.4: Flat structure:** Nodes are not organized into any form of structure (Bernardos *et al.*, 2006)

There are *three* kinds of routing approaches as follows:

- **R2.1: Proactive routing:** Routes are established and maintained by a node through constant broadcast of routing information to the entire network and so it may incur higher energy consumption
- **R2.2: Reactive routing:** Routes are established only when a source node wants to send packets to its destination node. The source node broadcasts Route Discovery, which is flooded throughout the network. When the destination node receives Route Discovery, it sends Route Reply to the source node so that it can establish the best route to the destination node
- **R2.3: Hybrid routing:** Hybrid routing is a combination of two or more routing approaches. The routing approaches may be applied in two manners. Firstly, the routing approaches are applied concurrently. For instance, different types of routing approaches can be applied for communication among intra-zone or inter-zone nodes in zone-based network structure (Wang *et al.*, 2008). Secondly, the routing approaches are applied in an alternative manner. For instance, Zhao *et al.* (2007) propose a routing scheme that switches among different routing approaches based on the rate of changes in network topology

There are five kinds of decision factors for energy-efficient hybrid routing schemes. A source node

may take account of any of the following decision factors while making routing decisions:

- **R3.1: Transmission distance:** Data transmission over longer physical distance between a node and its next hop increases energy consumption
- **R3.2: Residual energy:** Nodes with lower residual energy may cause link breakage
- **R3.3: Traffic load:** Different traffic load incurs different energy consumption. As an example, a routing scheme may switch between proactive and reactive routing approaches to reduce routing overhead and energy consumption (Figueiredo *et al.*, 2007). When traffic load is low, constant route maintenance is not necessary, and so reactive routing is applied. When traffic load is high, more Route Discovery packets may be sent in reactive routing compared to route maintenance messages in proactive routing, and so proactive routing is applied.
- **R3.4: Location:** Nodes are aware of their respective locations in location-aware networks. For instance, nodes choose the shortest routes to destination in order to reduce energy consumption (Priyankara *et al.*, 2010)
- **R3.5: Node heterogeneity:** Nodes may have different characteristics in heterogeneous networks. For instance, a few high-end nodes with higher transmission power and longer transmission range can relay large amount of packets in order to reduce energy consumption of non-high-end nodes (Priyankara *et al.*, 2010).

CHALLENGES

The challenges associated with energy-efficient hybrid routing schemes are divided into two categories. The node-level challenges are associated with issues related to individual nodes, such as traffic load and

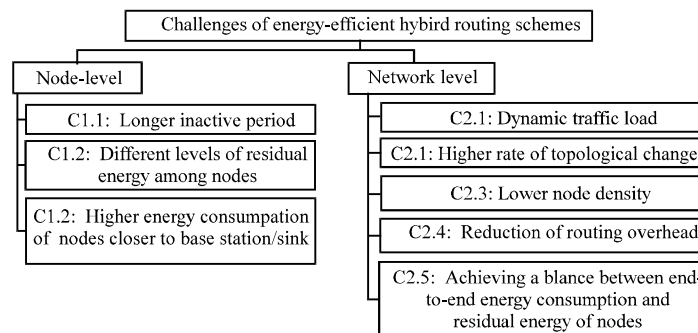


Fig. 3: Taxonomy of the challenges of energy-efficient hybrid routing scheme

energy consumption of a node. The network-level challenges are associated with issues related to the entire network such as end-to-end delay and routing overhead. Figure 3 shows the taxonomy of the challenges. The rest of this section presents the two categories of challenges.

There are three types of challenges in the node-level category, as outlined below:

- **C1.1: Longer inactive period:** Nodes incur higher energy consumption in active mode, as well as during transitions between active and inactive modes. The challenge is that, nodes should be made to sleep as long as possible without jeopardizing network performance as a result of packet loss during sleep. As an example, Bernardos *et al.* (2006) address this challenge using a scheduling scheme that only allows a node to send packets during a certain time frame. When a node is not permitted to send packets, the node switches to inactive mode
- **C1.2: Different levels of residual energy among nodes:** Nodes with lower residual energy may cause link breakage. For instance, clusterheads may incur higher energy consumption while handling higher traffic load in a clustered network structure, and so it may have lower residual energy. Tabibzadeh *et al.* (2009) address this challenge by rotating the role of clusterhead among nodes within a cluster
- **C1.3: Higher energy consumption of nodes closer to base station:** Nodes closer to base station may incur higher energy consumption while handling higher traffic load. Priyankara *et al.* (2010) address this challenge using flat routing among nodes closer to base station. Flat routing can establish multiple routes towards the base station, and this prevents hotspots, which tend to have lower residual energy.

