

Citation for published version:

Basurra, S, De Vos, M, Padget, J, Ji, Y, Lewis, T & Armour, S 2015, 'Energy efficient zone based routing protocol for MANETs', *Ad Hoc Networks*, vol. 25, no. Part A, pp. 16-37.
<https://doi.org/10.1016/j.adhoc.2014.09.010>

DOI:

[10.1016/j.adhoc.2014.09.010](https://doi.org/10.1016/j.adhoc.2014.09.010)

Publication date:

2015

Document Version

Early version, also known as pre-print

[Link to publication](#)

University of Bath

Alternative formats

If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Energy Efficient Zone based Routing Protocol for MANETs

Shadi S. Basurra¹, Marina De Vos¹, Julian Padget¹, Yusheng Ji², Tim Lewis³, Simon Armour⁴,

¹Dept. of Computer Science, University of Bath, UK

² Information Systems Architecture Science Research Division, National Institute of Informatics, Tokyo, Japan

³Toshiba Research Europe Ltd, Bristol, UK

⁴Dept. of Electrical and Electronic Engineering, Bristol University, UK

Email: shadi.basurra@bath.edu, {mdv,jap}@cs.bath.ac.uk, kei@nii.ac.jp, Tim.Lewis@toshiba-trel.com,
Simon.Armour@bristol.ac.uk

Abstract

Mobile Ad Hoc Networks (MANET) are self-configuring infrastructureless networks of mobile devices connected via wireless links. Each device can send and receive data, but it should also forward traffic unrelated to its own use. All need to maintain their autonomy, and effectively preserve their resources (e.g. battery power). Moreover, they can leave the network at any time. Their intrinsic dynamicity and fault tolerance makes them suitable for applications, such as emergency response and disaster relief, when infrastructure is nonexistent or damaged due to natural disasters, such as earthquakes and flooding, as well as more mundane, day-to-day, uses where their flexibility would be advantageous.

Routing is the fundamental research issue for such networks and refers to finding and maintaining routes between nodes. Moreover, it involves selecting the best route where many may be available. However, due to the freedom of movement of nodes, new routes need to be constantly recalculated. Most routing protocols use pure broadcasting to discover new routes, which takes up a substantial amount of bandwidth. Intelligent rebroadcasting reduces these overheads by calculating the usefulness of a rebroadcast, and the likelihood of message collisions. Unfortunately, this introduces latency and parts of the network may become unreachable. This paper discusses the Zone based Routing with Parallel Collision Guided Broadcasting Protocol (ZCG) that uses parallel and distributed broadcasting technique [8] to reduce redundant broadcasting and to accelerate the path discovery process, while maintaining a high reachability ratio as well as keeping node energy consumption low.

ZCG uses a one hop clustering algorithm that splits the network into zones led by reliable leaders that are mostly static and have plentiful battery resources. The performance characteristics of the ZCG protocol are established through simulations by comparing it to other well-known routing protocols, namely the: AODV and DSR. It emerges that ZCG performs well under many circumstances.

Keywords: Mobile Ad Hoc Networks, MANET, AODV, DSR, ZCG, Zone based routing, Routing algorithm, energy efficiency, collision guided broadcasting

1. Introduction

Routing protocols for a MANET can be categorised into three groups: reactive, proactive and hybrid [40]. In reactive routing, nodes have no prior location knowledge of the destination nodes and routes are determined on request, typically by flooding, such as in the Ad-hoc On-Demand Distance Vector (AODV) protocol [38]. The drawbacks of reactive protocols are the high cost of broadcast to establish routes and the latency inherent in the process of finding a route to the destination. In proactive routing, each node in the network continuously checks and evaluates paths to every node in the network to establish a complete or partial view of the network, such as in the destination-sequenced distance-vector (DSDV) routing protocol [39]. Consequently, routing latency is low, because paths to destinations can be calculated locally and quickly. The costs in a proactive approach are the high channel usage overheads for route update control messages and the time to convergence

of the network path data. Thus, hybrid techniques have been conceived, using zone and cluster-based routing, that aim to exploit the strengths and minimise the weaknesses of reactive and proactive approaches [2, 24, 44].

In a MANET, many routing protocols, such as the Ad hoc on-demand Distance Vector (AODV) [38], Dynamic Source Routing (DSR) [27], Zone Routing Protocols (ZRP) [23, 24], Location Aided Routing (LAR) [29] and Geographical Routing Protocol (GRP) etc use broadcasting to establish routes. Pure flooding guarantees high reachability and good routing time latency in low density networks. However, pure broadcasting uses a lot of network capacity and is prone to broadcast storms in dense networks, thus increasing routing delay. One solution to the storm problem is to send fewer redundant rebroadcasts by selecting a small set of forwarding nodes while ensuring broadcast coverage, but this may cause the rebroadcast chain to break and critical intermediate nodes not to receive rebroad-

as the ZL_IP field, which is used to publish the sender's current role (for further details, see Packet Format 1 on page 3 and Table 1 on page 3). The ZL_IP stores the ZL's IP address and if ZL_IP carries a null value then this indicates that the source of this Hello message is an idle node. On the other hand, if the ZL_IP equals the sender's IP address it means the sender is a ZL, otherwise, the source of the Hello is already member of an existing ZL with IP address equal to ZL_IP. Publishing a node's status via a Hello triggers all the consequent actions to form network zones.

During the initial phase when formatting the network backbone, all nodes will exist with an idle role and they will exchange Hello messages among themselves. Consequently, two or more nodes will realize their existence within their limited wireless range and that their roles are equal to idle. At this point, they automatically decide to perform the zone construction protocol in order to decide fairly on the most reliable node to become the ZL of this zone. Once selected, the remaining participants of the zone construction process that are located within a one hop count of the newly selected ZL, may change their status to member nodes and start publishing their ZL's IP via the Hello messages header in the ZL_IP field. In the following subsection the zone construction operation will be explained in further detail.

2.1. Identifying zone leaders

Packet Format 1 Shows the format of the HELLO message.

1										2										3											
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1
Type										R A O P Reserved										Prefix Sz Hop Count (TTL)											
ZL IP address																															
Destination Sequence Number																															
Originator IP address																															
Lifetime																															

The zone construction protocol is used to identify a zone leader so that nodes with the most desirable attributes, such as plentiful battery power, high connectivity degree and minimum mobility, are preferred for the ZL role.

When an idle node first receives a Hello, it sets a countdown timer to a predetermined value. It then calculates the number of active links to its direct neighbours that are not already ZLs or members of a nearby zone and this is used to regulate the speed of the countdown timer. The node with the highest degree of connectivity is most likely to become the Zone Construction Organiser(ZCO). The reason for this is to involve as many as possible idle nodes participating in the zone construction process, hence decreasing the number of clusters in the network. The ZCO immediately broadcasts a zone construction call and a zone construction end time with a determined TTL, so the call does not propagate the entire network. A moderate TTL value is used of 3-4. An idle node that receives the call cancels the

Field Name	Description
Type	2 (for HELLO)
R	Repair flag
A	Acknowledgment required
Reserved	Sent as 0; ignored on reception.
O	Zone construction organizer (ZCO) flag.
P	Zone construction participant (ZCP) flag.
Prefix Size	If nonzero, the 5-bit Prefix Size specifies that the indicated next hop may be used for any nodes with the same routing prefix (as defined by the Prefix Size) as the requested destination.
Hop Count	0 or 3
Destination Sequence Number	The destination sequence number associated to the route.
Originator IP Address	The IP address of the node which originated the HELLO for which the route is supplied.
Lifetime	ALLOWED_HELLO_LOSS * HELLO_INTERVAL

Table 1: Shows the descriptions for the packet header fields.

timer countdown process to become the ZCO, only if the process has been initiated, and sets its state to Zone Construction Participant(ZCP) and its timer to the received zone construction end time. The ZCO also changes its status to ZCP. Other nearby nodes that also receive the zone construction call, such as ZLs, member nodes and ZCPs that are part of a different zone construction process, will broadcast SORRY, explaining the reasons. This is done by declaring the node's current status or identifying the it's ZL if one exists. This is to prevent settled nodes that are ZL, already members of zones or already part of another zone construction process to change their status as this can unnecessary increase their communication overheads and can result into uncontrollable series of state oscillations i.e. when a node frequently change its state. To allow sufficient time for all neighbouring nodes to receive the zone construction call and to become a ZCP and prepare for the next step, the announced zone construction end time is calculated in a similar way to the NET.TRAVERSAL_TIME parameter calculated in the AODV protocol [38]. This represents the maximum time in seconds a source node needs to wait after sending a route request broadcast for the reception of a route reply unicast. If the route reply is not received within this NET.TRAVERSAL_TIME the source node sends a new request for a broadcast. The NODE_TRAVERSAL_TIME is a traditional way to calculate the average one hop traversal time for packets and should include queuing delays, interrupt processing times and transfer times and NET_DIAMETER, which calculates the estimate maximum number of hops between two nodes in the network. In this research, The ZONE.CONSTRUCTION_TIME is calculated dynamically and used to give just enough time for all ZCPs to send/receive all necessary messages to accomplish the zone construction procedure.

2.2. Role assignment

When the zone construction time ends, the ZCPs sort the received FFs and the first occurrence of the best FF identifies the ZL. Consequently, each ZCP should, independently, iden-

age capability, the battery power weight is set to become the highest to select a cluster head with the highest battery power, hence prolonging the overall energy lifetime of the sensor network. In the ZCG, the WCA weights are reconfigured in order to split the network into stable clusters. This is implemented by selecting ZLs that are less mobile and that exhibit a similar mobility pattern (in terms of speed, direction and manoeuvrability) with other members in the zone. Also, ZLs need to show reasonably high battery power to deserve this role. In the following, the main features of the FF algorithm are briefly discussed.

(i) The ZLs selection mechanism does not take a long time and it is not performed proactively/periodically, only being performed on demand. Moreover, they are selected based on reliability factors so as to prolong the life time of the zone they lead, which reduces the overheads associated with the ZCP and hence the computation cost.

(ii) In contrast to WCA algorithms [13, 14], the FF algorithm aims to reduce the number of clusters in the network by not limiting the number of nodes in the cluster. That is, the former supports a predefined threshold of nodes in each cluster for efficient medium access control (MAC) so as to avoid channel access delays. This is because the cluster heads in this protocol are designed to relay all inter communications between clusters/zones, whereas the ZCG's ZLs are only responsible for initiating the route discovery process and this leads to flat multi-hop routing rather than a hierarchical form.

(iii) Mobility is a fundamental factor when selecting a ZL. In this regard, a ZL that moves randomly and quickly relative to its neighbours causes frequent and dramatic changes to the zones' structure in the network. Mobility of the nodes in a MANET is inevitable and this is why the ZL selection mechanism aims to reduce their number in the network as well as choosing those with less mobility to take on the role. Hence, the majority of nodes that tend to move with high velocity and an unpredictable mobility pattern should become member or isolated nodes. The mobility of these nodes will result in minor updates whenever they leave or join another zone.

(iv) Another fundamental factor that is considered when selecting ZLs is battery power. Although the ZL is not responsible for the inter routing between the zones as is the case for cluster heads in other protocols, such as the: CGSR [15], HC [37], MOBIC [7] and the WCA [13, 14], it still consumes more battery power than other nodes in the ZCG protocol due to its associated high computation costs.

