SACJ 35(2) December 2023
Research Article

Spectrum-Aware Transitive On-Demand Routing Protocol for Military Cognitive Radio Ad Hoc Networks

Phetho Phaswana, Mthulisi Velempini

University of Limpopo, Department of Computer Science, South Africa

ABSTRACT
The advancement of wireless technology is increasing the demand for scarce spectrum. Cognitive radio ad hoc networks (CRAHNs) were proposed as a solution to spectrum scarcity which is also deployed in combat. However, military cognitive radio ad-hoc networks (MCRAHNs) are subject to destruction and frequent link breakages. The challenge with MCRAHNs routing is the timing-out of packets. This paper proposes the spectrum-aware transitive multi-cast on-demand distance vector (SAT-MAODV), optimised for throughput and delay. The relay nodes are selected based on zonal data and mobility. This is achieved through handshaking and sharing of location data. The nodes are expected to store location data of nodes encountered, which is used in routing and in determining the movement of the node. The mobility of military nodes is organised and structured, which simplifies routing. The SAT-MAODV was evaluated in network simulator 2 and the results show that the scheme is effective. Using SAT-MAODV instead of xWCETT, it reduced routing path and node relay delay by at least 65% and 13% respectively, and increased achievable throughput by 31%. It also improved the delivery ratio by 9% while reducing latency by 27% in comparison with MARSA.

Keywords Spectrum Depletion, Cognitive Radio Ad Hoc Network, Routing Path delay, Throughput

Categories • **Networks ∼ Network protocols, Network layer protocols, Routing protocols**

Email
Phetho Phaswana – phethopp@yahoo.com,
Mthulisi Velempini – mvelempini@gmail.com (CORRESPONDING)

Article history
Received: 26 March 2022
Accepted: 23 July 2023
Online: 14 December 2023

1 INTRODUCTION

In intermittent mobile networks, there are no guaranteed routing paths due to the instability of the network. A military cognitive radio ad hoc network (MCRAHN) is a network consisting of nodes such as soldiers with wearable devices, tankers, armoured fighting vehicles, armoury with sensors, and aircraft. If these nodes are destroyed, the routing paths may not be guaranteed. In the process of relaying data packets, the transmission may be interrupted due to the unavailability of relay nodes. This results in delays which may degrade the performance of

Phaswana, P., and Velempini, M. (2023). Spectrum-Aware Transitive On-Demand Routing Protocol for Military Cognitive Radio Ad Hoc Networks . *South African Computer Journal* 35(2), 3–24. https://doi.org/10.18489/sacj.v35i2.17389

SACJ is a publication of *SAICSIT*. ISSN 1015-7999 (print) ISSN 2313-7835 (online)

the network. Some packets are dropped due to prolonged buffering and timeouts. The delays which are incurred in MCRAHNs due to node destruction are spectrum mobility (SM), node relay (NR), and routing path (RP). The destruction of nodes also degrades achievable throughput as the packet drop rate increases exponentially (Tuukkanen, Couturier, Buchin, Braysy et al., 2018).

When designing a routing algorithm for MCRAHNs it is imperative to first address the destruction of nodes and route recovery mechanisms. Several routing algorithms have been proposed to address routing challenges in MCRAHNs. However, most of the algorithms do not address MCRAHNs delays. The reduction of delays and optimisation of the MCRAHNs for throughput and delays improves the efficiency of MCRAHNs. Applications which are intolerant to delay and latency are emerging, which also require high data rates and efficient protocols such as medium access control (MAC) and routing protocols (Ahmad et al., 2019; Akyildiz et al., 2020).

Spectrum mobility is another challenging factor that should be evaluated in MCRAHNs. Spectrum scarcity in MCRAHNs makes packet transmission more challenging. In designing routing algorithms that are optimised for frequent partitioning of the network due to node destruction, the following challenges should also be considered: spectrum access, spectrum and node mobility (Kumar, 2018). Spectrum access in MCRAHNs is different from CRAHNs in the sense that in MCRAHNs it has to be fast, efficient, and robust because packets must be transmitted immediately before any destruction occurs. In cases where destruction has occurred, spectrum access must take place in a partitioned network with missing nodes (Kumar, 2018). Route repair is therefore fundamental in MCRAHNs.

The proposed scheme, the spectrum aware transitive multi-cast on-demand distance vector (SAT-MAODV) seeks to address these MCRAHN challenges. SAT-MAODV integrates multi-cast routing, reactive distance vector routing, spectrum awareness and transitivity into a robust, efficient, and resilient scheme. Addressing the delay, spectrum and node mobility challenges of MCRAHN is significant to the success, stability and connectivity of military networks.

This paper is organised as follows: The related work is presented and analysed in Section 2 while Section 3 describes the proposed scheme and the techniques used. The results of the study are presented and discussed in Section 4. Finally, Section 5 concludes the study.

2 RELATED WORK

One of the most common methods used to mitigate delay in CRAHNs is the loosely coupled cross layered design (LCCLD) (Kumar, 2018). The network layers according to the Open Systems Interconnection (OSI) model are merged and optimised for quality of service (QoS) to form more robust layers which can reduce delay. Kumar (2018) proposed a routing scheme that combines routing with resource allocation for CRAHNs. The scheme routes packets based on the resources of spectrum channels that are supposed to provide sufficient QoS. When routing packets in CRAHNs, depending on the primary user (PU) activities and traffic load and density, the available spectrum resources vary between transmission attempts (Deng et al., 2018). The variations in QoS are caused by PU activities and the traffic load. More PU activities result in fewer resources to meet the QoS requirements. This means QoS for the secondary user (SU) may not be met.

One other routing method that is frequently used in mobile ad hoc networks is shortest path selection which is based on the Dijkstra algorithm (Towhidlou & Shikh-Bahaei, 2018). It is an efficient way of finding the shortest paths to the destination. Towhidlou and Shikh-Bahaei (2018) proposed a routing protocol called SACRP (spectrum aggregation-based cooperative routing protocol) which is based on aggregation, cooperative routing and shortest path selection. SACRP is efficient in reducing end-to-end delay. For route selection, SACRP uses the shortest path selection method as a first step to discover unutilised routes. It calculates the route distance of every unutilised route. The information about the unutilised routes is compared to the stored route information and the shortest path is then selected.

Routing based on channel conditions is a good method of reducing spectrum mobility delay. Channel conditions must be considered so that transmissions can be successful. SACRP (Towhidlou & Shikh-Bahaei, 2018) included a technique which incorporates features such as channel conditions in routing to reduce spectrum mobility delay in intermittent CRAHNs. It cannot buffer packets until routes are discovered. The buffered packets are dropped when new routes are not discovered soon. The features of SACRP can be integrated with a routing protocol designed for intermittent CRAHNs. The protocol should also be optimised for spectrum mobility delay reduction. Delay minimisation routing can be integrated with spectrum aggregation approaches where spectrum availability data is stored for reference to inform spectrum access decisions.