There are five types of challenges in the network-level category as shown below:

- **C2.1: Dynamic traffic load:** The choice of routing approaches can affect energy consumption of a network with dynamic levels of traffic loads. For instance, when traffic load is low, reactive routing, which does not require constant route maintenance, is applied (Figueiredo *et al.*, 2007). When traffic load is high, proactive routing is applied by a base station to construct a routing tree throughout the network. This avoids Route Discovery in proactive routing, and so it reduces energy consumption
- **C2.2: Higher rate of topological change:** Different routing approaches may be used when different levels of topological change are detected in order to reduce energy consumption incurred by the

distribution of routing information. For instance, when the rate of topological change is low, it is unnecessary to provide constant updates of routing information because established route can be reused, and so reactive routing is applied (Zhao *et al.*, 2007). On the other hand, when the rate of topological change is high, proactive routing is applied.

- **C2.3: Lower node density:** Lower node density may lead to lesser options for next-hop node selection, and hence the next-hop node may be physically further away. As a consequence, energy consumption increases due to longer transmission range. For instance, when the node density is high, cluster-based routing is applied so that clusterheads can aggregate redundant data from member nodes (He and Wei, 2008). However, when the node density is low, there is less redundant data, and so flat routing is applied
- **C2.4: Reduction of routing overhead:** Reducing unnecessary flooding of routing packets can reduce energy consumption. For instance, proactive routing is applied to maintain routes among two-hop neighbour nodes so that flooding of routing packets is reduced (Bernardos *et al.*, 2006)
- **C2.5: Achieving a balance between end-to-end energy consumption and residual energy of nodes:** A route comprised of nodes with higher (lower) residual energy may incur higher (lower) end-to-end energy consumption. For instance, when all nodes of a candidate route have sufficient amount of residual energy, it chooses a route with the lowest end-to-end energy consumption; otherwise, it chooses a route that avoids nodes with comparatively lower residual energy (Cano and Kim, 2002)

ENERGY-EFFICIENT HYBRID ROUTING SCHEMES

Table 1 shows the characteristics of, the challenges being addressed by, as well as the performance enhancement achieved by the energy-efficient hybrid routing schemes for wireless multi-hop networks. From Table 1, several energy-efficient hybrid routing schemes are categorized based on network structures rather than routing approaches. As an example, hybrid routing schemes by Zhu *et al.* (2008) and Tabibzadeh *et al.* (2009) are comprised of cluster-based R1.2 routing and flat routing R1.4. Additionally, the energy-efficient hybrid routing schemes may be comprised of two similar routing approaches. For instance, hybrid routing scheme by Cano and Kim (2002) is comprised of two reactive routing approaches, each having their own energy-efficient features. The rest of this section presents how the node-level and network-level challenges have been addressed by the existing hybrid routing schemes.

Table 1: Summary of routing characteristics and challenges of energy-efficient hybrid routing schemes

Challenges	Characteristics															References	
	Network structures					Routing approaches		Decision factors			Performance metrics						
	R1.1	R1.2	R1.3	R1.4	R2.1	R2.2	R3.1	R3.2	R3.3	R3.4	R3.5	P1	P2	P3	P4		P5
Node Level																	
C1.1: Longer inactive period					×		×		×		×					×	Bernardos <i>et al.</i> (2006)
C1.2: Different levels of residual energy among nodes	×	×			×				×		×		×			×	Tabrizadeh <i>et al.</i> (2009), Zhu <i>et al.</i> (2010)
	×	×									×						Munuganti and Fajjari (2008)
C1.3: Higher Energy consumption of nodes closer to base station	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	Priyankara <i>et al.</i> (2010) Abdulla <i>et al.</i> (2012) Sun <i>et al.</i> (2011)
Network Level																	
C2.1: Dynamic traffic load					×		×		×		×					×	Figueroa <i>et al.</i> (2007)
C2.2: Higher rate of topological change		×			×		×		×		×		×			×	Arabi (2010)
C2.3: Lower node density		×			×		×		×		×		×			×	Zhao <i>et al.</i> (2007) He and Wei (2007) Wang <i>et al.</i> (2006)
			×									×		×			Chen <i>et al.</i> (2007) Wang <i>et al.</i> (2008) Helmy (2005)
			×									×					Sato <i>et al.</i> (2010)
C2.4: Reduction of routing overhead				×			×		×		×		×		×		Kamboj and Sharma (2009) Ren <i>et al.</i> (2011) Zhou and Hou (2007)
C2.5: Achieving balance between end-to-end energy consumption and residual energy of nodes						×			×		×		×				Cano and Kim (2003)
R1.1: Tree, R1.2: Cluster-based, R1.3: Zone-based, R1.4: Flat, R2.1: Proactive, R2.2: Reactive, R3.1: Transmission distance, R3.2: Residual energy, R3.3: Traffic load, R3.4: Location, R3.5: Node heterogeneity, P1: Low energy consumption, P2: Lower control overhead, P3: Lower end-to-end delay, P4: Higher No. of alive nodes, P5: Higher packet delivery rate																	