Calculating the FF is performed using a weighted mean, which uses similar parameters to those used in the WCA [13, 14]. However, the WCA assumes the availability of the exact coordinates of the nodes' locations, possibly by using a GPS system and the signal strength detection mechanism. Such technologies add complexity and cost to a mobile device and consume high energy. Additionally, these technologies can cause PHY/MAC/NETWORK layers compatibility issues. Instead, the propagation delay of WLAN packets using Hello messages is adopted in order to determine the relative distance between two wireless nodes. This approach has been studied in [22], which used the IEEE 802.11 data/acknowledgement sequence to calculate the averaged round trip delay. They showed through

experimental study that the distance and the measured propagation delay correlate closely, only having a small error rate of a few metres. This is a feasible approach since messages are already being utilised in the WCA and ZCG and most clustering algorithms to sense neighbours in wireless ad hoc networks. Moreover, in the ZCG, knowing the exact physical distance between any two nodes is not necessary, for only an estimated measurement of the distance to know how far/close the nodes are located from each other during a time interval is required. This also helps the ZCG calculating the rate of change of the nodes' movement and possibly their mobility direction, which are the main factors that decide on how stable a node is relative to its surrounding neighbours. Moreover, only during the zone construction time will each Hello message require an acknowledgement from its receiver and this is unicast back to the Hello generator node.

Each ZCP needs to calculate the distance to its one hop neighbours using the time stamps from Hello/Acknowledgement packets received from all of them. Each node will store the distance and the delay times in a list in an entry in the neighbour routing table and each entry is uniquely identified by the neighbours' addresses (ID). Moreover, the packet propagation time used to compute the nodes' distances excludes the MAC processing time and queuing delays, the latter being one factor that shows the contention level between the nodes over the channel and therefore, is the node density within the wireless range. In addition, it is important that the nodes' local clocks are assumed to be synchronised. The following equation 1 is used to calculate the distance between nodes in metres [22]. During phase 1, each node that accepts the zone construction call sent by the ZCO, becomes a ZCP and forms a temporary cluster with all one hop neighbours during the zone construction mechanism (see Figure 3). Suppose there are T clusters $\vartheta = \{C_1, \dots, C_T\}$, and that $C_T = \{N_{i1}, \dots, N_{im}\}$, which means each cluster has a set of m nodes where for each $N_{ij} \in C_i$. In phase 2, during the zone construction time, each node N_{ij} calculates its fitness factor F_{ij} relevant to all its neighbours N_{im} in the cluster C_i .

$$d = \frac{c(t_{remote} - t_{local})}{2} \quad (1)$$

Where d is the distance and c is the speed of light $c \approx 3 \times 10^8$ m/sec. t_{remote} denotes the time duration between starting the transmission of a Hello packet and receiving the corresponding acknowledgement. t_{local} represents the time duration of receiving one Hello packet and sending out an acknowledgement. By subtracting the t_{local} from the t_{remote} the outcome result represents the approximate propagation time. To increase the accuracy of the distance estimation, the ZCG uses multiple delay observations. The sum of the distances to all its neighbours N_{il} is calculated so that $\kappa_{ij} = \sum_{l=1, l \neq j}^m d_{avg}(N_{ij}, N_{il})$. Subsequently, n Hello messages are sent in order to get the average distance within the time duration t , where $d_{avg}(N_{ij}, N_{ik}) =$

$\sum_{\Delta=1}^n \frac{d_{\Delta}(N_{ij}, N_{ik})}{n}$, where d_{Δ} is d in the above equation 1. The FF helps to distinguish reliable ZLs, so that the zones they are leading are stabilised for the longest possible time duration. In addition, an important element of reliability in ad hoc communication is links stability, which can be measured by the link expiration time that is the maximum time of connectivity between any two neighbouring nodes [34]. The ZCG calculates the distances between neighbour nodes from the Hello messages received during the ZONE_CONSTRUCTION_TIME. Moreover, under this protocol it is possible to predict the rate of growth/decay of the distance between any adjacent nodes and calibrate their direction. For example, using the λ_{ij} in 2, if the output value is positive, this means there is an increase of distance over time, which clearly indicates that the two nodes in question are moving apart, and therefore, the link will not be stable. This is because when the distance between two nodes becomes larger than the transmission range the nodes are likely to be disconnected [34]. On the other hand, if the value is negative, then this can be understood as a sign of the node movement being towards each other.

$$\lambda_{ij}^l(N_{ij}, N_{il}^{t_1}, N_{il}^{t_n}) = \left(\frac{d_{\Delta}(N_{ij}, N_{il}^{t_1})}{d_{\Delta}(N_{ij}, N_{il}^{t_n})} \right)^{\frac{1}{n}} - 1 \quad (2)$$

Let $N_{ij}^{t_1}$ be the position of node N_{ij} at time t_1 . For every node N_{ij} there is a set of m values of λ_{ij}^l . That is, $\lambda_{ij} = \{\lambda_{ij}^1, \dots, \lambda_{ij}^{m-1}\}$. Then, the degree-difference of the node N_{ij} mobility relative to all neighbours inside the cluster C_t needs to be computed. The n in $\frac{1}{n}$ represents the number of Hello message received during a defined time interval. The collective local mobility of a node N_{ij} can be found by computing the standard variation α_{ij} of the entire set of the neighbours' relative mobility values λ_{ij}^l as shown in the following 3. To form a reliable cluster in term of motion stability, each node is required to compute the relative mobility of all direct neighbours. This performed by measuring the variance of relative mobility for every neighbour, which allows the cluster nodes to select the node with the least mobility ratio with respect to all members and that with the lowest α_{ij} is elected to be their head for better cluster stability. A large α_{ij} value indicates that the set of λ_{ij}^l values, which shows average change rate in distance with $N_{il}^{t_n}$ over a particular time period, are highly spread out. This is an indication of the instability of node N_{ij} in relation to all neighbours N_{im} inside cluster C_T . That is, this node due to its group mobility and large distances within the group is likely to part company with them fairly soon.

$$\alpha_{ij} = \sqrt{\frac{1}{m-1} \sum_{l=1}^m (\lambda_{ij}^l - \bar{\lambda})^2} \quad (3)$$

where $\bar{\lambda} = \frac{\sum_{l=1}^m \lambda_{ij}^l}{m}$. ZCPs use the weighted mean formula of equation 4 to calculate their fitness value using local data, where

β_{ij} determines how much battery power has been consumed.

$$F_{ij} = (\omega_1 \cdot \alpha_{ij}) + (\omega_2 \cdot \kappa_{ij}) + (\omega_3 \cdot \beta_{ij}) \quad (4)$$

The values of α_{ij} here in m/sec and κ_{ij} are obviously highly correlated. For example, when a ZCP moves at a high rate in comparison to its neighbour, as indicated by a high α_{ij} value, the larger the κ_{ij} value, the larger the negative effect it introduces into the FF. This is because a distant node while moving at a higher speed is more likely to go quickly outside its neighbour coverage area. On the other hand, a node moving closer with a lower speed or the same is likely to stay longer within the neighbour coverage area than in the former case. The weights ω_1 , ω_2 and ω_3 are normalised such that they sum up to 1, i.e.

$$\sum_{i=1}^3 \omega_i = 1.$$

The weights considered for the FF calculation are $\omega_1 = 0.5$, $\omega_2 = 0.3$, $\omega_3 = 0.2$ for stable zones. That is, higher weights are given to α_{ij} and κ_{ij} than to β_{ij} in order to maximise the connectivity time between ZLs and their member nodes, hence, maximising the network zones' lifetime and the backbone channel through which ZLs communicate and exchange essential updates related to the network member nodes. Moreover, similar weight distribution was used in the studies [13, 14]. α_{ij} represents the rate of change in term of mobility and direction of movement in relation to the node's neighbours. As mentioned earlier, for high zone stability α_{ij} was given the highest weight so that the link between two nodes stays for the longest possible time due to the lack of relative motion between them. In fact, there are other factors than node mobility that can also cause link failures between nodes, such as multiple-user interference and packet collisions. However, the link failures caused by these factors are normally less severe and last for a shorter time interval before the link gets recovered so long as the neighbour to which the connectivity was lost physically still exists inside the wireless range of the node.

Less weights were given to the value κ_{ij} between the nodes. Higher or similar weights to α_{ij} could have been given here, especially if the generally accepted assumption was used that nodes located far away are likely to *quickly* move outside the wireless range of each other either due to mobility or channel quality [34]. However, this is not necessary true in all cases. For example, there would be some cases when a node is far a way, but moves towards another at a slow speed, as well as those nodes located far apart, but are moving in parallel and in the same direction with each other. In the former case, the node will stay inside the node coverage area for a longer time, because it will move inside the full radius of node x's wireless range. whereas in the latter case, the node will stay in the coverage area of node x for a long time, given that both nodes are moving at a similar speed then the variance of the nodes mobility represented as α_{ij} is equal to a small value, or even to zero in extreme cases if both nodes are moving at the exact same speed. The least weight was given to battery power, for although this is important, one of the ZCG's novelties is that the ZLs don't act as gateways to pass data between and inside the network zones. Instead, they only coordinate the routing process between the

network member nodes and this will be elaborated further in the following text. Eventually, the node having the smallest FF is selected as the ZL and its one hop neighbours automatically become member nodes of the zone (see Figure 3).

2.4. Network routing protocol

When a node becomes a ZL, it starts announcing its role through Hello messages. Any idle node that exists in the wireless range of the ZL and receives these Hellos can register itself as a member node to it so as to construct a zone. Member nodes of adjacent zones can distinguish themselves by broadcasting their ZLs' ID addresses in their periodic Hello messages.

If an idle node is located in the wireless range of two or more ZLs, then it becomes a member node to the nearest ZL by calculating the ETE delay² of all Hello messages received from them. The node broadcasts a SORRY message that includes the reason that influenced this selection, i.e. the ETE delay to the newly selected ZL node and given that this message is a broadcast all ZLs including the recently chosen one will hear this. Moreover, all ZLs can calculate the ETE delay of the SORRY to verify the integrity of the decision.

The ZL proactively multi-casts ID lists to all ZLs in the network to maintain a global view of all existing ZLs and their linked members in the network, which is necessary so that they can assist in the path discovery process (explained in the following subsection). This proactive data exchange is event based, whereby when a node joins/leaves a zone, its ZL will notify other ZLs of the event and provide the ID of the responsible node. A multi-cast of complete ID lists is only performed following new zone formation. The data exchanged between the ZLs is extremely lightweight (just ID addresses) and infrequently updated in comparison to topological data, which is large and frequently changing.

2.4.1. Zone failure

To address the case of a single point of failure, it is noted that the new ZL can be the member node of the second highest fitness value found during the zone construction protocol. However, after investigating various scenarios it was decided to allow the nodes to become idle again and perform a new zone construction process or simply join nearby zones as member nodes, if at least one ZL existed within their wireless range. This decision was made for the following reasons: the FFs of nodes can change quickly in a MANET; it is likely that nodes that join zones after the construction process has taken place have lower FFs than all the zone's member nodes and the node with the second lowest FF may not be located in a central location with all member nodes of the previous ZL. This will make a new zone construction process inevitable, being performed by the members of the old ZL whose locations are two hops away from the node with the second lowest FF. As the zones in

²End-to-end delay refers to the total time it takes for a packet to be transmitted across a network from a source to a destination. This includes the transmission delay, propagation delay, processing delay and queuing delay that the packet may experience on each hop along the path.