Spectrum mobility in MCRAHNs makes it more challenging to design efficient routing algorithms. Most routing algorithms fail to address the dynamic nature of spectrum bands and fail to utilise effectively, the available spectrum channels. Ji et al. (2015) proposed a spectrum-aware routing scheme for cognitive radio networks (CRNs) called spectrum-aware semi-structure routing (SSR). SSR is mainly based on the utilisation of the available spectrum. Unfortunately, most routing algorithms are not optimised for the dynamics of spectrum availability in CRNs (Hrabcak et al., 2018). SSR is a joint routing scheme, which combines routing with a power control framework. Power control is often used in wireless sensor networks (WSNs) to prolong the lifespan of a network (Bouallegue et al., 2018). It is also very important to consider it for MCRAHNs since unstable paths can cause nodes to buffer packets for a long time which requires a lot of energy.

Node mobility is another challenge which impacts the designing of routing algorithms in MCRAHNs. The location of nodes in ad hoc networks determines the routing approach. In large networks factors like the transmission range also contribute to this challenge whereby some nodes are outside the transmission range of the sending node. Geo-routing (geographic routing) is focused on dealing with this challenge. In geo-routing, the source node sends packets to the geographic location of the destination node.

Tayel and Rabia (2018) proposed a protocol called the Internet Protocol Spectrum Aware Geographic based routing protocol (IPSAG) for CRNs. The protocol uses geographic location

https://doi.org/10.18489/sacj.v35i2.17389

and spectrum awareness. IPSAG uses predefined knowledge of the spectrum and the geographical location of nodes.

In IPSAG, all the nodes have the required information about the geographic location of all the nodes that are within the specific network. When a node receives a packet, it first checks its buffer for the location of the destination node and then forwards the packet using the greedy forwarding strategy: the next hop must be the closest current node's neighbour to the destination (Anushiya & Suganthi, 2018). IPSAG also checks for the nodes which have common spectral quality before it forwards the packets. If the transmitting node has the option of transmitting to two or more nodes through the greedy forwarding strategy, then the spectral features are evaluated. The node that offers more QoS in terms of spectral quality is chosen.

2.1 Routing for Delay Sensitive Real-Time Critical Applications

MCRAHNs protocols cannot be directly applied to time-critical automation applications due to spectrum mobility, node mobility, and stochastic PU activities. A protocol called Delay-Minimised Routing (DMR) was proposed to address this problem (Sabbah et al., 2018). In designing DMR, a model was developed based on conflict probability. This model is used to detect any forms of routing conflicts in the network when routing paths have the same value (Sabbah et al., 2018). The model helps resolve such conflicts. In this study, a new routing metric called the minimum path delay was also proposed. This metric is used to evaluate the delay that is incurred in routing protocols. By using the conflict probability model, the DMR outperformed related protocols in end-to-end delay, minimum path delay, throughput, and packet loss rate.

In intermittently connected networks, packets are often replicated with the hope of reaching the destination. This routing approach causes unnecessary congestion in the network and at the nodes. Tegou et al. (2018) designed a routing protocol called Ferry Enhanced PRoPHET to address congestion caused by packet replication. Nodes called ferries are used to control the replication of the packets. The ferry nodes move within the network exchanging packet information. The packets that have already been delivered are marked delivered. The rest of the nodes are also informed about the delivered packet. The packets are then deleted when all the nodes have updated their buffers accordingly.

The comparative results show that the epidemic algorithm performs better than Ferry in terms of delivery ratio. Ferry was derived from an algorithm called Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) which uses transitivity to route packets in intermittent networks (Wen et al., 2018).

Most intermittent algorithms flood the network with copies of packets. They replicate the packets until the destination receives the packet. However, Ferry has fewer replicated packets compared to epidemic and PRoPHET algorithms. Ferry enhances PRoPHET however; it lacks spectrum awareness which is ideal for MCRAHNs. We considered the intermittent routing attributes of the Ferry in the design of our proposed scheme.

https://doi.org/10.18489/sacj.v35i2.17389

2.2 Routing Challenges and Delay

The challenge of relaying packets is very eminent in Sleep-Wake Cycling Wireless Sensor Networks (WSN) whereby the paths from source to destination are not guaranteed. Due to the limited energy, the nodes take turns to be active. Relaying packets poses a challenge when nodes sleep when idle. Such a network can be regarded to be intermittent since paths are not guaranteed. The main challenge is designing a routing algorithm which can perform well without incurring a lot of end-to-end delays and node relay delays.

Guo et al. (2018) discussed some of the delay-related algorithms. However, they lack the cognitive features required for opportunistic spectrum access. In our study, we incorporated some features of Sleep-Wake Cycling WSN since they share similarities with intermittent CRAHNs.

Gharajeh (2018) used neighbouring nodes to transmit data packets based on the residual battery energy. The depletion of battery energy results in the node becoming unavailable which partitions the network. This is similar to nodes being destroyed in military networks though, in the military, networks nodes can be destroyed at any given time. Their unavailability is not determined by the depletion of the battery energy. There is therefore a need to consider the sudden destruction of nodes.

Khanmohammadi and Gharajeh (2018) proposed a clustering-based routing protocol designed to extend the lifespan of a sensor network based on energy conservation. The objective of the protocol is similar to the approach by Gharajeh (2018) however, it is not optimised for military networks where the non-availability of nodes is caused mainly by their destruction in combat.

A neural networks-based protocol was proposed by Khanmohammadi and Gharajeh (2017) to prolong the lifespan of the network based on the residual battery, distance, and response time of the next hop. The protocol is novel however, it is not suited for military networks where the unavailability of a node is non-deterministic.

2.3 Military Networks and Multi Casting

A number of schemes were designed for military-related networks (Amanowicz et al., 2012; Bräysy et al., 2017; Onem et al., 2013; Suojanen & Nurmi, 2014; Tang & Watson, 2014) and optimised for end-to-end QoS. However, in military networks, survivability and fault tolerance of the network is fundamental and critical. The deployment of CRAHN in the military is key to the success of intermittent networks (Tuukkanen, Couturier, Buchin, Bräysy et al., 2018). Routing and MAC protocols are reviewed by Lee et al. (2021), while Kaszuba-Chęcińska et al. (2021) proposed a policy-based radio and a sensing method.

According to the literature, the following schemes are promising: multi-cast On-Demand Distance Vector algorithm (MAODV) (Jhajj et al., 2019), Extended Weight Cumulative Expected Transmission Time (xWCETT) (Kola & Velempini, 2018) and Mobility-Assisted Routing algorithm with Spectrum Awareness (MARSA) (Huang et al., 2014). The results show that they are best performing. These schemes were compared to our proposed scheme.

The performance of CRAHNs is degraded by several challenges such as node relay delay, node mobility, and spectrum mobility. These challenges affect mainly routing. When a link node moves out of range, packets which are being transmitted are dropped if alternative paths are not established on time which impacts negatively on the performance of the network. Spectrum mobility has the same effect. When a node is forced to switch from one band to another due to PU activity, it partitions the network leading to packets being dropped. This causes relay nodes to buffer packets for a long time in the event of link breakages while waiting for the establishment of new alternative routes. Furthermore, the depletion of batteries of relay nodes has the same effect. In MCRAHNs, similar challenges are also caused by the destruction of nodes in combat.