R1.1: Tree, R1.2: Cluster-based, R1.3: Zone-based, R1.4: Flat, R2.1: Proactive, R2.2: Reactive, R3.1: Transmission distance, R3.2: Residual energy, R3.3: Traffic load, R3.4: Location, R3.5: Node heterogeneity, P1: Lower energy consumption, P2: Lower control overhead, P3: Lower end-to-end delay, P4: Higher No. of alive nodes, P5: Higher packet delivery rate

Challenge C1.1: Routing Schemes with Longer Inactive Period. This challenge has been addressed by incorporating scheduling into routing in order to increase inactive period. Bernardos *et al.* (2006) proposed a hybrid routing scheme, which is comprised of proactive R2.1 and reactive R2.2 routing approaches. Each node applies proactive routing to establish routes to its two-hop neighbour nodes in order to avoid flooding otherwise reactive routing is applied. An enhanced scheduling scheme is applied to assign time slots to next-hop node so that the node can safely switch to inactive mode. Hence, nodes that are not involved in packet forwarding can stay inactive as long as possible to conserve energy.

Challenge C1.2: Routing Schemes for Addressing Different Levels of Residual Energy among Nodes. This challenge is commonplace in clustered-based networks R1.2 and it has been addressed by forming backbones of clusterheads, and rotating the role of clusterhead among nodes based on their respective residual energy (Sun *et al.*, 2011; Tabibzadeh *et al.*, 2009; Zhu *et al.*, 2008; He and Wei, 2008; Muruganathan and Fapojuwo, 2008). Tabibzadeh *et al.* (2009) and Zhu *et al.* (2008) proposed a hybrid routing scheme which is comprised of cluster-based routing R1.2 and flat routing R1.4. Due to the high traffic load at clusterheads, a backbone of clusterheads is formed to relay packets from member nodes to base station. This decreases transmission power and hence energy consumption, of clusterheads. Flat routing is applied to establish routes among the clusterheads. Similar approach has also been proposed by Muruganathan and Fapojuwo (2008) to establish a backbone of clusterheads. The hybrid routing scheme is comprised of cluster-based routing R1.2 and tree-based routing R1.1 approaches. The tree-based routing establishes routes to base station using a minimum spanning tree approach. Since clusterheads handle higher traffic load compared to member nodes, the role of clusterhead is rotated among the nodes (Tabibzadeh *et al.*, 2009; Muruganathan and Fapojuwo, 2008). This helps to achieve a balance in energy consumption among the nodes.

Challenge C1.3: Routing Schemes for Addressing Higher Energy Consumption of Nodes Closer to Base Station/Sink. Nodes closer to the base station may tend to exhaust its residual energy causing link breakage. This challenge has been addressed using flat routing so that these nodes do not forward packets all times (Sun *et al.*, 2011; Abdulla *et al.*, 2012; Priyankara *et al.*, 2010). Priyankara *et al.* (2010) proposed a location-aware R3.4 hybrid routing scheme, which is comprised of flat routing

R1.4 and cluster-based routing R1.2. The network is comprised of high-end nodes and non-high-end nodes. The high-end nodes have higher transmission energy for longer transmission range and they can be selected as clusterheads to perform more tasks; while the non-high-end nodes connect themselves to the high-end nodes in one or multiple hops in order to reduce energy consumption. Nodes closer to the base station apply flat routing, which relays packets in shorter transmission distance through multiple hops, to reduce energy consumption. Nodes further from the base station perform cluster-based routing. Abdulla *et al.* (2012) applied the similar approach (Priyankara *et al.*, 2010) in which flat routing is applied to reduce energy consumption. Sun *et al.* (2011) also applied the similar approach (Priyankara *et al.*, 2010) in which flat routing is applied to establish multiple disjoint routes between clusterheads and base station in order to avoid only certain links are used to send packets to base station.