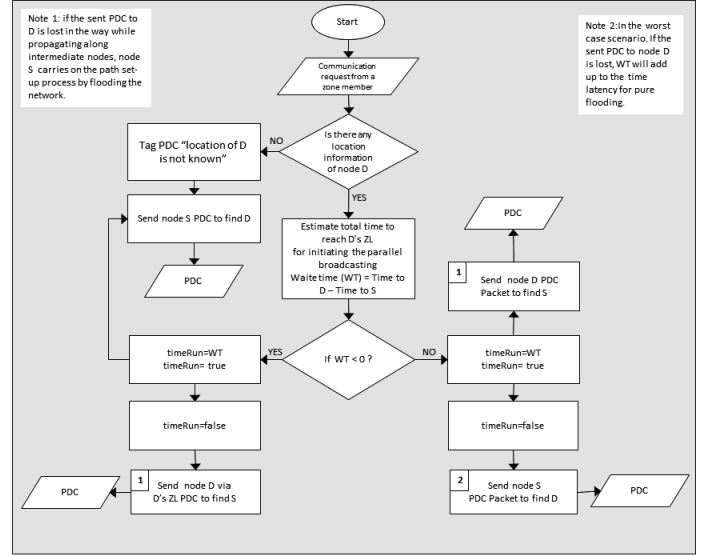


Figure 4: Basic flowchart for the initiation of the parallel collision guided broadcasting at the ZL of the source node S to discover node D.

the ZCG are highly distributed, i.e. only one hop count diameter from the ZLs, then ZL failures should not have any disastrous consequences for the network and their recovery should be manageable within a reasonable time scale. Basically, the zone exists in the network for as long as its ZL remains. If the ZL disappears for various reasons, such as motion or runs out of battery power, then the ZL entries stored at the zone members will expire as they are not being refreshed by Hello messages sent by the ZL. When these entries expire, all zone members will become idle nodes, and some/all can both join nearby zones and become zone members, or they can repeat the zone construction process to select a new ZL. The newly selected ZL immediately broadcasts a RREQ message to announce its existence to the network's ZLs, and constructs its view of the existing backbone channel.

2.4.2. Path discovery (parallel collision guided broadcasting in the ZCG)

Consider a node S in zone C that wants to connect node D in zone F (see Figure 1). Node S will place the request with its local ZL(C) node and the latter should know that the former exists in zone ZL(F) due to the proactive data exchange among the network ZLs. ZL(C) will calculate a time estimate that allows parallel broadcasting from both S and D during the routing phase. The outcome will help ZL(C) to decide on the timing and order when forwarding two Path Discovery Commands(PDC) message to ensure that they reach D via ZL(F) and S at the same time. Figure 4 illustrates ZL(C)'s operations. The PDCs contain the target ID address which each end S and D need to target during their broadcast, the ZTL value(explained later), the broadcast ID, and the broadcast initiation time.

When S and D receive the PDC message, they broadcast route request messages (RREQs) in order to find one another and rebroadcasting continues at intermediate nodes until a positive RREQ-collision occurs. That is, when an intermediate

node receives RREQs generated from both ends with identical broadcasting IDs and the source ID address of one RREQ is the same as the destination ID of the other and vice versa. If a bidirectional route is required, two route reply messages (RREPs) will be generated and forwarded to S and D by the node at which the RREQ-collision has taken place. On the other hand, if a unidirectional route is required, only one RREP is generated, which traverses back via intermediate nodes to S to set half of the newly discovered forwarding path to D, while the forwarding path constructed by the nodes to D is set by RREQs generated from D.

In order to increase the likelihood of RREQ-collision at intermediate nodes, upon the arrival of a ZCG parallel broadcasting packet RREQ at the intermediate nodes along the requested path, they immediately store any route request information in a temporary request table. Before the packet gets retransmitted the node checks its temporary request table for any broadcasting request that may have been received before or after the arrival of the other end request packet and a RREQ-collision would indicate the discovery of a new path between the source and destination pair. The wait between the request packet arrival and retransmission, if necessary, varies depending on: the network load, broadcast jitter, the channel quality and the effect of the presence of other competitive nodes in the MANET. Intermediate nodes may also perform some checks in their cache for any known path for the same destinations.

Searching routing tables at intermediate nodes is performed with hash tables to save routing entries, which take up a constant search time. That is, taking into consideration the nodes' low processing capability and capacity and the constantly changing routing data due to their mobility, small hash tables are used to speed up the access to data. This is because the cost of an efficient hash function can be more expensive in terms of a node's power consumption and capacity than if a search loop algorithm is used in a sequential list [19]. Moreover, many routing protocols use hash tables to implement caches, and the hash keys used in these cases are the nodes' MAC/ID addresses. For these reasons and because multiple requests for a particular destination may be initiated by different nodes at the same time, frequent hash collisions may occur, which leads to different keys mapping to the same hash value. In the ZCG, hash collisions can be handled by removing one of the two colliding entries by overwriting the old entry with the new item, so every entry in the table is up-to-date and has a unique hash value.

2.4.3. Reduction of redundant re-broadcasts(ZCG member nodes role)

Routing between distant nodes of two different zones is done by a similar strategy to the TTL in the AODV [38], but instead of hop numbers Zone to Live(ZTL) is used. This is the number of zones a RREQ needs to cross before it gets discarded, that is, when the ZTL value is zero. Member nodes act as defence walls to protect their zones from rebroadcasting unnecessarily. The ZTL value is maintained during the proactive data exchange between ZL nodes as these can readily identify the number of zones between themselves in the network.

2.4.4. Route maintenance

The ZCG supports link failure maintenance similar to that used in the AODV routing protocol [38]. That is, its nodes use periodic Hello messages or any packet such as RREQ and RREP to sense link status of their neighbours that are part of active routes, so when a link failure is perceived by one or more nodes, a Route Error Packet(RERR) message will be sent to announce a list of all unreachable destinations caused by this link failure to interested neighbours, known as the precursor list³, which are likely to use this node as the next hop to reach these destinations. The process of repairing a broken link requires the following (i) invalidate existing routes; (ii) grouping affected destinations; (iii) selecting the direct neighbours that are affected by the link breakage; (iv) sending a Route Error Packet (RERR) message to these neighbours. A Route Error Packet(RERR) can be broadcast if there are multiple precursors or unicast if only one precursor exists. Moreover, a node that detects a link breakage in an active route, and that exists upstream of the broken link has the option to repair locally the broken link, if it exists within a specific number of hops to the destination. To do so, it needs to increment the destination's sequence number and broadcast a RREQ for that destination. This message is sent with a determined TTL in order to control the broadcasts and prevent them from reaching unnecessary network branches. That is, utilising local repair reduces the amount of rebroadcasts required, if the route repair process is initiated by the source node. Also, the local repair mechanism reduces the time latency required to repair broken links in long paths. This is because a source node needs a longer time to realise a broken link located far away as this involves sending an (RERR) from the node detecting the link breakage as well as the source node needing to perform a pure flooding to establish new routes to the disconnected destination.

3. Energy Consumption Model

At each network node, the energy cost of each packet was computed as the total of incremental cost m relative to the packet size and b is a fixed energy cost associated with channel acquisition.

$$Cost_{watts} = m * size + b \quad (5)$$

In [20], the experimental results confirmed the accuracy of the linear model and were used to determine values for the linear coefficients m and b for various operations. The power consumption values for transmit and receive packets as measured in Feeny's experimental results [20] was used. Subsequently, the model was employed to compare the energy consumption in non-ideal simulation conditions to calculate the influence of interference and packet collision on energy consumption. By so doing, the precise measurements of energy consumption in the network nodes while forwarding routing/data traffic flow were

³ At intermediate nodes, each routing entry of valid and active routes stored at the node's routing table consists of a list of precursor nodes that have been forwarding packets on this route.

determined. Table 2 on page 9 illustrates the energy consumption results, specifying the linear coefficients for each packet-associated operation.

By implementing the equation 5 above, the total cost of the energy consumption associated with a packet was the sum of the energy acquired by the transmitting node/s and all the receiver nodes. Possible receiver nodes of the packet included the destination node, all the nodes that were in the wireless ranges of the source node and all those located inside the wireless range of the destination node. This energy model has been experimentally proven and is widely used as well as being accepted in many studies as forming a sound basis for the design and assessment of energy-aware/energy efficient routing protocols that use the IEEE 802.11 wireless technologies e.g. [3, 20]. In our study, it was assumed that the energy used by the node while being idle was null, because all the tested routing protocols shared the same energy consumption during the time when the node was in a idle state.

packet operations	$uW.sec/byte^8 * size + uW.sec$
point-to-point send	$0.48 * size + 431$
broadcast send	$2.1 * size + 272$
point-to-point receive	$0.12 * size + 316$
broadcast receive	$0.26 * size + 50$
promiscuous rcv	$0.39 * size + 140$
discard	$0.11 * size + 66$

Table 2: Power consumption measurements for LUCENT IEEE 802.11 11 Mbps card [20]

4. Experimental Plan

OPNET [36], a discrete event simulation tool, was used to simulate the ZCG, AODV and DSR routing protocols for MANETs in order to test and compare their routing performance and efficiency. All the protocols were simulated on a 1 km² grid with 100 nodes and for statistical reliability 2000 simulation runs with random seeds were performed. Most runs lasted 3600 seconds to allow sufficient time for the network to complete the set-up process [4], and to perform a reasonable number of attempts to establish routes (if they did not already exist) to all pre-specified mobile destinations. That is, in all scenarios a source node generated 5 unicast traffic packets (1024 bits/sec) to five defined destination nodes, with User Datagram Protocol (UDP) protocol in a constant packet inter-arrival time of 200 seconds. Note that all traffic sessions to the destinations were established independently in parallel while varying the time interval between each transmission to avoid channel contention and delays caused by a large number of queued packets. This light weight traffic was used because the aim was to test the fundamental routing discovery and maintenance procedures of the routing algorithms rather than the data packets order and their bit-error rate. Moreover, each protocol was tested with the same initial conditions and seeds.

All wireless node models are associated with 802.11 interfaces with 11Mbps data rate. The nodes wireless interface was

configured to cover an average area of approximately 250m² when no interference and physical obstacle was present. Also, all queued packets in/out packet streams were cleared out to emulate a realistic node failure. The standard random waypoint mobility model was employed to produce the nodes' motion, with uniform distribution to generate speed values between 0 and 15m/sec. That is, at the beginning of each simulation run, each node was given a random speed value covering: static, moving at an average human walking/running speed of 1.2-2.0m/sec, or as a vehicle at 2-15m/sec (4-55km/h).

In order to test the various aspects of the protocol efficiency, three different scenarios were set up which are described as follows.

a) In Section 6.1 all nodes were allowed to move freely using the aforementioned random waypoint model, while assigning different mobility speed and battery power to the nodes. This was performed to test all possible cases, and to check the protocols' performance and ability to adjust during uncontrolled network behaviour, structure and mobility speeds. b) In Section 6.2 some nodes' fitness factors and mobility parameters were controlled. That is, these nodes were given the highest fitness factor status, no mobility and distributed randomly in the network in order to become ZLs. This was carried out to control for the number of zones during all the simulation runs and helped in the understanding of the effect of the ZTL parameter (when controlled) and the stochastic broadcasting control due to the parallel collision guided.