The schemes which were designed to address these challenges have partially solved these challenges. In some instances, residual battery power is not considered in the selection of routing paths. Spectrum mobility may be considered in spectrum access decisions and for routing purposes. Furthermore, the uniqueness of MCRAHNs and the destruction of nodes in combat is not considered for routing purposes in most schemes.

3 OUR PROPOSED MODEL

SAT-MAODV uses a multi-cast technique called the Informed Centralised Multi-cast (ICM) technique where a specific zone of the network is selected for zonal routing based on the data stored by the MCRAHN nodes. The availability of a route also determines the selection of a given zone. If the zone does not have a link to the destination due to route breakages and network partition, the selected zone should have a higher probability of relaying packets to the destination. This is achieved through the implementation of the Node Roaming Area (NRA) technique. Each node in the MCRAHN has a specific zone that it is most likely to roam in given that military networks are structured and strategically positioned. In addition, nodes have a buffer to store the locations of encounters. The duration of data storage is dynamic given the mobility of nodes. When nodes exchange location data, the NRA computes the probability of given nodes moving into a given zone in the event of link breakages. We refer to the zone that a node frequents as the NRA zone.

SAT-MAODV is reactive; it does not proactively construct routes but constructs routes on demand. In the event of link breakages, SAT-MAODV employs the Energy Smart Transitivity (EST) technique to repair routes. The EST is an enhancement of the transitive routing method (Jaya et al., 2017). The transitive method is shown in Equation (1):

$$\forall A, B, C \in X, \text{ if } A \subset B \text{ and } B \subset C \text{ then } A \subset C \tag{1}$$

where $A, B, C =$ nodes with different energy level
$X =$ MCRAHN
$\subset =$ meeting likelihood (Jaya et al., 2017)

In Equation (1), if node A has a likelihood to be in the zone of node B and node B has a chance of encountering node C then we can infer that node A has a high probability of encountering node C. The transitive technique was first implemented in PRoPHET which was designed for routing in intermittent networks (Pathak et al., 2017). This routing technique relays packets through nodes with the highest probability of being in the destination node's zone in the event of route breakages or destruction.

The transitive technique was improved in our approach by including the energy factor. The traditional transitive method does not consider the energy of the nodes. It only relays packets based on the probability of encounters. In our proposed method, the EST is illustrated in Equation (2)

$$\forall A_{i1}, B_{i2}, C_{i3} \in X, \text{ if } A_{i1} \subset B_{i2} \text{ and } B_{i2} \subset C_{i3} \text{ then } A_{i1} \subset C_{i3} \tag{2}$$

if and only if $i3 \geq K$
where: $A, B, C =$ nodes
$i1, i2, i3 =$ different energy levels of nodes
$X =$ MCRAHN
$\subset=$ meeting likelihood
$K =$ threshold value

The EST improves the transitivity technique through the evaluation of the energy levels of nodes. When we infer that node A has a high likelihood of encountering node C, we first check the energy level of node C. If the energy level of node C is below the threshold value, then node A is not selected as a relay node since node C does not have sufficient energy to forward the packets. This is done to reduce the packet drop rate due to insufficient energy. The packet is instead relayed to the second-best node which is likely to move into the zone of the destination node or link node. This approach reduces RP delay and NR delay because in the case of route breakages, candidate nodes with a high likelihood to encounter the desired node are selected to repair routing paths. The technique increases the packet delivery ratio. EST does not waste bandwidth as most packets are delivered instead of being dropped. ICM, NRA and EST in SAT-MAODV are shown in Algorithm 1.

SAT-MAODV uses an integrated spectrum access technique referred to as Time-Based Availability (TBA). PU spectrum bands in some applications and technologies are deterministic and can be predicted. The PUs can utilise the spectrum at any time however, where usage patterns are predictable, spectrum usage can be modelled. Some spectrum bands are used at certain periods and are vacant at certain time intervals, for example, a day broadcaster or a regional broadcaster. SAT-MAODV uses TBA to first check the period when a spectrum band is required. The nodes then retrieve spectrum data of available bands during the required period. This approach reduces spectrum mobility delay since specific bands are considered instead of sensing several spectrum bands.

Algorithm 1 SAT-MAODV with ICM, NRA and EST techniques

for each node in the MCRAHN **do**
  if nodes encounter each other (1cm proximity) **then**
    Record the location in the buffer
  end if
end for
if node i_1 has to relay a packet to node l_{i2} **then**
  Send node l_{i2}'s location request to all the neighbouring nodes
  Two nodes with the highest encounters send the location record of node l_{i2}
end if
Let the network zone from source to destination be considered for centralized multi-cast
if there is route destruction in the selected network zone **then**
  if node $A_{i1} \subset$ node H_{i3} and node $H_{i3} \subset$ node l_{i2} **then**
    if $i3 > K$ **then**
      Let node X_{i1} relay packet to node H_{i3}
    else
      Let node i_1 buffer the packet
      Select the next node with a high encounter probability of node l_{i2}
    end if
  end if
end if

The TBA technique is modelled by Set 1:

$$S = \{s_1, s_2, \ldots, s_i\} \tag{Set 1}$$

where:
$S =$ set of spectrum bands availability states.

It is fundamental to note that since Set 1 is derived from the Markov chain model, the state of each spectrum band is not dependent on its predecessor's availability state. Each state is independent of its predecessor as shown in Equation (3):

$$k_{tm} = k_{tt}k_{mt} + k_{ti}k_{mi} + \cdots + k_{tm}k_{mm} \tag{3}$$

where:
$k_{tm} =$ the availability state of the spectrum channel
$k_{t\ldots} =$ the vacant spectrum channel when the routes are unavailable
$k_{m\ldots} =$ the vacant spectrum channel after route recovery

The main features of SAT-MAODV are ICM, NRA, EST and TBA. The relationship of SAT-MAODV and its optimisation is a multivariate linear regression model of four variables mod-

https://doi.org/10.18489/sacj.v35i2.17389

elled by Equation (4):

$$Y_i = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \beta_4 x_{i4} + \varepsilon_i \tag{4}$$

where:
Y_i = SAT-MAODV performance efficiency
α = intercept term for performance efficiency
β = the slope of the model
x_i = ICM
x_{i2} = NRA
x_{i3} = EST
x_{i4} = TBA
ε_i = Standard Error (constant)

The main features of SAT-MAODV are shown in Figure 1. The figure also shows how these features of SAT-MAODV interact in discovering and maintaining routes.