Challenge C2.1: Routing Schemes for Addressing Dynamic Traffic Load. This challenge has been addressed by using different routing approaches at different traffic load levels (Abdulla *et al.*, 2012; Figueiredo *et al.*, 2007). Figueiredo *et al.* (2007) and Arabi (2010) proposed a hybrid routing scheme, which is comprised of proactive R2.1 and reactive R2.2 routing approaches. The objective of the routing scheme is to switch between reactive and proactive routing approaches based on network traffic level. Whenever network traffic load is low, reactive routing is used because of its low energy consumption nature (i.e., constant broadcast of routing packets is not necessary). Whenever network traffic load is high, the base station switches from reactive routing to proactive routing to build a tree R1.1 throughout the entire network. By switching to proactive routing, the base station avoids nodes from further initiating reactive routing, and so this may reduce overall routing overheads.

Challenge C2.2: Routing Schemes for Addressing Higher Rate of Topological Change. This challenge has been addressed by switching to proactive routing when the rate of topological change is low (Zhao *et al.*, 2007). Zhao *et al.* (2007) proposed a zone-based routing scheme R1.3, which is comprised of proactive R2.1 and reactive R2.2 routing approaches. Proactive and reactive routing approaches are applied to establish routes among intra-zone nodes and inter-zone nodes, respectively. There are two techniques to improve energy efficiency. Firstly, in inter-zone routing, boundary nodes ensure that there is only a single Route Discovery message being distributed to other zones. Secondly, in intra-zone routing,

zones are combined based on traffic condition and traffic pattern to form a larger proactive routing area, which is more energy efficient. When the rate of topological change is low, it is unnecessary to provide constant updates of routing information because an established route can be reused, and so reactive routing R2.2 is applied. On the other hand, when the rate of topological change is high, proactive routing R2.1 is applied.

Challenge C2.3: Routing Schemes for Addressing Networks with Lower Node Density. This challenge has been addressed by using a more appropriate routing approach at different node density levels (He and Wei, 2008). Additionally, a routing scheme can also avoid low-density area in order to avoid high transmission power (Wang *et al.*, 2006). He and Wei (2008) proposed a hybrid routing scheme that switches from cluster-based routing R1.2 to flat routing R1.4 as node density decreases in a network in WSNs. In cluster-based routing, clusterheads aggregate redundant data, however, when nodes are sparsely distributed, there is lesser redundant data, and so the efficiency of data aggregation becomes lower. Due to this reason, flat routing outperforms cluster-based routing when node density is low.

Challenge C2.4: Routing Schemes for Reducing Routing Overhead. This challenge has been addressed using two methods. Firstly, a more appropriate routing approach is chosen to reduce routing overhead (Sato *et al.*, 2010; Kamboj and Sharma, 2009; Wang *et al.*, 2008; Chen *et al.*, 2007; Helmy, 2005). Secondly, multiple routes are established from a source node to its destination node to reduce routing overhead being incurred to re-establish a new link when a current link is broken (Ren *et al.*, 2011). Sato *et al.* (2010), Kamboj and Sharma (2009), Wang *et al.* (2008), Zhou and Han (2007) and Helmy (2005) proposed a hybrid routing scheme, which is comprised of proactive routing R2.1 and reactive routing R2.2, to minimize flooding in order to reduce routing overhead in a zone-based R1.3 network structure. Similar routing scheme has also been applied by Chen *et al.* (2007) in cluster-based network structure R1.2. Proactive routing is applied among intra-zone nodes, hence frequent updates about a node's changes (i.e., node joining and leaving), which incur routing overhead, is limited within the zones. Reactive routing is applied among inter-zone nodes to establish routes across different zones. A node sends unicast queries to a set of boundary nodes of its zone rather than all boundary nodes of its zone in order to reduce routing overhead. The boundary nodes, possess routing information of other zones, relay the queries their respective boundary nodes. Therefore, the queries are relayed among boundary nodes from one zone to another

until the destination node is found. Wang *et al.* (2008) applied an ant-based technique. There are two types of ant packets based on their respective traversing direction between a source and destination nodes, namely forward ant and return ant. To establish a route, a source sends forward ants to its destination, which subsequently replies with return ants. The ants deposit pheromone (i.e., an average metric) on each intermediate node; and a route with higher pheromone indicates a better route. In (Kamboj and Sharma, 2009) and (Zhou and Hou, 2007), location-aware R3.4 technique is applied in low- and medium-mobility networks. The location information is applied to determine next-hop nodes towards the direction of destination nodes. With reduced number of candidate next-hop nodes, the broadcast area of reactive routing overhead is limited. The reactive routing also considers residual energy of candidate nodes as one of the routing metrics.

Ren *et al.* (2011) proposed a hybrid routing scheme, which is comprised of proactive routing R2.1 and reactive routing R2.2, to minimize flooding in order to reduce routing overhead in a zone-based R1.3 network structure. The reactive routing approach applies an ant-based technique to establish multiple candidate routes; while the proactive routing approach maintains the dynamic routes. When there is a link breakage, alternative route can be chosen immediately in order to reduce energy consumption caused by retransmission and routing overhead. A node determines its next hop based on its residual energy level, link quality and congestion; therefore, there is lesser possibility of choosing next-hop nodes with lower residual energy.