5. Performance Parameters

In order to analyse the performance of the routing protocols, various quantitative metrics were used for comparisons of those selected and the parameters chosen were: total routing traffic received (bits/sec), reachability ratio, route discovery delay (seconds), network delay (seconds), total broadcast retransmission (packets). In other words, in order to test the routing protocols' effectiveness in discovering new routes to relay data in an ad hoc manner, it was deemed necessary to investigate each of these in turn as below.

routing traffic received : this represents the amount of routing traffic received in bits/sec in the entire network. This traffic includes all the protocol's control overheads, such as: Hello messages, route request/reply packets, route errors and maintenance packets, routing updates and acknowledgements. Routing traffic has a high impact on the network throughput, which is the average rate of successful message delivery over a communication channel. Usually, the larger the routing traffic used by a routing protocol, the less throughput is available for actual data traffic goodput. Goodput is the application layer throughput, which is the number of applicable information bits received from the network at particular destination nodes per second. All lower layer protocols overheads and retransmitted data packets were kept out during the calculation of goodput.

reachability : is defined as the fraction of possible reachable routes to all possible routes between some/all different

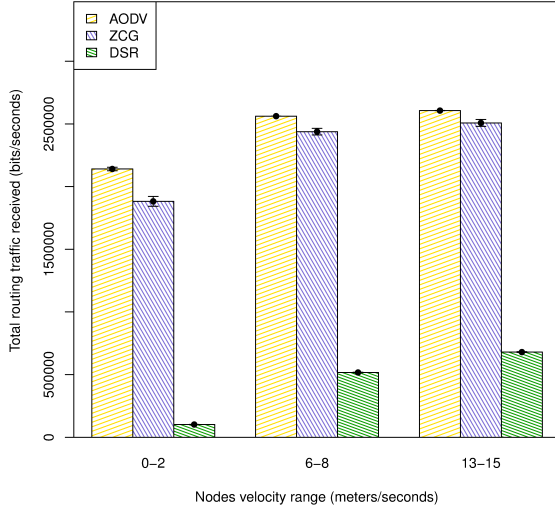


Figure 5: Routing traffic received (bits/sec)

sources to some/all different destinations [30]. This statistic was collected in order to measure the percentage of the successful routing discovery attempts that managed to discover at least a single route to every requested destination using the various discovery mechanisms out of the total number of routing discovery attempts during a simulation run.

route discovery delay : this represents the time delay needed to discover a route to particular destination nodes. This can be calculated from the moment when a route request is sent out by a source node to discover a route to a desired destination, until the time a route reply is received at the source node with a route to that destination.

broadcast retransmission : which is the average number of times each node in the network is required to rebroadcast packets to its neighbours whenever they receive packets in a single broadcasting session. Each broadcasting session is labelled by a unique identifier and broadcasting in routing protocols is normally used in order to discover new routes to one or more destination nodes. They may also be used to fix/refresh the routing tables of already existing routes.

6. Results

6.1. Varying nodes' speed

In this experiment all nodes were allowed to move freely using the aforementioned random waypoint model, with all being randomly associated with different mobility speed and power levels. This experiment was performed to examine all possible cases, and to check the protocol's performance and ability to adjust in uncontrolled network behaviour, structure and the various mobility speeds of the network nodes.

6.1.1. Total routing traffic received (bits/sec) (figure 5)

Figure 5 represents the total routing traffic received (in bits/sec). Any data traffic that is relayed by a node in wireless

ad hoc networks may be counted multiple numbers of times for this statistic (once at the source node and once at the receiver nodes), since both the source and destination nodes have to compete for their transmissions via a shared physical medium. This traffic includes routing traffic, routing maintenance/repair or actual traffic data. Such traffic is generated in various frequencies and its volume, as mentioned earlier, depends on the routing protocol type: reactive, proactive or hybrid. Moreover, all routing protocols use pure broadcasting at some stage during the route discovery phase. In addition to this, some unicast and multicast operations could occur for reasons such as sending path discovery acknowledgements and route maintenance. Each protocol acts differently to reduce redundant broadcasts from spreading thorough the network branches further than necessary before/after finding a route to the requested destination node. Figure 5 displays traffic in bits/sec. It is clear that the AODV produces the highest number of routing overheads, which is due to the pure broadcasting and the proactive use of Hello messages. Although the ZCG generates slightly fewer broadcast messages, the Hello messages and broadcasting (i.e. parallel and distributed broadcasts) are also used to find the desired destination. This finding, while preliminary, suggests that the ZTL technique and the stochastic broadcast control (caused by the parallel collision guided broadcasting) of the ZCG protocol manages to reduce redundant rebroadcasting somewhat.

The ZCG offers a further small reduction in the overheads generated by route replies prior to the occurrence of RREQ-collision. In the AODV when broadcasting is initiated and reaches the required destination, the route reply packet (RREP) generated in response by the destination node performs backward propagation through the entire newly discovered route to reach the source. On the other hand, when a RREQ-collision occurs due to the parallel broadcasting in the ZCG the RREP will be generated by the node at which the RREQ-collision has taken place, which is usually closer to the source node than the destination. This RREP traverses back via intermediate nodes to the source to set half of the newly discovered forwarding path to the destination node, while the forwarding path on the nodes to the destination node is set by broadcast packets from the other end.

From Figure 5 it can be seen that the DSR seems to work incredibly well in comparison to the former protocols. However, it would be misleading to interpret this as a sign of its superior strength without looking at its reachability ratio 6. This is because unlike AODV and ZCG, DSR is beacon-less and hence does not require periodic Hello message transmissions, which are used by a node to inform its neighbours of its presence. These Hello messages contribute hugely to the total number of overheads received by the network which is the case ZCG and AODV. However, these Hello messages have much less of an impact on the network in comparison to broadcast messages as they are transmitted to recipients that are only located within the sender's transmission range. These packets are ignored upon reception and do not get retransmitted. Moreover, in a MANET, there are other uncontrollable factors that can discard redundant/necessary packets during the path discovery process, such as: packet collisions, channel interference, temporary links dis-

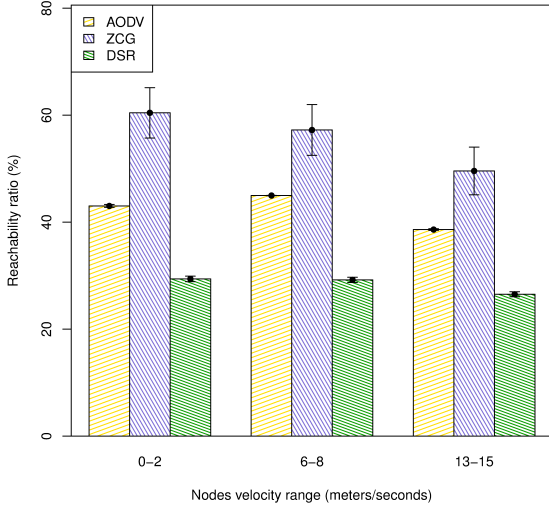


Figure 6: Reachability ratio

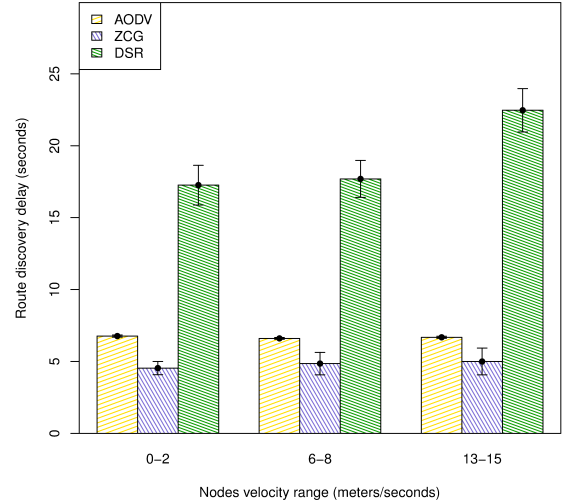


Figure 7: Route discovery delay (seconds)

connectivity/network partitions and routing tables update failures and all of these may impact greatly on reachability.

6.1.2. Reachability ratio (number of successful attempts over all path discovery attempts Figure 6)

Figure 6 shows the reachability ratio, which is the ratio of successful route discovery attempts to the total number of the protocol attempts to discover route/s to specific destination/s. An attempt was considered successful, if the source node got an acknowledgement in response to a route request packet. It is highly probable that multiple acknowledgements were received as a consequence of multiple paths being discovered to a single destination, or that further retransmission attempts were performed at intermediate nodes during a distinct path discovery session, due to channel interference or physical channel disconnection. However, all these cases were treated as a single successful attempt and in order to facilitate this, each path discovery attempt/broadcasting session was uniquely identified by an ID number.

According to the experimental plan, each protocol was set to attempt to establish routes after a 200 seconds time interval to a number of predefined destinations during each simulation run. It is important to mention that it was expected that in various scenarios, not all the tested routing attempts would be successful. This is not due to the protocol design efficiency or performance, but rather because uncontrolled edge cases, such as source/destination nodes, were out of network range. To overcome this, the same random seed sets were used while testing the protocol models and the simulation run-time was extended to 3,600 seconds.

In Figure 6 it can be observed that the DSR exhibits the worst performance of the protocols. However, although its reachability ratio is almost 50% less than that of the ZCG, it manages to stabilise in networks that consist of nodes with high velocity ranges. Figure 6 also indicates that the ZCG protocol has done well and its reachability ratio decreases gradually with nodes with higher speed. Moreover, the AODV shows almost

a similar reachability ratio when the nodes' velocity is slow, its performance degrades slightly when the nodes' velocity range is increased from 2 to 13 metres per second. Furthermore, the ZCG's large confidence intervals indicate high variation in the results obtained. In general, a high reachability ratio is a sign of the protocol efficient broadcasting technique, but this doesn't necessary imply there is a lesser amount of rebroadcasting performed by the network nodes. One obvious reason for the ZCG's high reachability ratio is its parallel collision guided broadcasting. Also, the ZLs' proactive nature requires them to maintain proactively a backbone channel for their intercommunications and this allows for indirect regular updating to active links that pass through this channel as well as maintenance of the routing cache stored at nodes that exist in the wireless range of those that are part of the same channel.

6.1.3. Route discovery delay (seconds) (figure 7)

Figure 7 shows the average routing delay that required the protocols to discover new paths to particular destination nodes. It is clear from Figure 7 that the DSR exhibits the largest delay during the path set up phase.

A possible explanation for this might be that its overheads are potentially larger during the path set up phase and during forwarding traffic in general. For instance, its packet headers may carry full routing information, whereas the routing information in the AODV and the ZCG packets mainly comprise the source and destination addresses plus some lightweight information. Moreover, the broadcast packets of these two protocols are of a fixed size, whilst the DSR's is directly proportional to the path length. Likewise, all unicast data packets (including route replies) in the DSR are also large since they carry a full list of the node addresses located along the newly discovered routes.