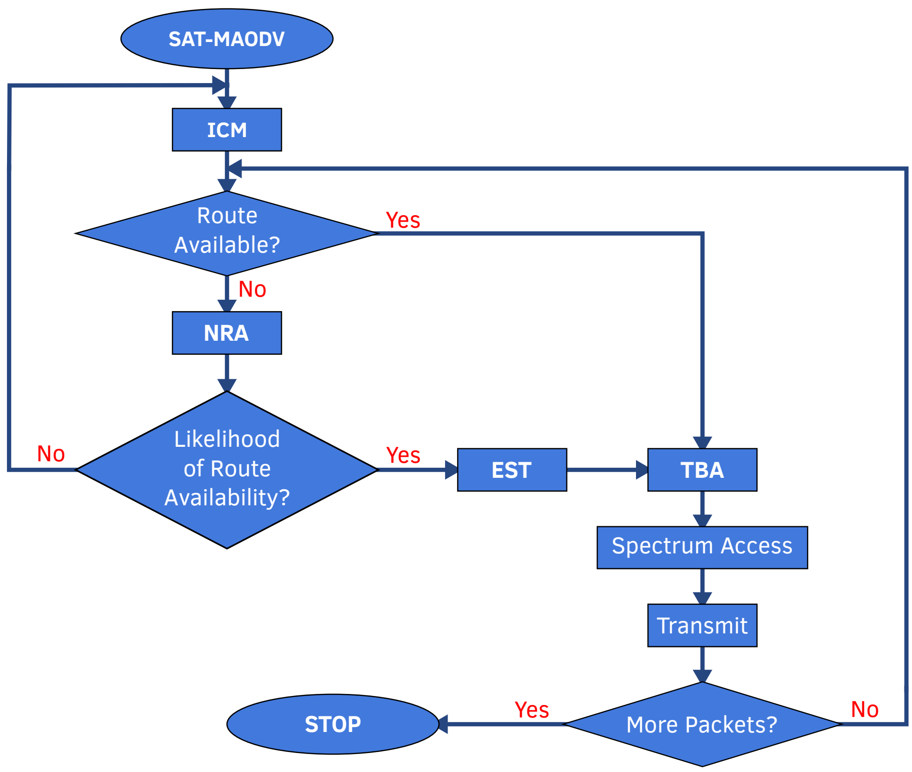

Figure 1: The discovery and the maintenance of routes in SAT-MAODV

Using the ICM, the SAT-MAODV first checks the availability of routes. If available, the TBA is evoked to facilitate the spectrum access under given constraints. Thereafter, the transmission can take place. If the route is not available, the NRA is used to determine the possibility of a route being available given the node mobility and neighbourhood data. For this purpose, the transitivity technique, the EST is employed before executing the TBA. However, if there is no likelihood of a route, the scheme backs off and retries to establish the route later.

The simulation scenarios consisted of different network sizes with 6, 35 and 70 nodes and the protocols were simulated for 100, 300 and 500 simulation seconds respectively. The simulation durations were directly proportional to the number of nodes since more time was required to investigate the behaviour of each network. Table 1 presents the parameters used in the simulation environment.

Table 1: Simulation parameters

Number of SUs	6, 35, 70
Simulation Time(s)	100s, 300s, 500s
Maximum Number of connections	15, 25, 35
Pause Time(s)	0, 50, 100, 250, 350, 500
Number of Radios	2
Simulated Algorithms	SAT-MAODV, AODV, MAODV, xWCETT, MARSA
Antenna	Omni-directional
MAC Standard	IEEE 802.11b
Number of PUs	6 (For each set of nodes)
Number of SUs	4, 33, 68 (For each set of nodes)

SAT-MAODV integrates multi-cast with spectrum awareness, reactive, and transitive routing. The main features of the SAT-MAODV are the ICM, NRA, EST, and TBA. The performance of the SAT-MAODV algorithm was evaluated and compared to Ad hoc On-Demand Distance Vector (AODV), Multi-cast On-Demand Distance Vector algorithm (MAODV) (Jhajj et al., 2019), Extended Weight Cumulative Expected Transmission Time (xWCETT) (Kola & Velempini, 2018) and Mobility-Assisted Routing algorithm with Spectrum Awareness (MARSA) (Huang et al., 2014). The next section presents and discusses the comparative results of these algorithms.

4 RESULTS

The algorithms were simulated in network simulator 2 (NS 2) version NS2.31 with the CRAHN patch ported into NS 2.31. The occurrences of node destruction were randomised to create the MCRAHN environment and to simulate the performance of the schemes in MCRAHN. This enabled the study to effectively evaluate the proposed scheme.

Several reactive routing algorithms are considered in MCRAHNs however only the two best-performing algorithms according to the literature are compared to our proposed scheme (Kola & Velempini, 2016, 2017). The algorithms are the Multi-cast On-Demand Distance Vector algorithm (MAODV) (Jhajj et al., 2019), and the Extended Weight Cumulative Expected Trans-

https://doi.org/10.18489/sacj.v35i2.17389

mission Time (xWCETT) (Kola & Velempini, 2018). These are compared to our scheme, the Spectrum-Aware Transitive Multi-cast On-Demand Distance Vector (SAT-MAODV).

Figure 2 depicts the first set of simulation results: The performance of the xWCETT scheme is evaluated against MAODV to ascertain which is a better scheme. This was necessary because xWCETT was compared with WCETT and AODV (Kola & Velempini, 2016, 2017). MAODV is the improvement of AODV as such, there is a need for such investigation.

In the scenario with 6 nodes, the results show that xWCETT incurs more delay than MAODV. This can be attributed to the fact that the xWCETT behaves the same as the AODV in packet transmission. When a packet has to be relayed from source to destination the entire network is considered. In xWCETT, route request (RREQ) and route response (RRESP) packets are sent to all the nodes in the network while in MAODV a chosen sub-net or zone is flooded with RREQ and RRESP packets. The xWCETT scheme also utilises partial routes to broadcast RREQ and RRESP if nodes are destroyed in MCRAHNs. Partial routes are only discovered when the RREQ packet reports an error in that specific route. MAODV only considered the optimal and complete routes in a given zone (Doomari & Mirjalily, 2017). The MAODV scheme is a multi-cast while xWCETT is a broadcast algorithm. As a result, xWCETT is subjected to longer delays than the MAODV.

In scenarios with 35 and 70 nodes, the graphs are clustered and it is not clear which algorithm is more efficient. We then considered the performance averages of these algorithms in Figure 4 to better characterise them. The results show that in the scenario with 35 nodes, AODV outperformed xWCETT. However, in the one with 70 nodes, xWCETT outperformed MAODV. In the scenario with 35 nodes, the better performance of MAODV can be attributed to the reason presented for the scenario with 6 nodes. It is interesting to note that MAODV performs better in small networks and poorly in large networks largely because multi-cast is more effective in small networks. In large networks characterised by frequent network portions, it degrades. The occurrences of node destruction were randomised to simulate MCRAHN. It was also done to effectively evaluate the algorithms in MCRAHN.

Given the results in Figure 2 in which we concluded that MAODV was outperformed by the xWCETT, we then evaluated our proposed scheme against the xWCETT in Figure 3. However, we also considered the best-performing algorithm in each scenario and compared these two algorithms to our proposed algorithm, the SAT-MAODV.

Figure 3 results show that our proposed algorithm performs better than both the xWCETT and the MAODV in the respective scenarios and that the SAT-MAODV is more efficient.