Challenge C2.5: Routing Schemes for Achieving a Balance between End-to-end Energy Consumption and Residual Energy of Nodes. This challenge has been addressed by achieving a balance between end-to-end energy consumption and residual energy of each node (Cano and Kim, 2002). Cano and Kim (2002) proposed a routing scheme which is comprised of two different kinds of reactive routing approaches: node-level and route-level. The route-level reactive routing approach establishes route with minimum energy consumption throughout the entire route; while the node-level reactive routing approach chooses nodes with sufficient residual energy level throughout the entire route. When the residual energy level of all the nodes along a candidate route is greater than a threshold, the route-level approach is used to establish a route; and when the residual energy level of any node in all candidate routes is lower than the threshold, the node-level approach used to establish a route to avoid node with a comparatively low residual energy.

PERFORMANCE ENHANCEMENT OF ENERGY-EFFICIENT HYBRID ROUTING SCHEMES

Table 1 shows the performance enhancement brought about by the routing schemes compared to traditional or existing schemes. The performance metrics applied in Table 1 are explained below:

- **P.1: Lower energy consumption:** Lower overall network energy consumption prolongs network lifetime. There are three kinds of network lifetime. Specifically, the time taken for: (1) the first node, (2) a certain number of nodes and (3) all nodes to exhaust its (their) residual energy
- **P.2: Lower control overhead:** Lower amount of routing overhead indicates lower energy consumption incurred by exchanging routing control packets
- **P.3: Lower end-to-end delay:** End-to-end delay is the time duration taken for a packet to traverse from a source node to its destination node. Lower end-to-end delay indicates higher successful transmission rate. This also indicates lower number of retransmissions and hence lower energy consumption
- **P.4: Higher number of alive nodes:** A higher number of alive node indicates lower number of nodes failure (i.e., exhausted their residual energy) and so it indicates lower energy consumption
- **P.5: Higher successful packet delivery rate:** A higher packet delivery success rate indicates lower number of retransmissions and hence lower energy consumption

OPEN ISSUES

Threshold determination: Firstly, further research could be pursued to determine a threshold, which may be dynamic in nature, based on network conditions so that a hybrid routing scheme switches to a suitable routing approach at the right time in order to reduce energy consumption. Each switch may be triggered if some conditions (e.g., rate of topological change) are less than or greater than a certain threshold. The threshold level may be dependent on multiple criteria, particularly energy consumption. An accurate calculation of the threshold enables a hybrid routing scheme to switch to the right choice of routing approach (i.e., proactive and reactive) at the right time. As an example, when the rate of topological change is lower than a certain threshold, which indicates

that an established route is likely to be available, reactive routing is applied because route maintenance may not be necessary, otherwise proactive routing is applied (Zhao *et al.*, 2007).

Multi-channel environment: Secondly, further research could be pursued to investigate energy-efficient hybrid routing scheme in multi-channel environment. To the best of our knowledge, most energy-efficient hybrid routing scheme has been investigated in a single-channel environment. Multi-channel environment reduces transmission interference and channel contention among neighbour nodes, and so it reduces number of packet retransmissions. Higher interference and channel contention may increase link failure, and so rerouting is necessary. Hence, routing in multi-channel environment may reduce routing overhead and energy consumption.

Optimal cluster/zone size: Thirdly, further investigation could be pursued to investigate the optimal cluster or zone size. Both cluster-based R1.2 and zone-based R1.3 routings divide the entire network into clusters and zones, respectively. Due to the similar concept, we refer to cluster and zone as group henceforth. Different routing approaches may be applied to inter-group and intra-group routings. The open issue is to determine an optimum group size in order to increase energy efficiency of the entire network. For instance, Helmy (2005) applied proactive routing R2.1 in intra-group routing, and reactive routing R2.2 in inter-group routing in a zone-based routing. When a group is too small, a node has limited knowledge about the entire network; and hence, reactive routing, which may incur more routing packets, higher energy consumption and routing delay, is applied to establish links. When a group is too large, a node must maintain a larger routing table, which increases routing overhead and energy consumption throughout the entire network.