The AODV path discovery mechanism has the second longest time delay, which is attributed to one side broadcasting, and packet collisions caused by blind packet flooding. By contrast, the ZCG had the fastest path set up mechanism amongst

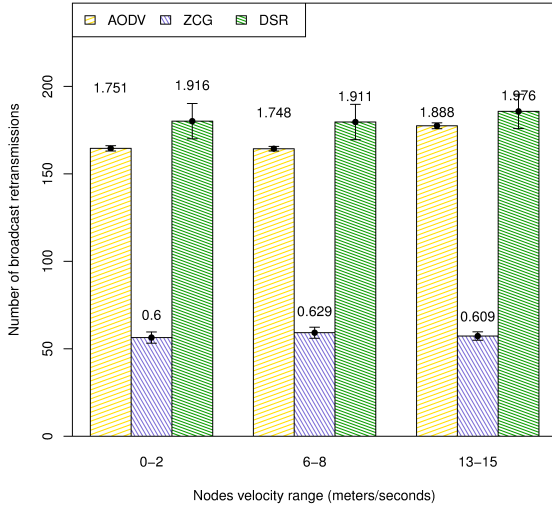


Figure 8: Number of broadcast retransmission

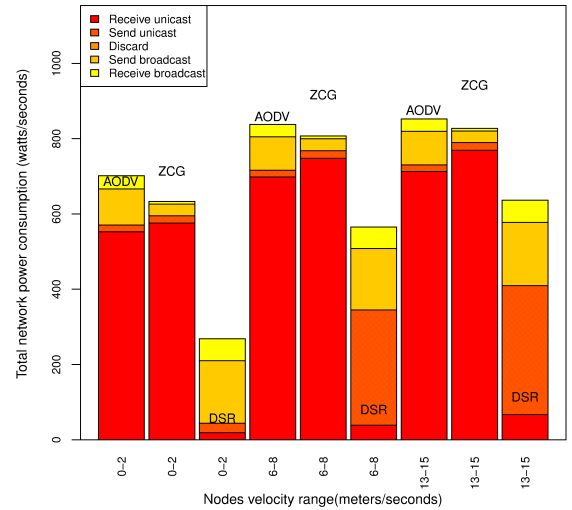


Figure 9: MANET power consumption varying speed stacked

the protocols tested, which is due to its parallel collision guided broadcasting technique. Another reason that allowed the faster route set up in the ZCG and the AODV, with the former being the faster, is the proactive broadcasting of the one hop Hello packets, although this is one of the main causes of the increase in both algorithms' overheads as depicted Figure 5.

6.1.4. Routing broadcast retransmission (figure 8)

Figure 8 shows the average number of broadcast retransmissions during each path discovery session. Theoretically, $N - 2$ forwarded broadcasts should be obtained, where N is the total number of nodes in the network, which is 100 excluding the sender and receiver nodes. However, this is an average number of broadcast retransmissions of five broadcasting sessions performed sequentially and run in parallel to discover routes to five distinct destinations during a defined time interval. Moreover, factors such as link disconnection, packet collisions, queue overflow and temporary loops could have been caused by possible broadcast storms. All these reasons could have made the number of rebroadcasts exceed N . This statistic is a good measure to evaluate protocol performance in terms of detecting and discarding redundant packets from being rebroadcast during broadcast sessions.

In this experiment, the ZCG showed the highest reachability ratio, while it produced a reasonably low number of redundant rebroadcasts as illustrated in Figure 8. On the other hand, the DSR and AODV, higher to lower, produced extremely high numbers of redundant rebroadcasts, while their reachability ratio degraded when the networks were tested with high ranges of node velocities. This is due to the problem of broadcast storm, which causes packet collisions and possible loops. Although the DSR uses the highest number of rebroadcast messages, it has the lowest reachability ratio. Considering the DSR routing overheads shown in 5, most of these can be confidently attributed to the illustrated high broadcast redundancy shown in Figure 8 and this is because the model limits the number of routing overheads by piggybacking the routing information in

the packet header, which causes broadcast packets to be larger in size than number. In fact, it also uses blind broadcasting to fix broken links stored at intermediate node caches.

The number of tags shown in the Figure 8 indicates the average number broadcasts performed by each node in the network during the simulation. This of course excludes the source and destination nodes.

6.1.5. Energy consumption

The simulation results in Figure 9 illustrate the energy consumed (in watts/sec) by the routing protocols, being from left to right the: AODV, ZCG and the DSR.

The results represent the estimated total energy consumption required by the network in watts/sec, while clearly identifying the energy required for each traffic type, such as transmitting data using the unicast/broadcast mechanism, receiving packets and discarding packets due to packet collisions and redundancy based on various routing related mechanisms. These results include energy for total network traffic, such as routing and data traffic, and the DSR in this case is receiving data in promiscuous mode.

As was observed above, the DSR exhibited the best performance with regards to the network bandwidth usage, but here it can be seen that it has high energy consumption. For example, in Figure 9 it clearly be seen that this protocol uses noticeably more energy for sending and receiving broadcast packets. Additionally, it has dramatically higher power consumption for dropping and broadcasting control packets, which is due to its use of promiscuous mode as discussed above. Nevertheless, despite the partial proactive behaviour for maintaining the ZLs' backbone, the ZCG shows a reasonable power consumption when node velocity is lowest at 0-2 metres/seconds, and it continues to perform as the second best energy efficient protocol when compared to the AODV. Notably, the AODV and ZCG consume relatively similar energy levels for sending and receiving unicast packets and discarding, however, the ZCG outperforms the AODV in respect of the energy required to send and receive

broadcast messages.

6.2. Varying the ratio of reliable nodes (ZLs in ZCG)

For this experiment, the number of reliable nodes in the network was increased by setting their fitness factors higher and hence, those nodes exhibited low speed or no mobility at all. They were also set to have infinite battery resources in order to become ZLs. ZLs nodes were randomly uniformly positioned at the beginning of each simulation run. In addition, the zone construction protocol was disabled in order to control the number of ZLs during the tested scenarios and thus, a large amount of the traffic associated with the ZL selection mechanism was excluded from these experiments. However, this traffic was not significant since most of this mechanism was included in the Hello messages used to sense the existence of neighbouring nodes within the ZLs' wireless coverage area. Disabling the ZL selection mechanism allowed for the quantification of the effect of the number of ZLs in the network in terms of the protocols' scalability factor and the different dependency levels of the member nodes by varying the number ZLs in the network. Moreover, it provided information that could be use to assess the correlation between the protocols' overheads and ZLs. The random waypoint mobility model was used to simulate the nodes' mobility pattern and their mobility speeds were uniformly distributed in the range 0-15 m/sec. These experiments were performed by testing a network that consisted of 100 nodes, while increasing the number of ZLs in the network from 20%, 35%, and 50%. The last is the extreme case and refers to when the protocol assigned one ZL for each member node in the network, which meant that at least half of the network nodes were static with high power resources. In order to maintain fairness when testing the other protocols that do not exercise the concept of clustering and ZLs, the tests were configured to the extent that the selected nodes, which were chosen to take the ZL role in the ZCG scenarios, also had: the same initial position, the same mobility pattern/speed and resources.

6.2.1. Total routing traffic received (bits/sec) (figure 10)

Figure 10 illustrates the routing traffic received in the network and it can be seen that the ZCG produces less overheads than the AODV with 20% and 35% ZLs. Notably, the former's overheads increase with 50% ZLs, whereas the latter's continued to decline gradually with more reliable nodes, i.e. nodes with low/no mobility and infinite power resources.

This contradicts the zone construction protocol design concept, which aims to minimise the number of ZLs in the network and results in frequent and large multicast updates between ZLs since the network backbone consists of large numbers of them. These results show clearly that even though ZLs help to reduce the network overheads through the ZTL mechanism of the ZCG protocol, they should be kept to a minimum. Otherwise, they would be likely to undermine the system and exhibit the reverse effect. Note that the DSR starts with the lowest overheads and they continue to slightly decrease, the more reliable nodes there are in the network.

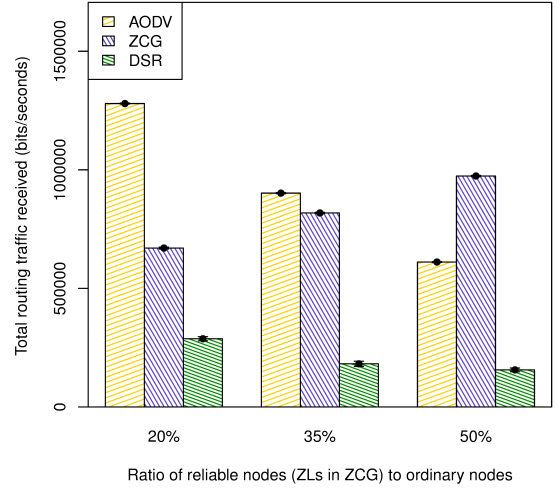


Figure 10: Total routing traffic received (bits/sec)

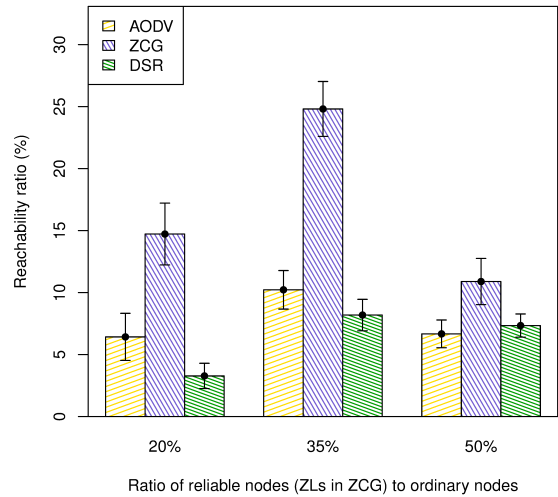


Figure 11: Reachability ratio

6.2.2. Reachability ratio (figure 11)

Figure 11 presents the results for the reachability ratio, which is the ratio of successful route discovery attempts to the total number of route discovery attempts to find and set a path to a particular destination node/s in the network. First of all, it is observed that this ratio for all three protocols is quite low in comparison to the values obtained from the other experiments and shown in Figure 6. From Figure 11 it can also be seen that the ZCG has the highest reachability ratio with all proportions of ZLs. Notably, all the protocols start with a low reachability ratio at 20%, then have a high level at 35%, especially the ZCG. However, all their reachability ratios degraded again at 50% to a slightly lower score than that shown with 35% ZLs. There are two explanations for this result. First, because the nodes were placed uniformly at random positions inside the domain, some of these (including the source and destination) were likely to be positioned at disconnected/isolated locations and this situation was exacerbated by these nodes' lack of mobility, which means their isolation persisted throughout the simulation and hence the

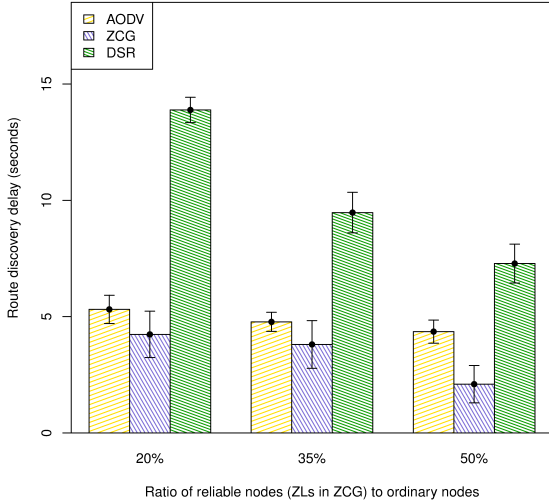


Figure 12: Route discovery delay (seconds)

low reachability score. The rest of the network's mobile nodes provided temporary wireless coverage, depending on their mobility pattern and speed, by linking those nodes with the network temporarily, which is why the experiment produced this result. The second explanation is that the random positioning of the static nodes created continuous dense regions, i.e. during the entire simulation run, which provided high levels of interference and high packet collisions as a result of the competition between the nodes for transmissions over a shared channel.