In Figure 4, we can observe that our proposed algorithm, the SAT-MAODV, incurs the least RP delay. This can be attributed to the fact that SAT-MAODV uses transitive routing and a multi-cast approach. Node transitivity coupled with the direction of mobility helps SAT-MAODV ascertain which node is likely to be a relay or link node. The RP delay can be prolonged by nodes in a given zone which are moving away from the desired zone thereby portioning and degrading the performance of the network. The SAT-MAODV addresses the challenge through the transitive technique, history of encounters and use of the location data of nodes.

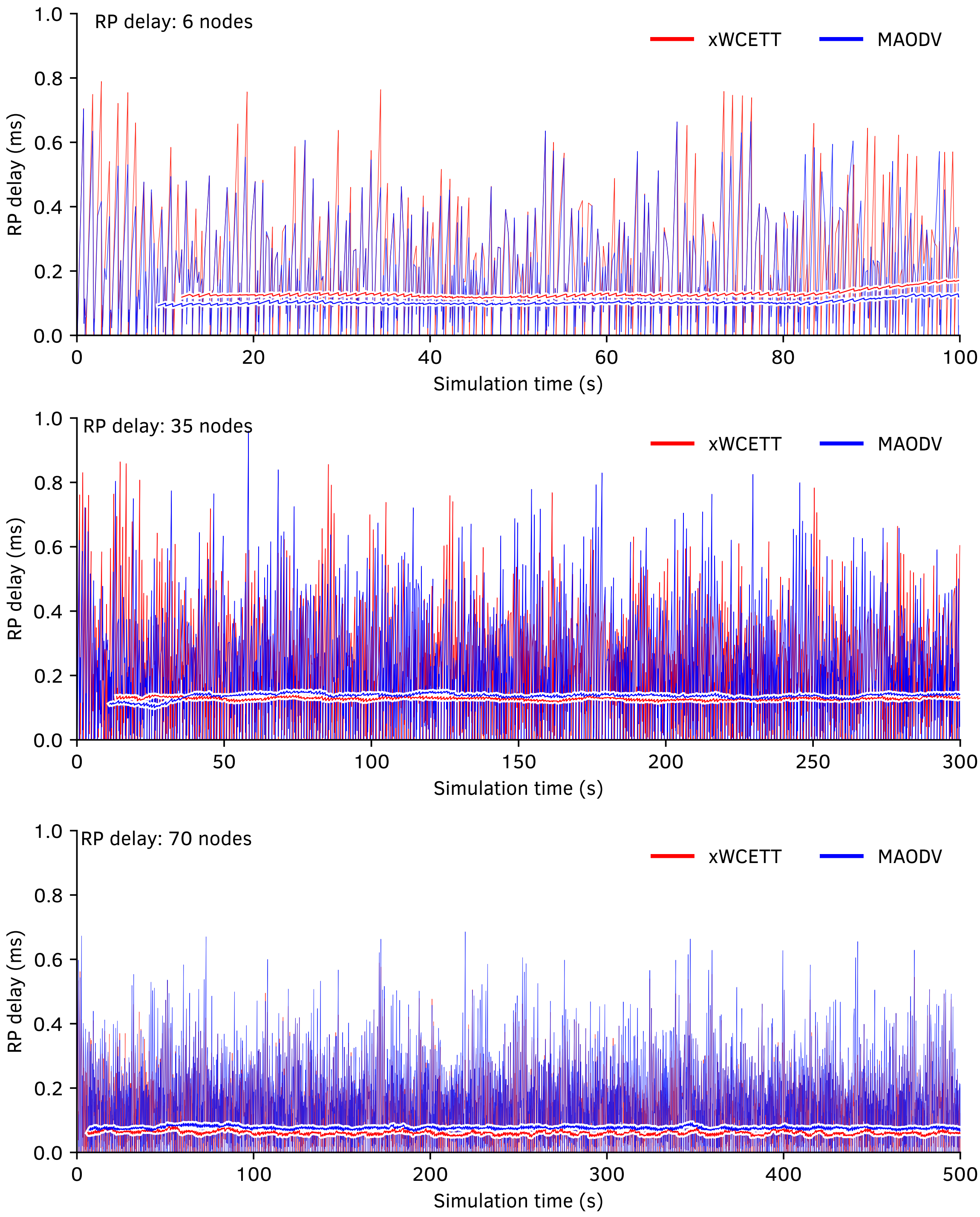

Figure 2: Comparative routing path delay results of xWCETT and MAODV. Moving averages overlaid to give an indication of the trends.