Real world implementation: Fourthly, there has been lack of real-world implementation of energy-efficient hybrid routing schemes, and so further research could be pursued in this area. Most of the existing energy-efficient hybrid routing schemes have been evaluated through simulation. Real-world implementations are important to analyze the open issues and performance enhancements achieved by the proposed schemes in practice. Environmental factors, such as hardware limitation, may affect network performance of the proposed scheme. To the best of our knowledge, there is only a single implementation of energy-efficient hybrid routing scheme

(Zhou and Hou, 2007). The hybrid routing scheme is developed and tested on Atmel and Philips evaluation boards running in an embedded workbench.

Fifthly, further investigation could be pursued to investigate the characteristics of energy-efficient hybrid routing schemes. Table 1 shows a wide range of potential routing characteristics (i.e., network structure, routing approaches and routing decision factors) that can be further investigated to address various challenges associated with energy-efficient hybrid routing schemes. For example, the application of tree-based (Krishna and Doja, 2012) and zone-based network structure have not been investigated with respect to challenge C2.3 (or lower node density); while zone-based network structure has not been investigated with respect to challenge C1.2 (or longer inactive period). Further investigation can be performed to explore the applications of various approaches in order to address the challenges, for example the scalability of existing energy-efficient hybrid routing schemes (Nazir *et al.*, 2006).

Finally, further investigation could be pursued to investigate the performance enhancement achieved by the energy-efficient hybrid routing scheme. Table 1 shows a wide range of potential performance enhancements that can be further investigated to improve energy efficiency. For example, further investigation can be performed to understand the effects of the hybrid routing schemes on the amount of control overhead P.2 (Dan-Yang *et al.*, 2009) and end-to-end delay P.3 while addressing the challenge C2.3 (or lower node density). Further investigation can also be performed to improve energy efficiency in other kinds of networks, particularly low-power personal area networks (Oliveira *et al.*, 2011) and heterogeneous networks (Cui *et al.*, 2011). Improving security of energy-efficient hybrid routing schemes can also be investigated to improve the vulnerability of wireless networks (Sharma *et al.*, 2007; Alsaade, 2011).

CONCLUSIONS

Energy-efficient hybrid routing schemes have been shown to improve energy efficiency of wireless multi-hop networks through combinations of several routing approaches, particularly proactive and reactive approaches. With the recent development of IEEE 802.11s, in which hybrid routing schemes have been incorporated into the standard, energy-efficient hybrid routing scheme is expected to draw significant research interests in the near future. This article provides an extensive review on energy-efficient hybrid routing schemes, their characteristics, challenges and performance enhancements. This article also discusses open issues

associated with the energy-efficient hybrid routing schemes. Certainly, there is a great deal of future work in addressing the open issues raised in this article.

REFERENCES

- Abdulla, A.E.A.A., H. Nishiyama and N. Kato, 2012. Extending the lifetime of wireless sensor networks: A hybrid routing algorithm. *Comput. Commun.*, 35: 1056-1063.
- Al-Rawi, H.A.A. and K.A. Yau, 2012. Routing in distributed cognitive radio networks: A survey. *Wireless Pers. Commun.* 10.1007/s11277-012-0674-7.
- Alfawaer, Z.M., G.W. Hua, M.Y. Abdullah and I.D. Mamady, 2007. Power minimization algorithm in wireless ad-hoc networks based on PSO. *J. Applied Sci.*, 7: 2523-2526.
- Alsaade, F., 2011. Proposing a secure and reliable system for critical pipeline infrastructure based on wireless sensor network. *J. Software Eng.*, 5: 145-153.
- Arabi, Z., 2010. HERF: A hybrid energy efficient routing using a fuzzy method in wireless sensor networks. *Proceedings of the International Conference on Intelligent and Advanced Systems*, June 15-17, 2010, Kuala Lumpur, Malaysia, pp: 1-6.
- Azcorra, A., T. Banniza, D. Chieng, J. Fitzpatrick and D. Von-Hugo *et al.*, 2009. Supporting carrier grade services over wireless mesh networks: The approach of the European FP-7 STREP Carmen. *IEEE Commun. Mag.*, 47: 14-16.
- Banchs, A., N. Bayer, D. Chieng, A. de la Oliva and B. Gloss *et al.*, 2008. CARMEN: delivering carrier grade services over wireless mesh networks. *Proceedings of the IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, September 15-18, 2008, France, pp: 1-6.
- Bernardos, A.M., J.R. Casar and P. Tarrío, 2006. Efficient social routing in sensor fusion networks. *Proceedings of the 9th International Conference on Information Fusion*, July 10-13, 2006, Florence Italy, pp: 1-8.
- Cano, J.C. and D. Kim, 2002. Investigating performance of power-aware routing protocols for mobile ad-hoc networks. *Proceedings of the International Mobility and Wireless Access Workshop*, October 12, 2002, Texas, USA., pp: 80-86.
- Chen, J.L., H.W. Tzeng and C.P. Lai, 2007. Routing mechanism for reliable sensor network applications. *Proceedings of the 2nd International Conference on Systems and Networks Communications*, August 29-31, 2007, Cap Esterel, pp: 34.