6.2.3. Route discovery delay (seconds)(figure 12)

Figure 12 shows the time latency of the route discovery process, while increasing the number of ZLs in the network. In Figure 12 it is seen that the ZCG is doing quite well with larger number of ZLs in the network. In most cases the DSR takes 8-13 seconds to find routes to a destination, while this time decreases with a higher ratio of reliable nodes. This is because this protocol was designed to work well with networks with a large proportion of static nodes. By contrast, the AODV takes a range of 4 to 5.5 seconds to find a route to the destinations, and its route discovery latency decreases with a higher ratio of reliable nodes. Notably, some correlation between these results 12 and those of Figure 13 that present the protocols' average broadcast retransmissions is observed. For example, the ZCG's route discovery latency is quite high with fewer ZLs, which could be the result of a large volume of blind broadcasting performed by the member nodes. This is corroborated by looking at the route discovery time reduction of the ZCG with 50% ZLs. Moreover, from Figures 12 and 13 it emerges that both broadcasting overheads and route discovery time latency decrease with large numbers of ZLs, which is due to the large size of the ZL backbone covering large parts of the network. This increases the probability of having large chunks of the routes between nodes going over the backbone. This leads to the routing entries being maintained for longer owing to the ZLs' frequent multicast updates and their reliability characteristics.

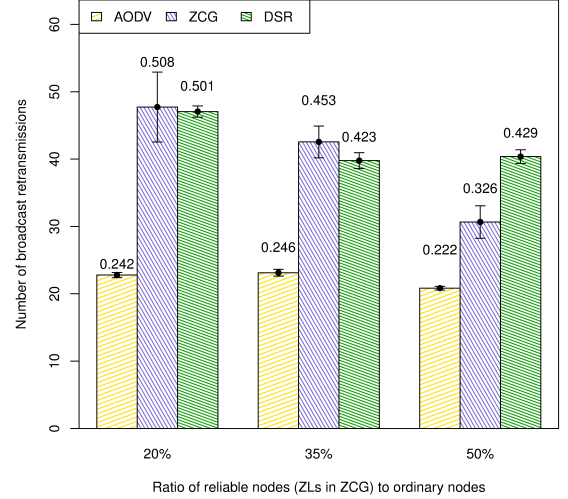


Figure 13: Number of broadcast retransmissions

6.2.4. Routing broadcast retransmission (figure 13)

Figure 13 indicates the average number of forwarded route rebroadcasts during the path discovery process. The figure also indicates the average number of packets each node in the network has rebroadcast during the simulation, which can be seen in the top label of each bar in the figure. From the results in Figure 13 it can also be seen that the number of broadcast retransmissions in the ZCG and DSR is quite high. In fact, these two protocols exhibit broadly similar results when the presence of ZLs in the network is around 20%. Referring back to the results regarding the total routing traffic received (Figure 10) and those shown here (Figure 13), it is observed that the parallel and distributed broadcast in the ZCG is not the main cause of route overheads, for large chunks of its routing traffic come from: the multicast between ZLs, Hello packets and route maintenance.

It can also be seen that the rebroadcasting in the ZCG decreases, the more ZLs there are in the network. This could be due to the ZTL technique that stops redundant messages from being flooded to unnecessary network branches. In addition, the existence of a backbone that consists of a large number of ZLs, makes it more likely to have large chunks of the routes between the nodes over this backbone, which means fresh entries for these routes will be kept for longer by getting their timers frequently reset by the multicast between the ZLs as well as there being fewer route failures due to the ZLs' reliability features.

Notably, the AODV has the fewest rebroadcast overheads, which can be attributed to the cached replies. For example, when a node receives a route request and is not its target, it looks up its routing table to decide whether it has any route to the target of the request. If so, the node sends back a "cached route reply" and does not rebroadcast the request packet. This is confirmed by the AODV reachability ratio shown in Figure 11.

6.2.5. Energy consumption

Here, the effects of varying the number of zone leaders ZL/stationary nodes are explored over various random scenar-

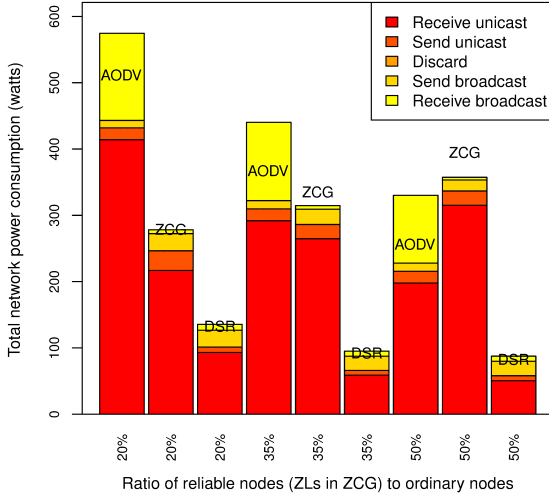


Figure 14: MANET power consumption varying zones stacked

ios.

Looking at Figure 6.2.5, the stacked bars illustrate the power consumption associated with the various types of messages. For example, the AODV has the highest power consumption for receiving broadcast messages, although its consumption for sending these broadcasts is not very large. The ZCG on the other hand, uses the least energy for receiving and sending broadcast messages, but uses a lot of that node's energy for receiving unicast messages. It also has the highest energy consumption for dropping data, which can be as result of packet collisions, long in/out stream queues or redundant packets. However, although these are negative attributes they all contribute to the overall overhead efficiency of the ZCG when there is an adequate number of ZLs in the network, as demonstrated earlier in 9. In addition, the energy used to transmit and receive broadcast packets decreases the more ZLs are added to the network, because the ZTL technique also becomes more efficient as the number of ZLs increases, and also because of the positive RREQ-collision of the parallel guided broadcasting techniques. On the other hand under these circumstances, the energy used in the ZCG to send and receive unicast routing packets increases steadily, due to the proactive edge node related updates being forwarded between more ZLs. In this case the protocol performances come second best to the DSR. It is noteworthy that the DSR and AODV's power consumption falls the greater the number of ZLs/static nodes in the network. Overall, the ZCG performance in terms of energy consumption is shown to be reasonably good when a moderate number of ZLs are allowed to function in a MANET network.

7. Conclusion

It is concluded from the above results that the ZCG generally performs well in terms of reachability and time discovery delay, in most cases, in comparison to the AODV and DSR. However, it has also emerged that the ZCG produces noticeably higher routing overheads than the rest of the protocols, which is con-

tradictory to one of the ZCG's design objectives. However, the traffic size, load and frequency of the ZCG overheads are produced in a distributed fashion, which causes less impact on the protocol performance than if the same traffic is generated from typical one-sided broadcasting, which often leads to broadcasting storms.

The results indicate that the DSR has the least overheads during the path set up phase. However, because of its purely reactive behaviour, its path set up phase is the longest and its routing cache at intermediate nodes is highly likely to be inconsistent, due to link failures in highly dynamic networks. On the other hand, it has outstanding performance in comparison to the AODV and ZCG in terms of overheads and reachability in static networks.

One of the drawbacks of the ZCG that was not considered during the protocol design phase, is that although endeavour was made to ensure the establishment of the network backbone using slow moving nodes and reliable links, all the nodes at each zone compete to use the physical medium for sending all their messages regardless of whether these are sent over the backbone links or not. This can cause delay which impacts on the parallelism of the collision guided broadcasting technique.

A significant problem with the ZCG is the number of multicast updates required between ZLs as a result of member nodes change of location/status. That is, there are repeated cases of unnecessary traffic volume exchanged between the ZLs that contain no member nodes, or inactive member nodes (i.e. member nodes that show minimal communicative demands). In the first case, most of the ZL multicast traffic received by isolated ZLs is likely to be unnecessary and a waste of bandwidth, although ZLs are assumed to act like normal nodes, i.e. are not confined to relay data and initiating the ZCG parallel collision guided process.

The ZCG's logical clustering procedure and zone selection mechanism may constrain its scalability in highly dynamic ad hoc networks. Although it piggybacks the clustering information and necessary data for the ZL selection mechanism in periodic Hello messages, dynamic networks cause the selection mechanism to be frequently triggered, because of the change of the nodes' geographical locations due to their highly dynamic mobility nature. This will cause large and frequent updates to be multicast to the network for the purpose of notifying the ZLs about the newly selected ones and their members, which form the new zones.

8. Evaluation

Reducing the time required for routing is an obvious benefit of the ZCG protocol for two reasons: (i) the parallel broadcasting from source and destination nodes; (ii) searching routing tables for requested destinations at intermediate nodes is fast, as the table entries are indexed by creation time and the ZCG searching algorithm only checks recently created entries.

The parallel broadcasting from the source and destination nodes utilises the fact that jitter delay is higher in broadcast

than it is in unicast packets. Jitter ⁴ (standardized by the Internet Engineering Task Force (IETF) in RFC 5148 [16].) at the network layer was designed to work alongside the Multiple Access with Collision Avoidance for Wireless (MACAW) [9] or the IEEE 802.11 RTS/CTS [43] at the lower MAC layer to avoid the packet collision problem and its related issues caused by simultaneous packet transmission of neighbouring nodes in wireless mobile ad hoc networks. Using the parallel collision guided broadcasting allows the ZCG to reduce the number of slow broadcasts by increasing the unicasts that in general are faster and hence use less energy, i.e. trade-off the number of unicasts against the number broadcast during a single path discovery session. Hence, reducing total broadcast jitter, which is the main factor that influences the total average route discovery and network delays. Additionally, the distribution of broadcasts, i.e. the simultaneous broadcast initiations from the two ends of a route, leads to their fast spreading to cover the whole network.

In the ZCG, a positive RREQ-collision, which indicates a path discovery, only occurs based on up to date information. A similar approach is used in the AODV, through the route request sequence number. For example, when a route to a new destination is required, the node broadcasts a RREQ to discover a route to the desired destination. A route can be found if the RREQ arrives at either the destination itself, or an intermediate node with knowledge of a fresh route to the destination. A fresh route is a valid route entry for the destination whose associated sequence number value is equal or higher that contained in the RREQ.

However, such knowledge can be inconsistent/outdated in a highly dynamic network and one solution to this problem was discussed is dynamic nix-vector routing [32]. Under this approach, for example, while searching for a destination node by flooding the network with path discovery packets (RREQ), when already stored routing information that leads to the required destination node D is found in intermediate node X, information will not be used immediately. Instead, node X needs to evaluate the freshness of the information by unicasting a discovery packet from the current node to destination node D. If node D receives the packet, which establishes the consistency of the data found, the destination node will unicast an acknowledgement back to the search generator through X, otherwise no acknowledgement is received within a predetermined time and broadcasting path discovery packets will continue from that point (i.e. from node X) onwards. Perhaps the most serious disadvantage of this method is the waiting time required to verify the freshness and the consistency of the cached routes at the intermediate nodes.