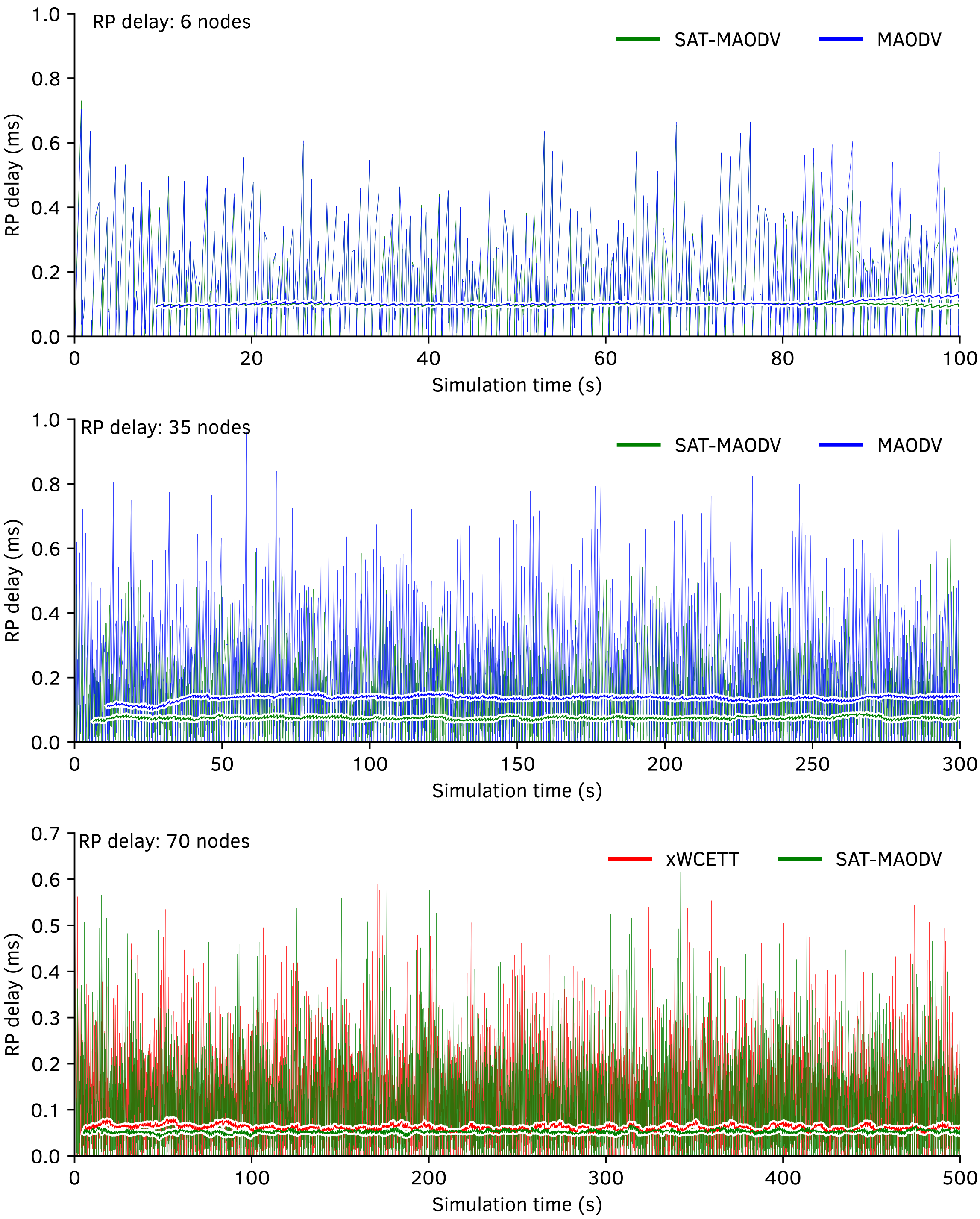

Figure 3: Comparative routing path delay results of xWCETT and SAT-MAODV. Moving averages overlaid to give an indication of the trends.

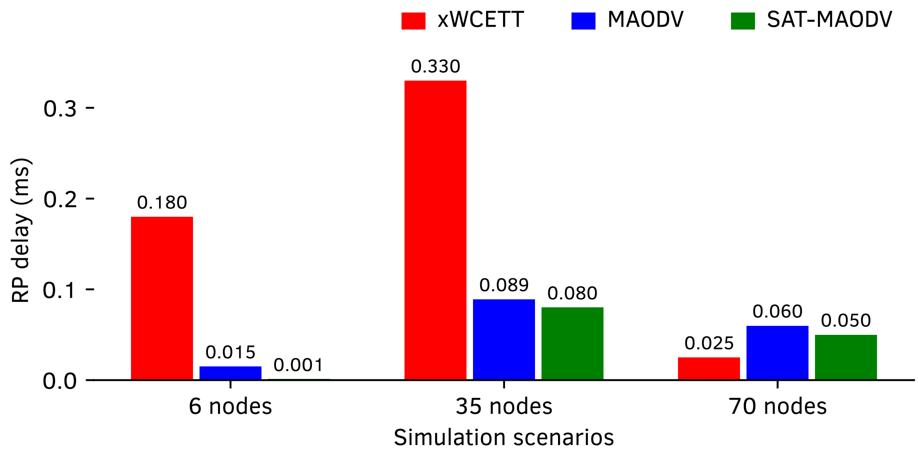

Figure 4: The average path delay results of xWCETT, MAODV, and SAT-MAODV

The other metric that we considered in our study is the NR delay. Figure 5 depicts the NR delay results of xWCETT, MAODV and SAT-MAODV. The results show that the SAT-MAODV is more efficient than the two algorithms while the average results of the three algorithms in Figure 4 provide more clarity in the analysis of the RP Delay results in Figures 2 and 3.

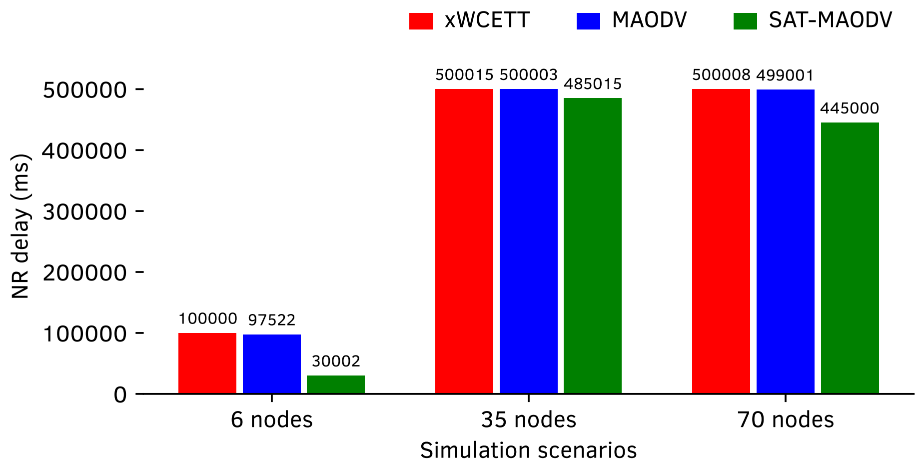

Figure 5: The node relay delay results of xWCETT, MAODV, and SAT-MAODV

The performance of SAT-MAODV is superior in NR delay because of the use of the Multi-cast (CM) and the Energy Infused Transitivity (EIT). In CM, packets are transmitted to specific zones (Nakhale & Khan, 2018). CM reduces NR delay because paths extending beyond the multi-cast group can be selected. In a complementary form, EIT is used to select the link or relay nodes with high residual energy.

The superiority of our scheme in delay can be observed in the scenario with 70 nodes in which delay slightly decreases instead of increasing. The NR delay is not solely dependent on the number of nodes. The NR delay is still measured from one node to the next. It is a one-hop-related delay. The SAT-MOADV reduced the RP delay by at least 65% in comparison with xWCETT and by at least 11% when compared with MAODV. The NR delay results also show that the SAT-MOADV is the most efficient scheme. It reduced the node relay delay by 13% compared to xWCETT's performance and by at least 11% compared with MAODV.

We also evaluated the performance of the SAT-MAODV in terms of achievable throughput. Figure 6 depicts the achievable throughput of xWCETT and MAODV. The better scheme in this instance is compared to our proposed scheme, the SAT-MAODV in Figure 7.

In the scenarios with 6 and 35 nodes, MAODV outperforms xWCETT. The MAODV uses a faster destination location mechanism the "sequence numbers approach". The sequence numbers help in maintaining the routing tables and maintaining up-to-date routing information. MAODV discovers broken routes faster than xWCETT, in small networks which results in more achievable throughput as the broken routes are avoided. In a scenario with 70 nodes, xWCETT outperformed MAODV. We observed that where there is high PU and SU activity, and high node and spectrum mobility, xWCETT manages routing better. The xWCETT is designed for CRAHNs and it uses the expected transmission count (ETC) and the expected transmission time (ETT). It performs better in large CRAHNs (Kola & Velempini, 2018).

The ETC and ETT are used to select the best path based on path availability, the expected hops, and the time interval when the transmission is expected to take place. The ETT and ETC select the shortest path if the spectrum availability is guaranteed. The ETT and ETC increase the likelihood of the presence of the spectrum during transmission. This feature is effective in large networks like the case of the scenario with 70 nodes. The SAT-MAODV improved the achievable throughput by 31% in comparison with xWCETT and 17% compared with MAODV.