- Chieng, D., D.V. Hugo and A. Banchs, 2010. A cost sensitivity analysis for carrier grade wireless mesh networks with Tabu optimization. Proceedings of the INFOCOM IEEE Conference on Computer Communications Workshops, March 15-19, 2010, San Diego, USA., pp: 1-6.
- Cui, Y., Y. Xu, R. Xu and X. Sha, 2011. A multi-radio packet scheduling algorithm for real-time traffic in a heterogeneous wireless network environment. *Inform. Technol. J.*, 10: 182-188.
- Dan-Yang, Q., M. Lin, S. Xue-Jun and X. Yu-Bin, 2009. SRRG: An effective self recovery routing game for mobile ad hoc network. *Inform. Technol. J.*, 8: 1006-1012.
- Figueiredo, C.M.S., E.F. Nakamura, A.A.F. Loureiro and L.B. Ruiz, 2007. An event-detection estimation model for hybrid adaptive routing in WSNs. Proceedings of the IEEE International Conference of Communications, August 24-28, 2007, Glasgow, Scotland, pp: 3887-3894.
- He, G. and Z. Wei, 2008. A hybrid routing scheme for wireless sensor network. Proceedings of the IEEE International Conference on Networking, Sensing and Control, April 6-8, 2008, Sanya, China, pp: 961-965.
- Helmy, A., 2005. Contact-extended zone-based transactions routing for energy-constrained wireless ad hoc networks. *IEEE Trans. Veh. Technol.*, 54: 307-319.
- Hietz, G.R., D. Denteneer, S. Max, R. Taori, J. Cardona, L. Berlemann and B. Walke, 2010. IEEE 802.11s: The WLAN mesh standard. *IEEE Wireless Commun.*, 17: 104-111.
- Kamboj, P. and A.K. Sharma, 2009. Location aware reduced diffusion hybrid routing algorithm (LARDHR). Proceedings of the 2nd International Conference on Emerging Trends in Engineering and Technology, December 16-18, 2009, Nagpur, India, pp: 1156-1161.
- Krishna, M.B. and M.N. Doja, 2012. Analysis of tree-based multicast routing in wireless sensor networks with varying network metrics. *Int. J. Commun. Syst.*, (In Press).
- Kwong, K.K., A. Ting, D. Chieng and M. Abbas, 2011. WiFied up Malaysia villages: A case study of using WiFi technology to increase internet penetration rate in Malaysia rural areas. Proceedings of the IEEE 10th Malaysia International Conference on Communications (MICC), October 2-5, 2011, Kota Kinabalu, Sabah, pp: 7-12.
- Lin, Y.D., S.L. Tsao, S.L. Chang, S.Y. Cheng and C.Y. Ku, 2010. Design issues and experimental studies of wireless LAN mesh. *IEEE Wireless Commun.*, 17: 32-40.
- Loziak, K., M. Natkaniec, J. Gozdecki, E. Chin, D. Chieng and V. Teh, 2010. Monitoring system for carrier grade MESH networks. Proceedings of the Future Network and Mobile Summit, June 16-18, 2010, Florence, Italy, pp: 1 -8.
- Muruganathan, S.D. and A.O. Fapojuwo, 2008. A hybrid routing protocol for wireless sensor networks based on a two-level clustering hierarchy with enhanced energy efficiency. Proceedings of the IEEE Wireless Communications and Networking Conference, March 31-April 3, 2008, Las Vegas, NV., USA., pp: 2051-2056.
- Nazir, M.B., M.S.H. Khiyal and T.U. Rahman, 2006. Scalability of zone routing protocol extensions for mobile Ad-hoc networks. *Inform. Technol. J.*, 5: 373-385.
- Nurul Huda, M., F. Yasmeen, E. Kamioka and S. Yamada, 2007. Optimal path selection in MANET considering network stability and power cost. *Inform. Technol. J.*, 6: 1021-1028.
- Oliveira, L.M.L., A.F. de Sousa and J.J.P.C. Rodrigues, 2011. Routing and mobility approaches in IPv6 over Lo WPAN mesh networks. *Int. J. Commun. Syst.*, 24: 1445-1466.
- Priyankara, S., K. Kinoshita, H. Tode and K. Murakami, 2010. A clustering/multi-hop hybrid routing method for wireless sensor networks with heterogeneous node types. Proceedings of the IEEE GLOBECOM Workshops, December 6-10, 2010, Miami, FL., USA., pp: 207-212.
- Ren, J., Y. Tu, M. Zhang and Y. Jiang, 2011. An ANT-based energy-aware routing protocol for ad hoc network. Proceedings of the International Conference on Computer Science and Service System, June 27-29, 2011, Nanjing, China, pp: 3844-3849.
- Sato, Y., A. Koyama and L. Barolli, 2010. A zone based routing protocol for ad hoc networks and its performance improvement by reduction of control packets. Proceedings of the International Conference on Broadband, Wireless Computing, Communication and Applications, November 4-6, 2010, Fukuoka, Japan, pp: 17-24.
- Serrano, P., P. Patras, X. Perez-Costa, B. Gloss and D. Chieng, 2009. A MAC layer abstraction for heterogeneous carrier grade mesh networks. Proceedings of the ICT-Mobile Summit, June 10-12, 2009, Santander, Spain.
- Sharma, S., R.C. Jain and S.S. Bhadauria, 2007. SBEVA: A secured bandwidth efficient variance adaptive routing protocol for mobile Ad hoc network. *Asian J. Inform. Manage.*, 1: 1-10.
- Shi, Z., Z. Pu and Z.Q. Yu, 2010. A routing protocol based on energy aware in ad hoc networks. *Inform. Technol. J.*, 9: 797-803.