Many routing protocols try to reduce the number of broadcast messages using time to live value (TTL) inserted in the header of the packet, which gets decremented by 1 at each hop on the route to destination. When the TTL value reaches zero, the packet will be discarded. However, this technique is efficient only if the TTL value to reach the destination is known

already (possibly in static networks) or can be estimated from the nodes message exchange or signal strength. That is, if the TTL value is slightly shorter than that required, rebroadcasting will be performed again with a higher TTL value in order to reach the destination, which can be more expensive than flooding route discovery packets to the whole network in the first place. The ZCG is very efficient, in the sense that if both ends succeed in initiating the broadcast of RREQs simultaneously, RREQ-collision between the two is very likely to occur at the first attempt. In addition to this, there is some probability that RREQ-collision can stop further redundant flooding of RREQs in parts of network branches, i.e. regions. The ZCG collision guided technique can be viewed as a new stochastic approach to control broadcasting. In Fig 1 the RREQ-collision stops redundant rebroadcasts from reaching the network branches A, B, G, H, K and part of zone D.

In most zone routing protocols [6, 44], all nodes belonging to a zone need proactively to maintain partial network topology data. However, in the ZCG only lists of ID addresses plus other small amounts of data are (infrequently) exchanged between ZLs as compared with topological data that are large and need frequent updating.

In the ZCG, the zones are formed by one ZL with links to nodes of one hop diameter from the ZL radio range and if the zone's ZL disappears owing to movement or interference, re-constructing a new zone, if necessary, can be done quickly with insignificant control overheads.

Moreover, a single path discovery search operation in the ZCG is likely to cause multiple RREQ-collisions and extra routes to a single destination can always be used as a backup in cases of link failure. It is important to clarify that the ZCG is not *only* a routing protocol, but also a routing technique that might be used with other existing routing protocols. For example, when a route discovery packet needs to create and carry a list of all previously visited nodes, which can subsequently be used for route formation, such as in swarm intelligent routing [10],[17] and the DSR [27]. The ZCG's parallel collision guided technique can be used in the DSR to file multiple route requests from both ends S and D to carry less than the entire list size, while traversing different regions of the network simultaneously and therefore, exploiting different parts of the network and balancing the load.

As in many protocols which try to establish underlying infrastructure, such as zones and clusters, the time needed for the nodes implementing the ZCG to converge at the network initial phase is long. Another downside of this protocol is the waiting time needed for synchronizing broadcasting of RREQs at both ends. In the worst case scenario, when a Path Discovery Commands(PDC) packet traversing to one end gets lost, the other end still performs a broadcast and hence the waiting time for parallel broadcasting will increase the broadcast time latency. Nevertheless, the benefit from using the ZTL remains.

As with the TTL, the ZTL technique is more efficient when used with moderate values, i.e. when $ZTL \leq \frac{1}{2}$ network diameter or even smaller. That is, a large ZTL value can make this useless since the packets will propagate the entire network before it reaches zero. However, large ZTL values can

⁴The term "Jitter/jittering" in this context means positive random delay added to the packet transmission time by the wireless nodes.

still benefit the system by breaking infinite routing loops if they occur during broadcasting control messages.

ZCG synchronisation cannot be constantly precise because: (i) local clocks of mobile nodes drift at different rates, and (ii) delay is introduced by congestion in intermediate nodes' queues.

Finally the protocol performance degradation, due to control overheads exchanged between ZLs through the backbone to maintain the zone infrastructure, is relatively minor. Although such overheads are small when compared to the topological information exchanged in purely proactive routing protocols, it still burdens the ZCG's performance, especially in highly dynamic mobile networks.

9. Discussion

A similar technique to parallel collision guided (ZCG) has been published, namely, the Destination-assisted Routing Enhancement Protocol (DARE) [1], which is conceptually similar, but differs in implementation and execution. In DARE, the destination node participates in routing by assisting the source node in finding itself. This is accomplished by the destination generating beacon packets independently and randomly at a low rate and with a low TTL value, for low overheads. The beacon randomly traverses via intermediate nodes to refresh their cache entries, which route to the destination and a beacon packet gets discarded at intermediate nodes when it exceeds its associated TTL value. The objective of these beacons is not to discover the source node, but to announce the existence of a destination node to other close by nodes. Conversely, the ZCG technique is performed on-demand and both the destination and the source, equally and concurrently, participate in routing.

By allowing the destination to send random beacons, DARE may seem to outperform ZCG's overheads from the ZLs' proactive connectivity used for the backbone channel maintenance. However, the former assumes that there is a single destination in the network, which is not realistic in a MANET, where all nodes are potential destinations. Therefore, this concludes that DARE has high overheads and will behave like other zone and cluster-based protocols [2], where nodes proactively keep routing data about neighbours with a defined hop count.

Some may argue that instead of initiating a new route discovery process to find/establish a route to a destination node, the underlying ZLs' backbone channel should be used. This is because this connects all ZLs, and they have links to most member nodes in the network. Moreover, because of the ZLs' reliability features and the proactive multicast between them over the backbone for synchronization and selective routing purposes, the backbone channel will always exist. This stance is addressed briefly as follows:

1. The infrastructure link may not be the shortest between the nodes, since ZL zones establish connectivity among themselves based on reliability criteria;
2. It would not be wise to use those links repetitively to accommodate all connectivity sessions amongst all nodes in

the network, since these links will quickly be overloaded. The original purpose of the backbone is to establish a reliable, long-lasting link between ZLs to exchange lists of lightweight ID addresses and some information for synchronization purposes;

3. The ZCG uses ZLs only during the route establishment phase, but they are not used as gateways to forward the nodes' data that can cause unbalanced node traffic as well as making routing sensitive to gateway node failures [21]. The ZLs in this protocol are also considered normal nodes, i.e. self-interested nodes that can initiate private communication sessions with any other node in the network.

10. Summary and Future Work

A zone-based routing protocol with parallel collision guided broadcasting (ZCG) has been put forward in this paper and tested along with two other protocols, the DSR and the AODV, in order to assess the foremost's effectiveness. It was found that the ZCG can speed up the routing process in a MANET through its on-demand parallel collision guided broadcasting, which is because it reduces redundant rebroadcasts via: (i) RREQ-collisions occurring through the parallel broadcast from the source and destination nodes; (ii) the zone to live (ZTL) technique, which is the number of zones a broadcast needs to propagate through before it gets discarded by member nodes. Under this procedure, member nodes act as a defence wall to protect their zones from receiving needless broadcasts. In sum, the simulation results indicate that the ZCG meets its design objectives and in fact is better than the AODV protocol.

One future aim is to increase fairness among nodes by, for example, protecting zone members from possible selfish behaviours⁵ associated with the ZLs' dominant role in the ZCG, respectively, as they are responsible for initiating the fast and efficient parallel collision guided broadcasting. In the protocols developed for this research, this issue was resolved by allowing the zone members to continue their route discovery process as a pure broadcast without the destination assistant (i.e. sending the simultaneous collision guided broadcasting), which can lead to a broadcast storm problem that wastes large network bandwidth and causes high power consumption as well as network latency.

One possible extension to the issue of fairness would be to adopt a similar approach to that found in [41], which involved using collaborative and energy efficient routing for a WSN through the use of game theory. This approach allows for the network nodes in such a network to act as players competing over the resources comprising the nodes' energy and data. Given the nature of a WSN, the nodes understand that their

⁵“Non-cooperative actions of misbehavior are usually termed as selfishness, which is notably different from malicious behavior. Selfish nodes use the network for their own communication, but simply refuse to cooperate in forwarding packets for other nodes in order to save battery power. A selfish node would thus utilize the benefits provided by the resources of other nodes, but will not make available its own resources to help others. They have no intention of damaging the network.”[5]

actions and choices have a great impact on those located upstream, however, they are also conscious of the fact that they have no choice but to use these nodes to relay their data along the multi-hop path to the sink. Similar circumstances exist in the nodes implementing the ZCG protocols, in that zone members know that in order to initiate faster, with high reachability and to have an efficient route discovery mechanism, their route requests have to be processed and handled by their zone leaders. However, they also understand that they are responsible for operating the ZTL in MANET, which pertain to the number of zones a broadcast needs to cross through before it gets discarded by zone members. Hence, these nodes act as defence walls to protect the zones and their leaders from receiving and reforwarding unwanted broadcasts from outside, thereby saving their: power resources, channel capacity and preventing contention.

Another game theory based approach can be used to solve issues such as selecting the most reliable nodes in the zones and to limit the chances that dishonest nodes deceive others about their actual capabilities. Such an approach can force the ZL role to be assigned to the node with the most resources, and prevent unreliable nodes owing to their mobility, poor security and/or weak battery resources, from taking such role. For example, the current implementation of the ZCG protocol assumes all the network nodes as honest and cooperative. Therefore, additional rules would need to be introduced in the system so that violators receive just punishment, and those who comply and cooperate sincerely are rewarded. Such an extension could be adopted with the current design of the ZCG for a MANET, because it already uses SORRY messages to exclude nodes that are already part of other zones from participating in a new zone construction protocol, as well as using them to verify whether or not such a decision is accurate, by calculating the propagation time and current role of the node.

It is put forward that WMNs [18] and VANETs [33] are an ideal setting for the ZCG protocol and closely related alternatives, as ZLs are special nodes that can maintain remote-to-remote traffic via one or more hops, while preserving the wireless connectivity via mobility constraints. Further, these networks have more planned configuration, and can be deployed to provide dynamic and cost effective connectivity over a specified geographic area. Moreover, in such networks the ZL nodes can become special nodes with no mobility and may only move according to network demands to provide wireless coverage to an unconnected group of nodes in case of network split. In addition, ZLs would become unlimited in terms of resources compared to other nodes, thus they can be highly utilised to perform functions that demand high network resources. The backbone channel that interconnects ZLs could be maintained via a second radio channel, e.g. using WLAN IEEE 802.11 3-channel system. Consequently, the ZCG would require fewer multicasts since the ZL selection mechanism would be performed infrequently or even eliminated due to the hardware features of the ZLs, such as: unlimited power resources, static motion and multi-radio access technologies for high network capacity. Moreover, the ZCG's synchronised arrangement for initiating parallel CG broadcasting would become more accurate

and faster, resulting in greater efficiency.