In Figure 7, SAT-MAODV was compared to the two algorithms based on the results in Figure 6. In scenarios with 6 and 35 nodes respectively, SAT-MAODV outperformed MAODV which was more efficient than xWCETT in Figure 6. SAT-MAODV uses energy infused transitivity approach. When a path is broken in a zone, a relay node is chosen using energy-infused transitivity and multi-casting techniques. It is optimised for high achievable throughput as it ensures that relay nodes have adequate energy to relay packets or to buffer packets until connectivity is re-established. In the scenario with 70 nodes, the SAT-MAODV outperformed the xWCETT however, the difference is marginal. This, however, demonstrates that the proposed scheme is efficient and performs well in both small and large networks.

4.1 The PDR results for SAT-MAODV and MARSA

The results in Figures 3 to 7 show that SAT-MAODV is more efficient than AODV, MAODV and xWCETT. In this section, we evaluate the performance of SAT-MAODV in comparison with MARSA. The two schemes were evaluated in terms of packet delivery ratio and latency. The MARSA results generated in (Huang et al., 2014) and the PDR results are shown in Figure 8.

In Figure 8, we can observe that SAT-MAODV outperformed MARSA in terms of packet delivery ratio results. The performance of SAT-MAODV can be attributed to the efficiency of

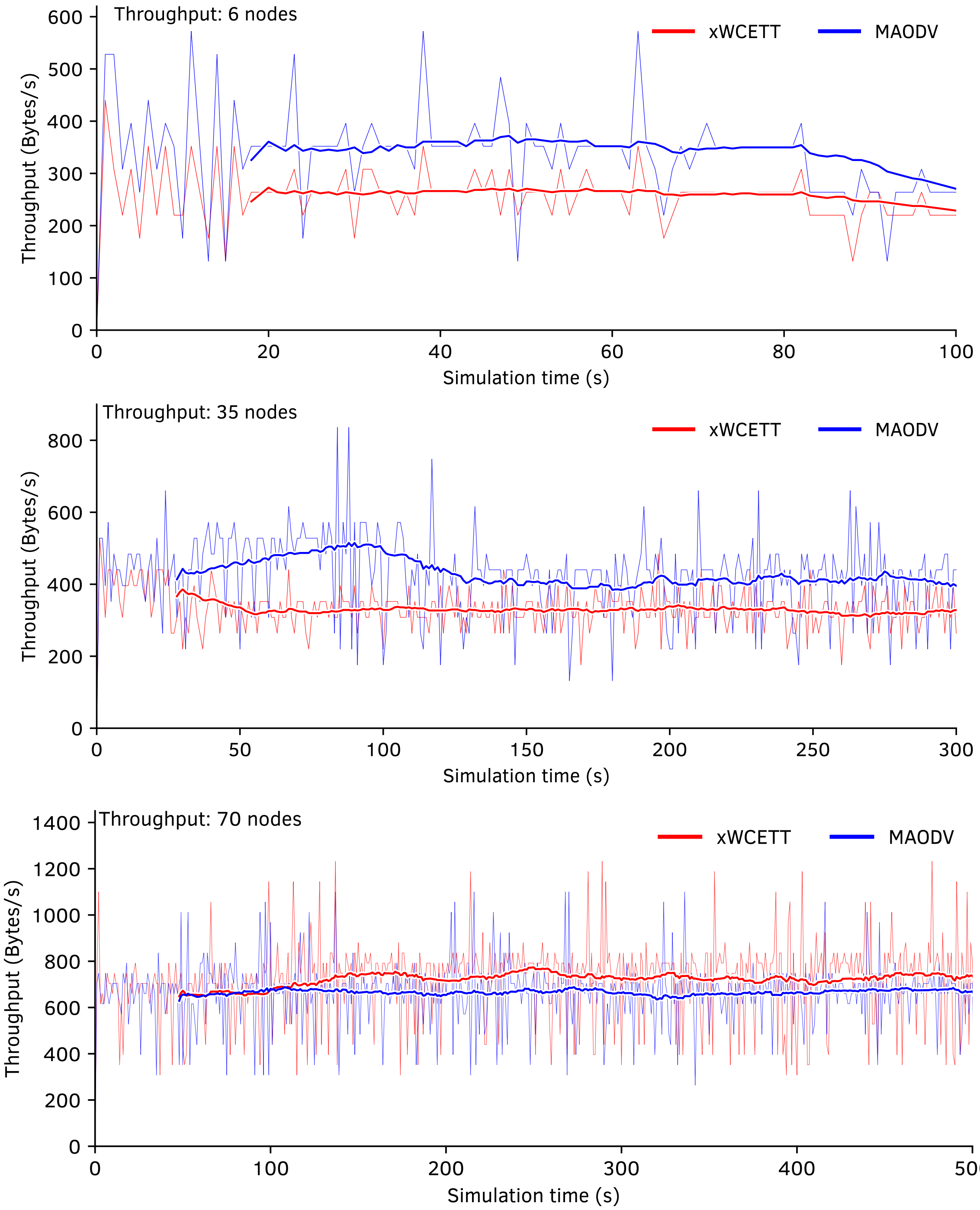

Figure 6: The achievable throughput results of xWCETT and MAODV. Moving averages overlaid to give an indication of the trends.