- Simsek, B., J.Y. Chen, D. Chieng, M. Natkaniec and K. Loziak, 2009. Self Configuration Architecture for Carrier Grade Mesh Network (CARMEN). Proceedings of the ICT-Mobile Summit, June 10-12, 2009, Santander, Spain.
- Sun, N., Y.B. Cho and S.H. Lee, 2011. A distributed energy efficient and reliable routing protocol for wireless sensor networks. Proceedings of the IEEE 14th International Conference on Computational Science and Engineering, August 24-26, 2011, Dalian, China, pp: 273-278.
- Tabibzadeh, M., M. Sarram and F. Adibnia, 2009. Hybrid routing protocol for prolonged network lifetime in large scale wireless sensor network. Proceedings of the International Conference on Information and Multimedia Technology, December 16-18, 2009, Jeju Island, South Korea, pp: 179-183.
- Thangammal, C.B., P. Rangarajan and J.R.P. Perinbam, 2012. Maximization of wireless sensor network's lifetime using losningen cross-layer approach. Asian J. Sci. Res., 5: 133-142.
- Ting, A., D. Chieng and K.H. Kwong, 2011. Capacity and coverage analysis of rural multi-radio multi-hop network deployment using IEEE802.11n Radios. Proceedings of the IEEE 10th Malaysia International Conference on Communications (MICC), October 2-5, 2011, Kota Kinabalu, Sabah, pp: 77-82.
- Tingrui, P., Z. Zhi, Z. Wenli and Z. Zhaoxia, 2011. A cognitive improved hierarchical AODV routing protocol for cognitive wireless mesh network. Inform. Technol. J., 10: 376-384.
- Viswacheda, D.V., L. Barukang, M.Y. Hamid and M.S. Arifianto, 2007. Performance evaluation of mobile ad hoc network based communications for future mobile tele-emergency system. J. Applied Sci., 7: 2111-2119.
- Wang, J., E. Osagie, P. Thulasiraman and R.P. Thulasiram, 2008. HOPNET: A hybrid ant colony optimization routing algorithm for mobile ad hoc network. Ad Hoc Networks, 7: 690-705.
- Wang, T., S. Hao, P. Wang and G. Peng, 2006. Efficient and density-aware routing for wireless sensor networks. Proceedings of the 15th International Conference on Computer Communications and Networks, October 9-11, 2006, Arlington, USA., pp: 207-212.
- Wei, D., H.A. Chan and M.B. Rawoot, 2007. Hybrid routing protocol to decrease delay and to extend lifetime for mesh networks. Inform. Technol. J., 6: 518-525.
- Zhao, Q., L. Tong and D. Counsil, 2007. Energy-aware adaptive routing for large-scale Ad Hoc networks: Protocol and performance analysis. IEEE Trans. Mobile Comput., 6: 1048-1059.
- Zhou, H. and K. Hou, 2007. CIVIC: An power- and context-aware routing protocol for wireless sensor networks. Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing, September 21-25, 2007, Shanghai, China, pp: 2771-2774.
- Zhu, A.D., W.M. Zhao and J.G. Xing, 2010. A novel hybrid routing model for wireless grain depot surveillance system. Proceedings of the IEEE/ASME International Conference on Mechatronics and Embedded Systems and Applications, July 15-17, 2010, Qingdao, China, pp: 263-268.