References

- [1] Yousef M. Abdelmalek and Tarek N. Saadawi. Destination-assisted routing enhancement (DARE) protocol for ad-hoc mobile networks. In *SARNOFF: Proceedings of the 32nd international conference on Sarnoff symposium*, pages 386–391, USA, 2009. IEEE Press.
- [2] Mehran Abolhasan, Tadeusz Wysocki, and Eryk Dutkiewicz. A review of routing protocols for mobile ad hoc networks. *Ad Hoc Networks*, 2(1):1–22, 2004.
- [3] Géraud Allard, Pascale Minet, Dang-Quan Nguyen, and Nirisha Shrestha. Evaluation of the energy consumption in MANET. In *Proceedings of the 5th international conference on Ad-Hoc, Mobile, and Wireless Networks, ADHOC-NOW*, pages 170–183, Berlin, Heidelberg, 2006. Springer-Verlag.
- [4] D. Arora, E. Millman, and S.W. Neville. On the statistical behaviors of network-level features within MANETs. In *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*, pages 1145–1150, September 2011.
- [5] K. Balakrishnan, Jing Deng, and V.K. Varshney. TWOACK: preventing selfishness in mobile ad hoc networks. In *Wireless Communications and Networking Conference, 2005 IEEE*, volume 4, pages 2137–2142, March 2005.
- [6] Leonard Barolli, Yoshitaka Honma, Akio Koyama, Arjan Duresi, and Junpei Arai. A selective border-casting zone routing protocol for ad-hoc networks. In *DEXA: Proceedings of the Database and Expert Systems Applications, 15th International Workshop*, pages 326–330, Washington, DC, USA, 2004. IEEE Computer Society.
- [7] P. Basu, N. Khan, and T.D.C. Little. A mobility based metric for clustering in mobile ad hoc networks. In *Distributed Computing Systems Workshop, 2001 International Conference on*, pages 413–418, April 2001.
- [8] S.S. Basurra, M. De Vos, J. Padget, T. Lewis, and S. Armour. ZCG: A zone-based routing protocol with parallel collision guidance broadcasting for manet. In *Communication Technology (ICCT), 2010 12th IEEE International Conference on*, pages 1188–1191, November 2010.
- [9] Vaduvur Bharghavan, Alan Demers, Scott Shenker, and Lixia Zhang. MACAW: a media access protocol for wireless lan's. *SIGCOMM Comput. Commun. Rev.*, 24(4):212–225, October 1994.
- [10] Gianni Di Caro, Frederick Ducatelle, and Luca Maria Gambardella. Anthocnet: An adaptive nature-inspired algorithm for routing in mobile ad hoc networks. *EUROPEAN TRANSACTIONS ON TELECOMMUNICATIONS*, 16:443–455, 2005.
- [11] I.D. Chakeres and E.M. Belding-Royer. The utility of hello messages for determining link connectivity. In *Wireless Personal Multimedia Communications, 2002. The 5th International Symposium on*, volume 2, pages 504–508, October 2002.
- [12] Perkins and Elizabeth Belding-Royer Charles, Samir Das, and Ian Chakeres. Aodv@ietf project @ONLINE, 2012.
- [13] Mainak Chatterjee, Sajal K. Das, and Damla Turgut. A weight based distributed clustering algorithm for mobile ad hoc networks. In *Proceedings of the 7th International Conference on High Performance Computing, HiPC*, pages 511–521, London, UK, UK, 2000. Springer-Verlag.
- [14] Mainak Chatterjee, Sajal K. Das, and Damla Turgut. WCA a weighted clustering algorithm for mobile ad hoc networks. *Journal of Cluster Computing (Special Issue on Mobile Ad hoc Networks)*, 5:193–204, 2001.
- [15] Ching chuan Chiang, Hsiao-Kuang Wu, Winston Liu, and Mario Gerla. Routing in Clustered Multihop Mobile Wireless Networks with Fading Channel. In *Proc. IEEE SICON*, pages 197–211, April 1997.
- [16] T. Clausen, C. Dearlove, and B. Adamson. Jitter Considerations in Mobile Ad Hoc Networks (MANETs). RFC 5148 (Informational), February 2008.
- [17] G. Di Caro, F. Ducatelle, and L.M. Gambardella. Swarm intelligence for routing in mobile ad hoc networks. In *Swarm Intelligence Symposium, 2005. SIS 2005. Proceedings 2005 IEEE*, pages 76–83, June 2005.
- [18] Richard Draves, Jitendra Padhye, and Brian Zill. Routing in multi-radio, multi-hop wireless mesh networks. In *ACM MobiCom*, pages 114–128. ACM Press, 2004.
- [19] SparkNotes Editors. *Hash Tables in C language*. SparkNotes LLC, SparkNotes.com, July 2012.
- [20] L.M. Feeney and M. Nilsson. Investigating the energy consumption of a wireless network interface in an ad hoc networking environment.

- In *INFOCOM 2001. Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, volume 3, pages 1548–1557, 2001.
- [21] Stefan Funke, Leonidas Guibas, An Nguyen, and Yusu Wang. Distance-sensitive information brokerage in sensor networks. In Phillip B. Gibbons, Tarek F. Abdelzaher, James Aspnes, and Ramesh Rao, editors, *Distributed Computing in Sensor Systems, Second IEEE International Conference, DCOSS 2006*, volume 4026 of *Lecture Notes in Computer Science*, pages 234–251, San Francisco, USA, 2006. IEEE, Springer.
 - [22] André Günther and Christian Hoene. Measuring round trip times to determine the distance between WLAN nodes. In *Proceedings of the 4th IFIP-TC6 international conference on Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks; Mobile and Wireless Communication Systems, NETWORKING*, pages 768–779, Berlin, Heidelberg, 2005. Springer-Verlag.
 - [23] Z.J. Haas. A new routing protocol for the reconfigurable wireless networks. In *Universal Personal Communications Record, 1997. Conference Record., 1997 IEEE 6th International Conference on*, volume 2, pages 562–566, October 1997.
 - [24] Zygmunt J. Haas and Marc R. Pearlman. The performance of query control schemes for the zone routing protocol. *IEEE/ACM Trans. Netw.*, 9(4):427–438, 2001.
 - [25] Zygmunt J. Haas, Marc R. Pearlman, and Prince Samar. Intrazone Routing Protocol (IARP). Internet Draft draft-ietf-manet-iarp-02.txt, IETF, July 2002.
 - [26] Zygmunt J. Haas, Marc R. Pearlman, and Prince Samar. The Zone Routing Protocol (ZRP) for Ad Hoc Networks. Internet Draft draft-ietf-manet-zone-zrp-04.txt, IETF, July 2002.
 - [27] David B. Johnson and David A. Maltz. Dynamic source routing in ad hoc wireless networks. *IEEE Transactions on Mobile Computing*, 1996.
 - [28] David B. Johnson, David A. Maltz, and Josh Broch. DSR: The dynamic source routing protocol for multi-hop wireless ad hoc networks. In *In Ad Hoc Networking*, edited by Charles E. Perkins, Chapter 5, pages 139–172. Addison-Wesley, 2001.
 - [29] Young-Bae Ko and Nitin H. Vaidya. Location-aided routing (LAR) in mobile ad hoc networks. *Wirel. Netw.*, 6:307–321, July 2000.
 - [30] Chander Kumar, Shailender Gupta, and Bharat Bhushan. Impact of various factors on probability of reachability in MANET: A survey. *International journal on applications of graph theory in wireless ad hoc networks and sensor networks*, 3(3):13–24, September 2011. ISSN: 0975 - 7023[Online].
 - [31] Seungjoon Lee, Bobby Bhattacharjee, and Suman Banerjee. Efficient geographic routing in multihop wireless networks. In *MobiHoc: Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing*, pages 230–241, USA, 2005. ACM.
 - [32] Y.J. Lee and G.F. Riley. Dynamic nix-vector routing for mobile ad hoc networks. In *Wireless Communications and Networking Conference, 2005 IEEE*, volume 4, pages 1995–2001, March 2005.
 - [33] Fan Li and Yu Wang. Routing in vehicular ad hoc networks: A survey. *Vehicular Technology Magazine, IEEE*, 2(2):12–22, 2007.
 - [34] Md. Mamun-Or-Rashid and Choong Seon Hong. LSLP: Link Stability and Lifetime Prediction Based QoS Aware Routing for MANET. In *Proc. Joint Conference on Communications and Information (JCCI)*, Phoenix Park, Korea, May 2007.
 - [35] S. S. Manvi and M. S. Kakkasageri. Multicast routing in mobile ad hoc networks by using a multiagent system. *Inf. Sci.*, 178(6):1611–1628, 2008.
 - [36] *OPNET Modeler Documentation*, 2011. www.opnet.com.
 - [37] Abhay K. Parekh. Selecting routers in ad hoc wireless network. *Proceedings of the SBT/IEEE International Telecommunication Symposium, ITS*, August 1994.
 - [38] C.E. Perkins and E.M. Royer. Ad-hoc on-demand distance vector routing. In *Mobile Computing Systems and Applications, 1999. Proceedings. WMCSA. Second IEEE Workshop on*, 1999.
 - [39] Charles E. Perkins. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *In Proceedings of ACM SIGCOMM Conference*, pages 234–244, 1994.
 - [40] E. Royer and Chai-Keong Toh. A review of current routing protocols for ad hoc mobile wireless networks. *Personal Communications, IEEE [see also IEEE Wireless Communications]*, 6(2):46–55, 1999.
 - [41] Alexandros Schillings and Kun Yang. VGTR: A Collaborative, Energy and Information Aware Routing Algorithm for Wireless Sensor Networks through the Use of Game Theory. In Niki Trigoni, Andrew Markham, and Sarfraz Nawaz, editors, *GeoSensor Networks*, volume 5659 of *Lecture Notes in Computer Science*, pages 51–62. Springer Berlin / Heidelberg, 2009.
 - [42] Brad Williams and Tracy Camp. Comparison of broadcasting techniques for mobile ad hoc networks. In *MobiHoc*, pages 194–205, New York, NY, USA, 2002. ACM.
 - [43] Kaixin Xu, M. Gerla, and Sang Bae. How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks. In *Global Telecommunications Conference, 2002. GLOBECOM. IEEE*, volume 1, pages 72–76, November 2002.
 - [44] Chun-Chuan Yang and Li-Pin Tseng. Fisheye zone routing protocol: A multi-level zone routing protocol for mobile ad hoc networks. *Comput. Commun.*, 30(2):261–268, 2007.

Shadi Saleh Basurra is a research fellow at Birmingham City University. He received his Bsc degree in Computer Science from Exeter University 2007 and MSc in Distributed Systems and Networks from Kent University at Canterbury 2008. He obtained his Ph.D. in 2013 from the University of Bath in collaboration with Bristol University. His research interests include simulation and emulation of networks (vehicular, mesh and sensor ad-hoc network), game theory, multi-agent systems and dynamic simulation of zero carbon design and retrofit of buildings.



Marina de Vos is a senior lecturer in the Computer Science department at the University of Bath. She completed her Doctor of Science degree in 2002 at the Vrije Universiteit Brussel, Belgium. Marina research activities involve knowledge representation, answer set programming and its applications, game theory and its applications, multi-agent systems, artificial intelligence, theoretical computer science, the use of logic in computer science.



Julian Padget is a senior lecturer in the Computer Science department at the University of Bath. The central theme of his research is formal and computational models of normative systems and their interaction with intelligent agents and mixed human-agent societies. Application domains include distributed artificial intelligence, sensors networks, policy modelling, security, virtual environments, legal reasoning, energy and social simulation. He received his PhD from the University of Bath in 1984 and his BSc from the University of Leeds in 1981.



Yusheng Ji is a professor of Information Systems Architecture Research at the National Institute of Informatics (NII), Japan. She is also a visiting Professor at the University of Science and Technology of China. She received her



Doctorate of Engineering from the University of Tokyo in 1989. She is editor and a member of many prestigious academic journals, and published over a hundred of publications that focus on various aspects of networking including the future architecture of networks, resource management and scheduling schemes in wireless networks, Communication Protocols in Wireless Sensor and Ad Hoc Networks.

Tim Lewis is a research fellow at Toshiba Research Europe Ltd, UK. He received his Ph.D. in Computer Science from the University of Edinburgh 2001, Msc in Computer Science from Edinburgh 2001, and MA Hons in Mathematics from the University of Cambridge in 1991. His research focus on various aspects of networking including the quality of services, resource allocations and management and routing algorithms in Ad Hoc Networks.



Simon Armour has been an academic at Bristol since 2001 and has held the post of Senior Lecturer since 2007. He obtained his BEng degree from the University of Bath in 1996 and his PhD from the University of Bristol in 2001. His research interests cover a variety of wireless communications techniques. Having originally specialised in Physical Layer work and OFDM in particular, he has in recent years expanded his interest to cover more MAC and RRM aspects of wireless and has embraced a cross layer approach to wireless system design.