https://doi.org/10.18489/sacj.v35i2.17389

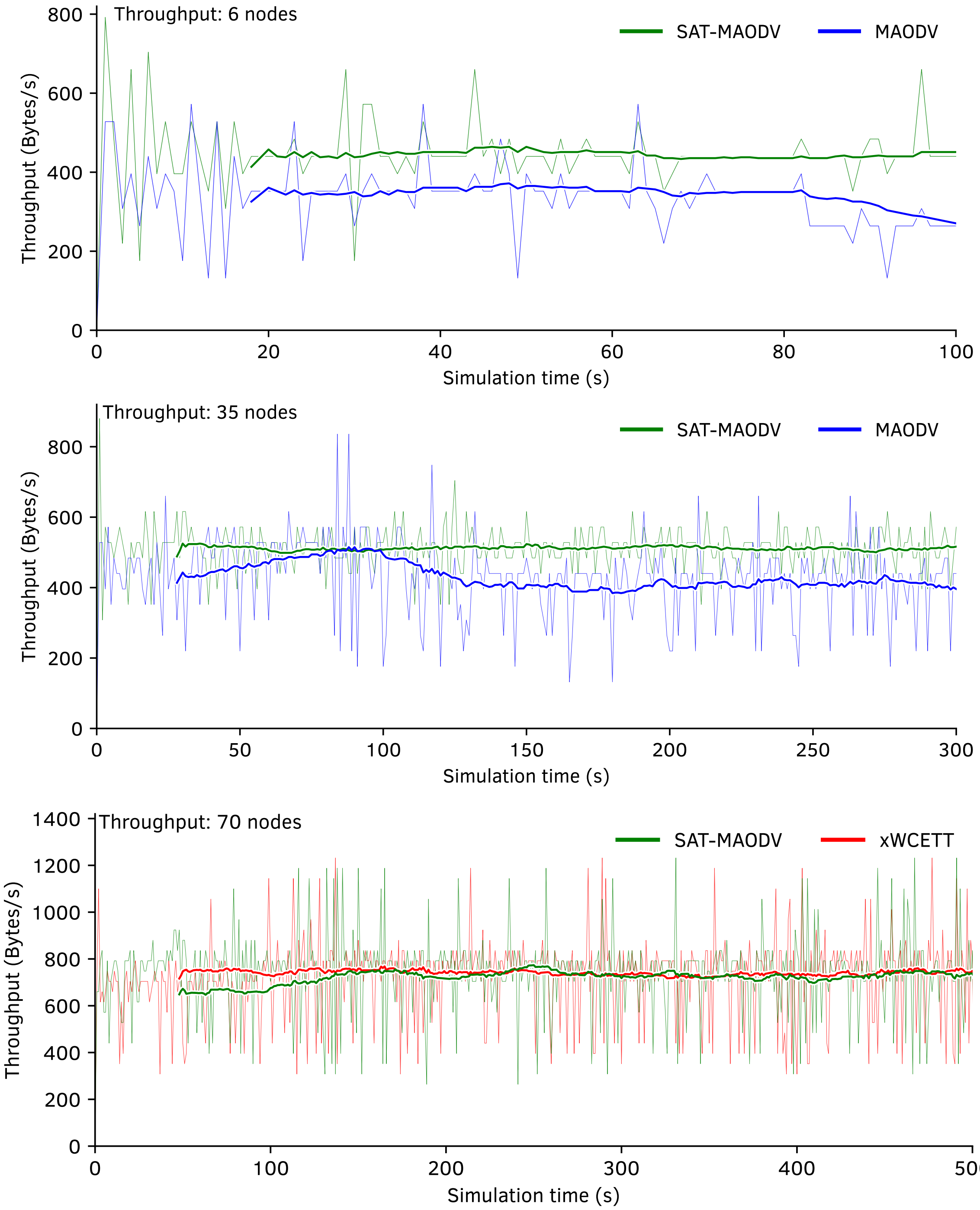

Figure 7: The achievable throughput results of xWCETT and SAT-MAODV. Moving averages overlaid to give an indication of the trends.

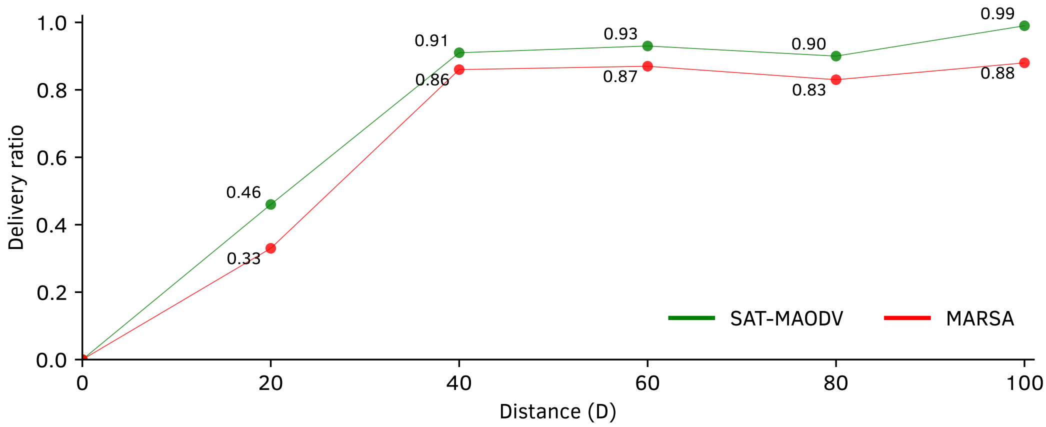

Figure 8: Packet delivery ratio simulation results for MARSA and SAT-MAODV

the transitivity technique. MARSA uses traditional buffering techniques to buffer packets. In cases where routes are unavailable, most packets for MARSA are timed-out. SAT-MAODV uses transitivity to relay packets to nodes with the highest likelihood to have an encounter with the destination nodes. The delivery ratio results show that SAT-MAODV improved the packet delivery ratio by 9% compared with MARSA. The latency results are shown in Figure 9.

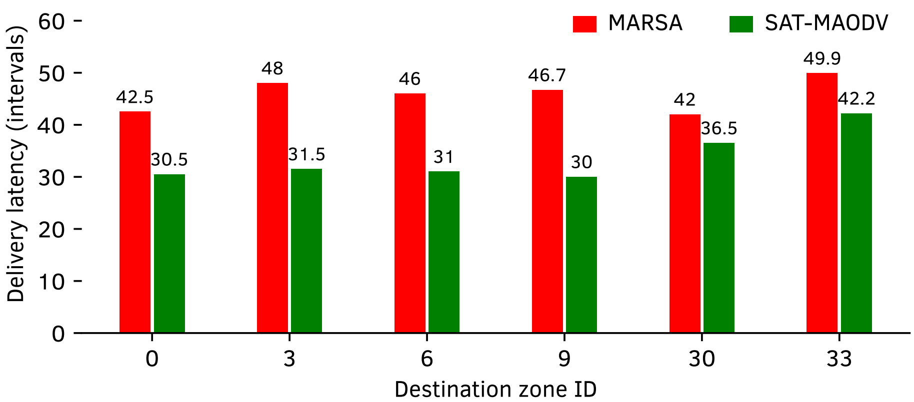

Figure 9: Delivery latency results of SAT-MAODV and MARSA

Figure 9 presents the latency results of SAT-MAODV and MARSA. We observe in the figure that SAT-MAODV incurred lower latency than MARSA for all the nodes. Delivery latency is closely linked to packet delivery ratio in terms of the factors contributing to its delay. If a packet takes too long in the network without being delivered, it results in a time-out. The delivery latency is inversely proportional to the packet delivery ratio. We observed that SAT-MOADV was superior to MARSA. It reduced the MARSA latency results by at most 27%.

The performance of SAT-MAODV is attributed to the transitivity technique which relays packets to nodes which are likely to move into the zone of the destination nodes. In the case of MARSA, the packets are buffered until another route is re-established. The need for the re-establishment of routes sometimes is caused by spectrum mobility. As a result, packet delivery is delayed resulting in packets being lost or dropped.

5 CONCLUSION

The objective of the study was to address routing challenges in MCRAHNs. MCRAHNs is an intermittent network characterised by the destruction of nodes in combat which partitions the network. We proposed the SAT-MAODV scheme and evaluated its performance using the following metrics: RP delay, NR delay, SM delay, and throughput.

The performance of the proposed algorithm, the SAT-MAODV which consists of unique techniques such as the CM approach, Time based Spectrum Awareness, Transitive Routing and EIT, was compared with xWCETT, MAODV and MARSA. The results show that the SAT-MAODV is the best-performing algorithm and that it is efficient in both small and large networks. It degrades gracefully in large networks.

Node and spectrum mobility coupled with the destruction of nodes is still a challenge for the delay and latency-intolerant network technologies such as the fifth generation and the envisioned sixth generation of communication and beyond technologies. The efficiency of SAT-MAODV in route selection can be improved by incorporating the channel selection in the selection of the next hop based on the PU activity.

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